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DELIVERABLE 2.4.4 – EVALUATION AND SINGLE WELL MODELS FOR THE DEMONSTRATION WELLS

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Single-well models and Evaluation of Treatments

Two single-well models were developed for Michelle Ute and Malnar Pike wells. The perforated intervals span thousands of feet in both the wells. Geological properties were calculated for all the perforated beds. The information was used to develop models for these two wells. These were comprehensive models since they took into account all the perforated beds.

Model parameters

Both Michelle Ute and Malnar Pike wells are perforated in multiple beds. Michelle Ute is perforated in 69 beds, while Malnar Pike is perforated in 55 beds. The models were developed for a 40 acre (1320 feet in the x and y directions) area surrounding the wells. The property values observed at the well bores were assumed continuous over the entire 40-acre area surrounding the well. The numerical values used for various parameters are listed in Table 1.

The models had 8 blocks with x and y dimensions 165 feet (in the x and y directions each). Low-porosity, low-permeability blocks separated the blocks representing perforated zones. This resulted in 109 layers in the vertical direction for the Malnar Pike model and 137 layers for the Michelle Ute model. The thickness of the grid blocks varied according to the log calculated thickness data. The initial saturation varied according to the values calculated from logs. The initial pressure varied with depth at a gradient of 0.5 psi/foot. The bottom-hole pressure was 3000 psi for the first year of production and 2000 psi in subsequent years of production. The initial GOR was set to the average GORs observed during the first month of production in each well.

Initial History match

The field production operations were duplicated for the history match. Therefore, it is not clearly understood which beds in any particular well are responsible for production. Even though the wells were perforated in multiple beds, all the beds were not perforated at the same time. This was taken into account in the models by opening up the respective beds at appropriate times. The permeabilities of the grid blocks representing the perforated beds were adjusted to match the field oil and gas production. Initially, only the permeabilities of the beds perforated at that time were adjusted until the next sets of perforations were added. When the new set of perforations were added, only the properties of newly perforated beds were adjusted. The properties of the set of perforations already open were not changed. In order to match the production data, the overall permeabilities were reduced after the last sets of perforations were added for both the wells. For Michelle Ute well the overall permeabilities were reduced to 8% of the original values, while for Malnar Pike well the overall permeabilities were reduced to 1% of the original value.

The model predictions for the cumulative oil and gas productions for Malnar Pike well are compared with the field data in Figures 1a and 1b. Figures 2a and 2b show the comparisons for Michelle Ute well. As can be seen from the figures, the model predictions are in close agreement with the field data. The oil production match is better than the gas production, though the gas production predictions are not significantly different than the field data.

The permeabilities and the fracture properties used to obtain the history match are listed in Table 1. Extremely low permeability values of these properties were needed to obtain the production history match. There was a significant difference between the matrix permeability values used for the two models. The matrix permeability for Malnar Pike model varied between 0.1 - 2.5 mD, while for Michelle Ute model it varied between 0.005 - 0.09 mD. For both the models, the fracture porosity was only 0.02% of the reservoir volume. The fracture frequency was 1 per 165 feet for Michelle Ute model and 1 per 125 feet for Malnar Pike model. The fracture permeability was constant at 0.23 mD for Michelle Ute model and varied between 0.02 - 0.22 mD for Malnar Pike model. These were adjusted when evaluating the performances of treatments in these wells.

The numerical models (four-section, as well as single-well) do a reasonably good job of matching the field production data. The numerical parameters used for the matrix rock permeability and the fracture properties are extremely low. The low values of the matrix permeability are close to the experimentally observed values. Other researchers also have observed extremely tight reservoir bed rocks in the Bluebell Field (1, 2). Because of the tight nature of the reservoirs, the production from the Altamont and Bluebell fields is due to the presence of naturally occurring fracture networks (1, 2, 3). The high production from the wells in the west four-section area is due to the good quality of the reservoirs. These reservoirs have sands with high cumulative thickness and average porosity. Even these good quality sands do not produce up to their full potential due to the low values of fracture properties used. The extreme low values of the fracture properties in all the models suggest that the fractures are not fully contributing to the production. Wagner (4) analyzed some of the cores from the Bluebell Field for fractures. A large number of the fractures were filled with calcite, pyrite or clay. One of the other reasons for non-contributing fractures could be damage to the formation near the well bore. Frequent treatment to the reservoir rocks could damage the near well bore region. It could also fill the fractures near well bore, rendering them ineffective for fluid flow. For the Michelle Ute and Malnar Pike wells, the overall permeability values had to be reduced significantly to match the production. The permeability reductions were applied only to the well bore blocks and not to the entire model. The values were reduced after the final sets of perforations were added to the wells. These extreme reductions in the permeability values (92 % for Michelle Ute and 99% for Malnar Pike) suggest that the near well bore formations have been damaged with time. The reductions required can be used to quantify the level of damage.

Model Sensitivity

The numerical values of a number of parameters required for the development of the models were unknown and obtained by trial and error during the history match. This reduced the uniqueness of the numerical models. The sensitivity of the models to changes in various parameters was studied for Michelle Ute model. The variation in oil and gas production was studied with respect to the following parameters.

- Block dimensions
- Fracture porosity
- Fracture frequency
- Fracture permeability

Effect of variation in block dimensions

The initial models were developed with 8 grid blocks with x and y dimensions of 165 feet. The number of blocks were varied by varying the block size from 82.5 to 660 feet in both the x and y directions. Due to the limitations in the flow simulator, the lowest possible block size was 82.5 feet. The production results for various block sizes are plotted in Figure 3. The change in block size did not have significant effect on oil or gas production. The fracture frequency was kept the same for all the models to ensure the same amount of fracture to matrix fluid transfer.

Effect of variation in fracture porosity

The value of the fracture porosity used to obtain the history match was extremely low. The total fracture volume was $2x10^{-6}$ times the entire reservoir volume. The fracture porosity was varied from $2x10^{-6}$ to $2x10^{-2}$ and the effect on overall production was studied. The results are shown in Figure 4

Increasing the fracture porosity from $2x10^{-6}$ to $2x10^{-2}$ had little effect on the cumulative oil production. Comparing the gas production results it can be seen that except for the highest porosity, the cumulative gas production numbers are close to each other. For porosity of 0.02, the gas production was higher than the other models. The average pressure in the reservoir for the models with fracture porosity lower than 0.02 is about 4170 psia. For the model with fracture porosity 0.02 the average pressure is 4090 psia. Comparing the fracture pressures, it can be seen that during most of the production, the pressure for model with high fracture porosity is lower than the models with low fracture porosity. Increased fracture porosity means larger fractured reservoir volume resulting in faster depletion of the reservoir. As the pressure drops below the bubble point pressure, free gas is formed in the reservoir, which is produced preferentially.

Effect of varying the fracture frequency

Fracture frequency is one of the most important parameters characterizing the fracture networks. Fracture frequency is defined as the number of fractures per unit length. For the Michelle Ute well, the fracture frequency used was 1 fracture per 165 feet in the x and the y directions. The fracture frequency was varied from 1 per 165 feet to 1 per 10 feet. The resulting oil and gas production predictions are compared in Figures 5a and 5b.

As can be seen from Figure 5a, a as the number of fractures is increased, the cumulative oil increases steadily. In the dual-porosity, dual-permeability models, the fracture frequency is used to calculate the shape factor in the matrix to fracture transfer function. The shape factor is calculated from effective matrix block dimensions. The effective matrix block dimension decreases with increased fracture frequency, which results in higher value of shape factor. Thus, the amount of oil transferred from matrix to fracture increases with the fracture frequency. With the increased amount of oil transferred to the fracture, the rate of oil production and cumulative oil production increases. Even though reservoir models with higher fracture frequency produce more oil than the ones with lower frequency, the total amount of oil in place is the same for all the models. Increased oil production results in reduced average pressure. The average pressure at the end of the simulations for the model with a frequency of 1 fracture per 10 feet was 4090 psi. For the model with a frequency of 1 fracture per 1320 feet the average pressure was 4370 psi. For the models with high fracture frequency, the amount of gas produced increased due to two reasons. Increased oil production results in increased gas production because of the dissolved gas associated with the produced oil. The second reason is that the lower reservoir pressure results in increased amount of free gas in the reservoir. As the amount of free gas in the reservoir increases, gas is produced preferentially. Thus, for the models with high fracture frequency along with the increased oil production the gas production also increases.

Effect of variation in fracture permeability

To obtain the production history match, both the matrix and the fracture permeability values were varied. The effect of variation in permeability was studied by varying the values of fracture permeability while keeping the matrix permeability values constant. In the Michelle Ute model, the value of fracture permeability used was 0.23. To see the effect of fracture permeability, it was varied between 0.1 to 50 mD. The oil and gas production results for different fracture permeability values are compared in Figures 6a and 6b.

Increasing the fracture permeability increases the oil as well as gas production for fracture permeabilities up to 5 mD. Above 5 mD, increasing the fracture permeability does not have a significant effect on the production. In the dual-porosity, dual-permeability approach, the oil present in fractures is produced faster since only fractures are connected to the production well. As the amount of oil present in the fracture systems decreases, the production is limited by the rate of oil transfer between matrix and fracture. Since matrix has large storage capacity (hence more oil in place than fractures) it acts as the source of oil to the fractures. The transfer between the matrix and fractures is limited by matrix permeability as well as fracture density. If the values of matrix permeability and fracture frequency are kept constant, increase in fracture permeability above 5 mD does not result in higher production. For the values of different properties used in this model, the fracture permeability cutoff appears to be 5 mD. For another set of values this value may be different.

Model Updates and Prediction of the Performance of the Treatment

In Malnar Pike, two test intervals were treated; test interval 3, between 12950 to 13050 feet and test interval 4 between 12,680 to 12,730 feet. A bridge plug was set at 13060 feet so that the perforations below this depth were not contributing to production. Because of the treatment, the oil production increased from about 20 barrels/day to about 35-40 barrels a day.

The dual-porosity, dual-permeability model employed previously to match oil and gas production from Malnar Pike was modified to assess the treatment. Relevant matrix and fracture properties used in the model are presented in Table 1. The model aerial extent was 40 acres. The well intersected 109 layers; 55 oil bearing layers separated by 54 non oil bearing zones. Each of the zones were assigned appropriate depths.

When measured water saturations were used in the model, water produced from the model was two times the actual water produced in the field. In order to match the field water production, water relative permeabilities were altered. The new set of relative permeabilities are shown in Table 2.

The cumulative oil, gas and water production by October 1997 as predicted by the model are compared with the field totals in Table 3. As can be seen from the table, the agreement between the model predictions and field data is excellent. Even though this end-point history match reasonably good, the oil, gas and water production results from the model differ considerably from the field results (Figures 7, 8 and 9). The oil production from the field is still reasonably well matched; however water and gas data could be improved. Considering the complexity of the data set and the interdependency of data types, the history match is reasonable. The difference between this history match exercise and that reported previously is that an attempt has been made to match the water production data as well.

The model predicted a total oil rate of 16 barrels/day in October 1997. Several different strategies were attempted to match the post treatment rate of about 40 barrels/day. Only the properties in the affected zones were changed at the treatment time. All of the strategies and corresponding rates after treatment are listed in Table 4. It was hypothesized that the treatment would have increased fracture permeabilities, extent of fracturing and or frequency of fracturing. Each of these options were examined either in isolation or in combination with other options. One final option of adding a new zone was also examined.

As seen in Table 4, it is possible to realize the gains in production by a variety of methods. Increasing the fracture permeability to 22 md appeared to provide the most realistic increase in production. However, in most of the strategies examined, the production rate decreased to about 25 barrels/day after about 6 months. Only in the scenario where an equivalent new zone was added to the reservoir, the production remained steady at around 31 barrels/day well after the zone was opened. The zone was 30 foot thick with a porosity of 0.14 and an initial oil saturation of 0.7. The zone had a matrix permeability of 1.5 and fracture permeability of 2.2 md (properties of the older zones). Assuming only 3% recoverable oil from the zone (based on the performance of the well) it was hypothesized that net reserves of about 27,000 barrels were added the well.

The Michele-Ute model was also revised. Field water production from Michele-Ute is shown in Figure 10. There are apparently two distinct regimes in the water production behavior. The water production rate is very low for about 2700 days of production (December 1992). Only about 5300 barrels of water are produced to this point. The rate drastically increased at this time and the total production reached about 25,000 barrels at 4600 days of production (June 1998). In order to match this behavior, two sets of water relative permeabilities were employed; a set for the first 2700 days and a different set after 2700 days. These relative permeabilities are shown in Table 5.

Michele Ute treatment did not change the oil production rates over the long term. The treatment once again could have increased fracture permeabilities or extent of fracturing. However, since the production rate did not increase over the long run, the fractures must have gone back to their original characteristics.

Summary and Conclusions

The initial history match of the two project wells was reasonably successful. All of the perforated intervals were included. The key feature of both the models was time-varying permeabilities. In the modified models, apart from being able to match the post-treatment rates, attempt was made to match water production from the project wells. In the Michele-Ute well time-varying relative permeabilities were employed. The end-point match for the Malnar Pike well for the cumulative oil, gas and water was excellent. The comprehensive history match over the entire time period was reasonable.

Of the five different possibilities identified in having caused the post-treatment production rate enhancement in Malnar-Pike, increase in fracture permeability was determined to be the most likely factor leading to consistent increase in production rate. Analysis performed by adding a new producing zone showed that the treatment added additional reserves of about 27,000 barrels of oil.

Table 1- Parameters for the comprehensive models for Malnar Pike and Michelle Ute wells.

Parameter	***Malnar Pike***	**Michelle Ute**
Reservoir extent (ft.)	9582 - 14360	10,413 - 14,445
Grid	8 * 8 * 99	8 * 8 * 137
Grid block size (x and y)	165 feet	165 feet
Porosity	0.0 - 0.21	0.0 - 0.16
Matrix permeability	0.1 - 2.5	0.005 - 0.09
Fracture porosity	0.000002	0.000002
Fracture frequency	1 per 125 feet	1 per 165 feet
Fracture permeability	0.02 - 0.22	0.23
Pressure	0.5 psi / foot	0.5 psi/feet
Oil gravity	35 API	35 API
Gas gravity	0.75	0.75
Initial GOR	1100 scf/stb	900 scf/stb
Initial bubble point pressure	4795 psi	4146 psi
Initial oil saturation	0.1 - 1.0	0.0 - 0.86
Bottom hole pressure	3000 psi	3000 psi

Table 2: Relative permeabilities used to obtain the history match for the Malnar Pike well

Water Saturation	Relative permeability to water	Relative permeability to oil
0.22	0.0	1.0
0.3	0.05	0.1
0.35	0.1	0.05
0.4	0.15	0.0175
0.5	0.5	0.0073
0.6	0.7	0.005
0.8	0.9	0.003
0.9	0.96	0.001
1.0	1.0	0.0

Table 3: Production match between the model and field data - Malnar Pike well

* -extrapolated from available data

Production as of December 1993				Production as of October 1997			
Field Data		Model Predictions		Field data		Model Predictions	
Oil (Mstb)	93	Oil (Mstb)	100	Oil (Mstb)	113	Oil (Mstb)	125
Gas (MMscf)	79	Gas (MMscf)	87	Gas (MMscf)	96*	Gas (MMscf)	119
Water (Mstb)	100	Water (Mstb)	102	Water (Mstb)	122*	Water (Mstb)	110

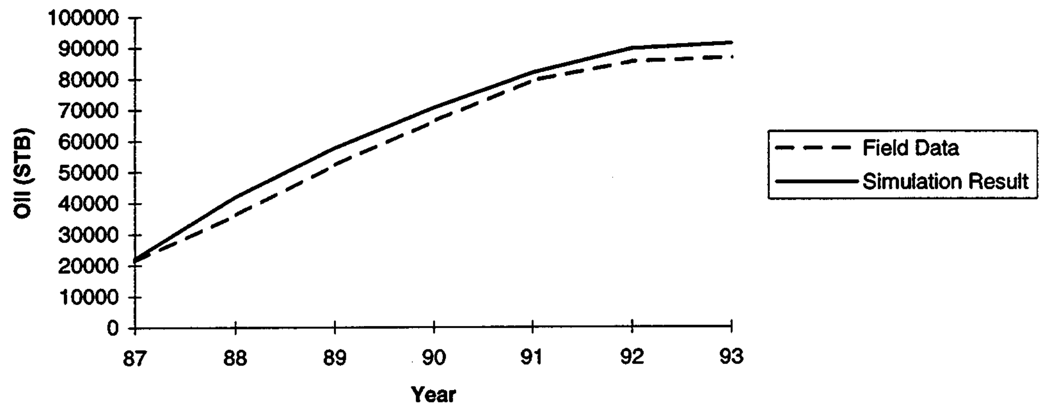
Table 4: Different strategies used in emulating the treatment in Malnar Pike

Strategy	Production rate immediately after treatment (stb/day)	Production rate 4 months after treatment (stb/day)
1. Increase fracture permeability in affected zones from 2.2 to 22 md	39	25
2. Increase extent of fracturing in the affected zones from 495 feet to 660 feet	29	22
3. Combine strategies 1 and 2	35	23
4. Increase fracture frequency to one every 5 feet	41	24
5. Add a new zone 12 feet thick of porosity 0.1 and oil saturation 0.7	39	31

Table 5: Relative permeabilities used is matching water production from Michele-Ute over the entire time interval

Water Saturation	Water relative permeability for the first 2700 days	Water relative permeability for the after 2700 days	Oil relative permeability
0.22	0.0	0.0	1.0
0.3	0.0	0.0	0.7
0.4	0.0	0.0	0.4
0.5	0.003	0.02	0.3
0.6	0.009	0.06	0.05
0.8	0.015	0.1	0.03
0.9	0.021	0.14	0.0
1.0	0.03	0.2	0.0

a)



b)

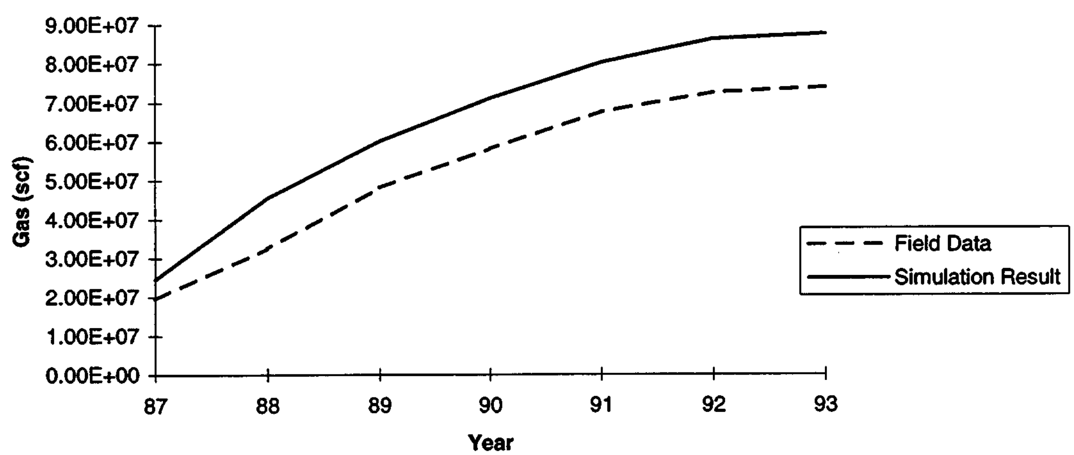
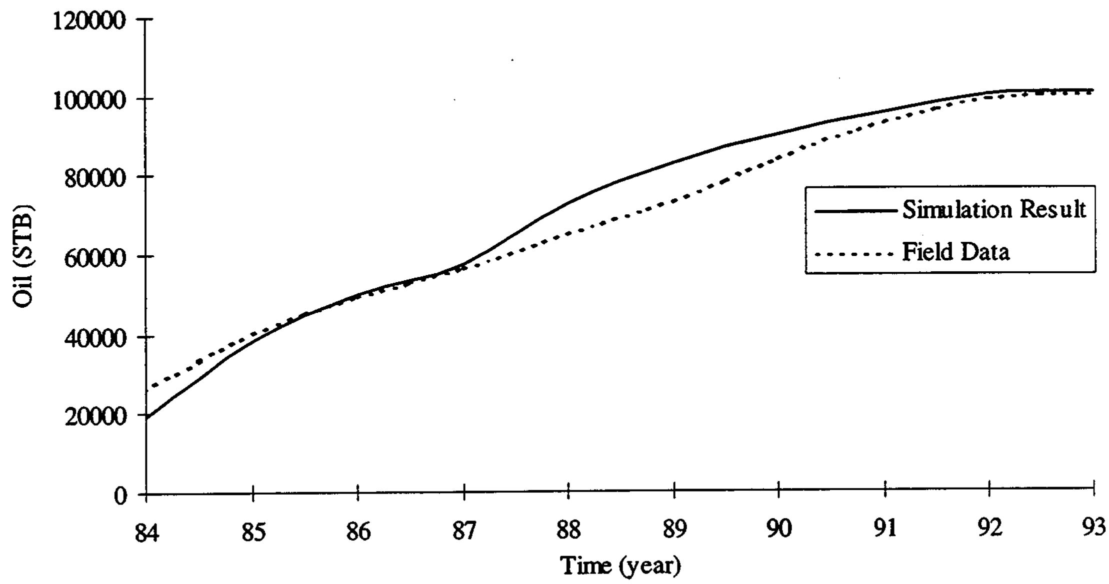


Figure 1: Field production comparison with the original model predictions for the Malnar Pike well: a) cumulative oil production, b) cumulative gas production.

a)



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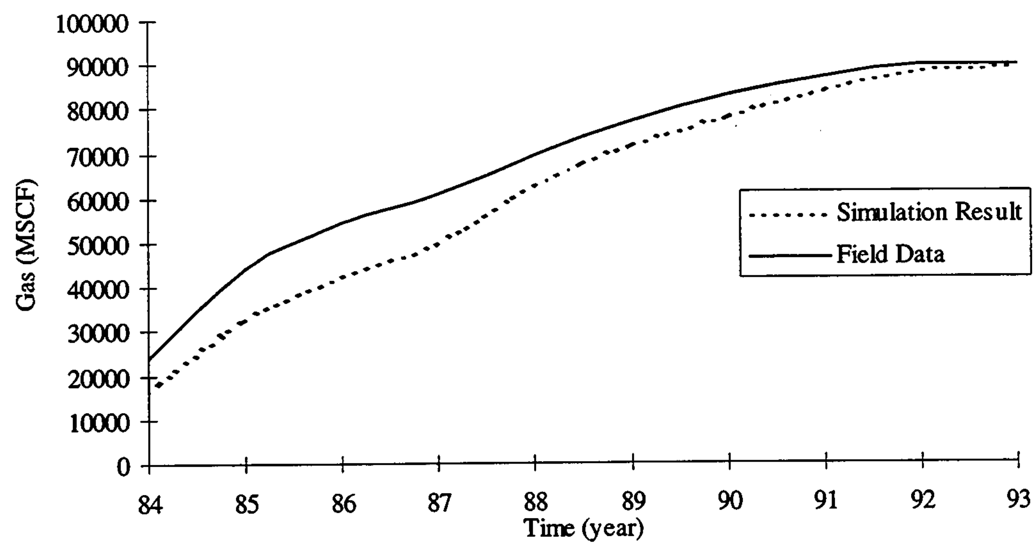
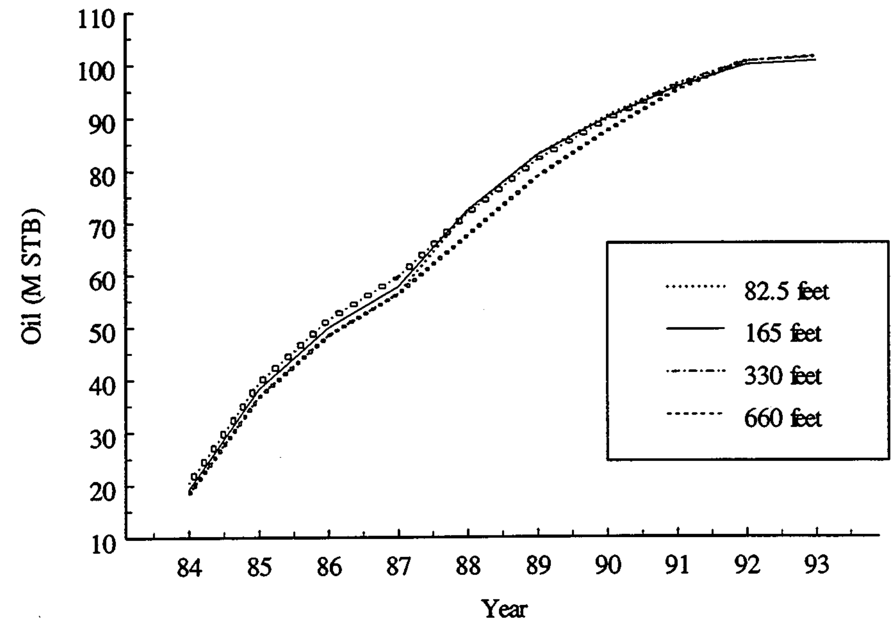


Figure 2: Field production comparison with the original model predictions for Michelle Ute well: a) cumulative oil production, b) cumulative gas production.

a)



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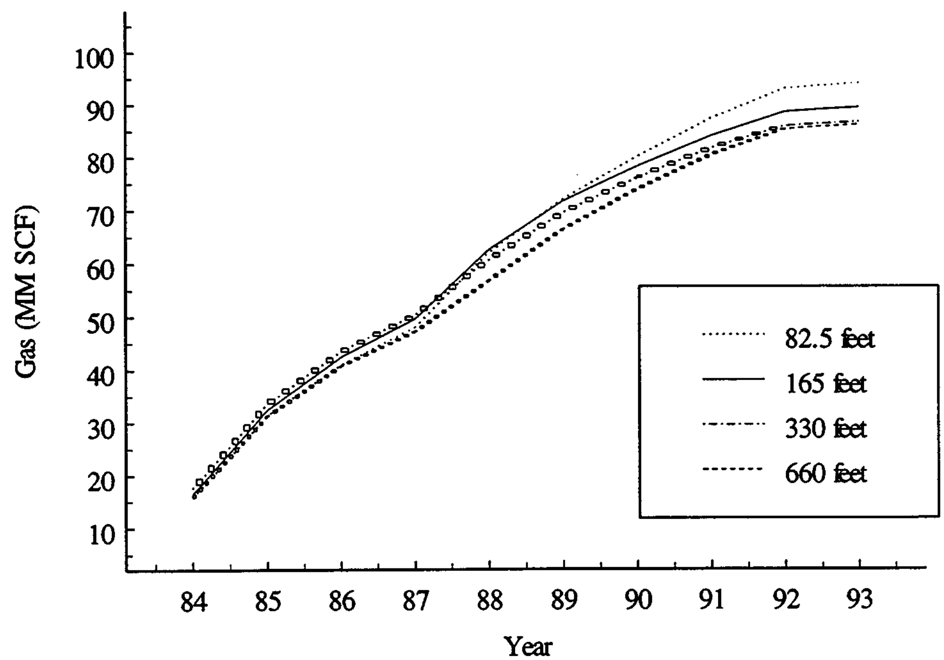
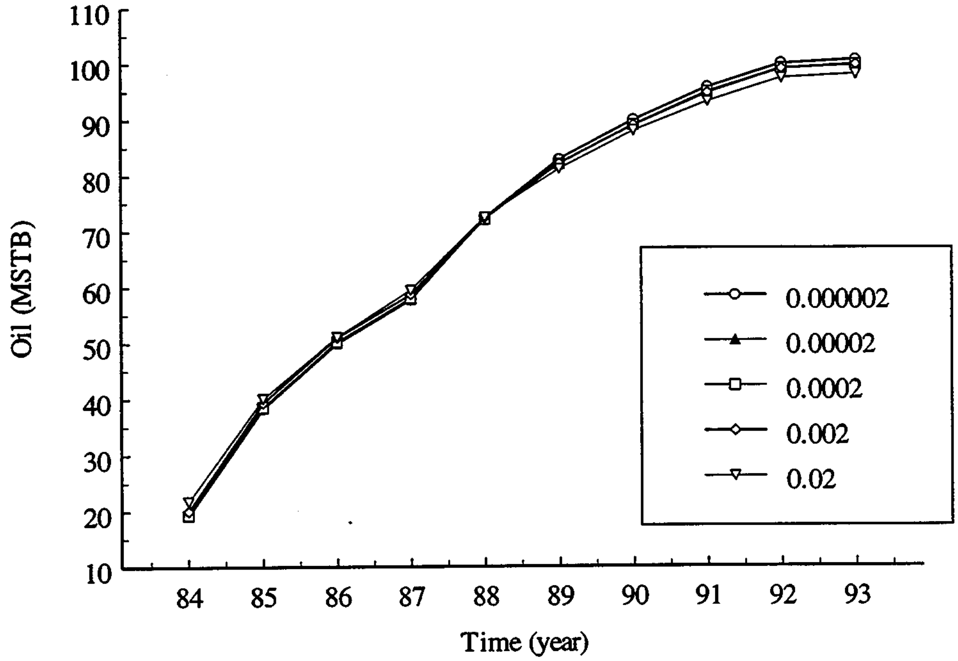


Figure3: Effect of block size on cumulative production for Michelle Ute well: a) oil, b) gas.

a)



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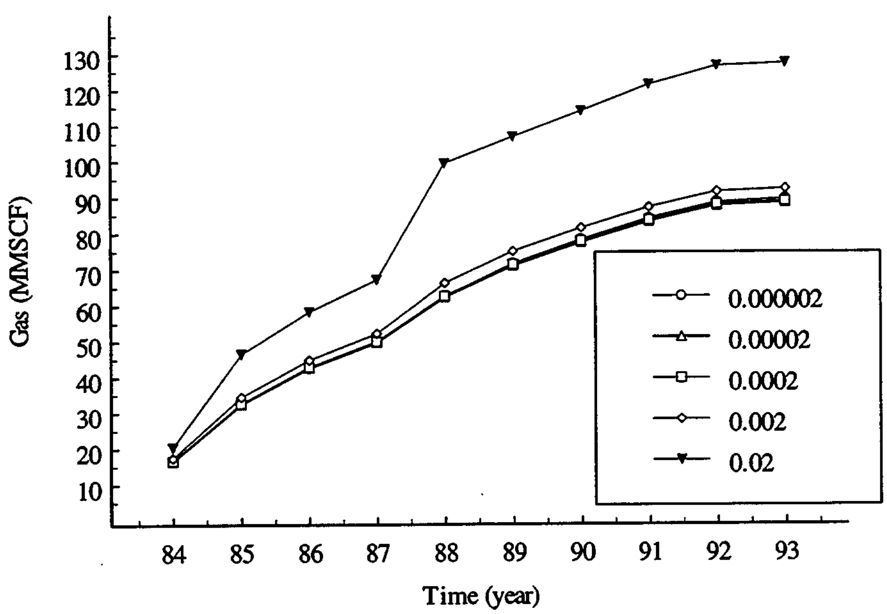
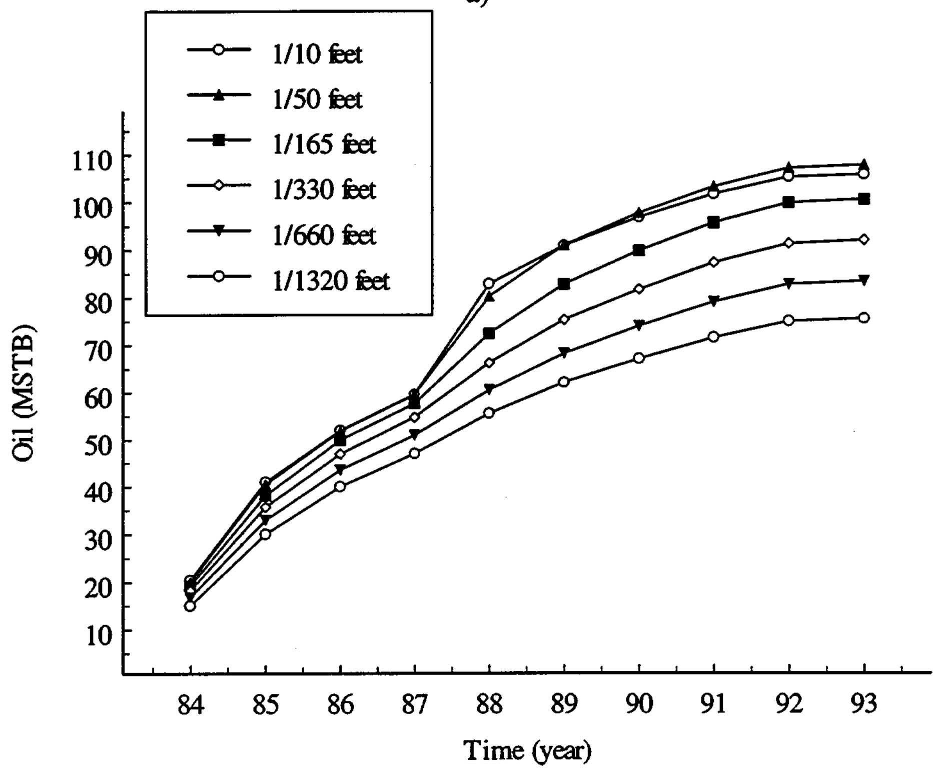


Figure 4: Effect of fracture porosity on cumulative production from Michelle Ute well: a) oil, b) gas.

a)



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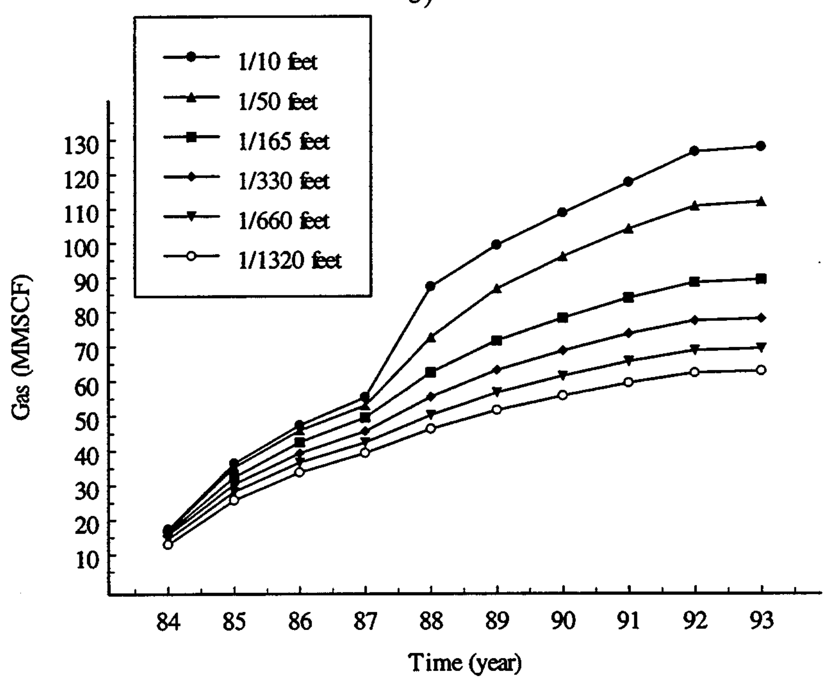
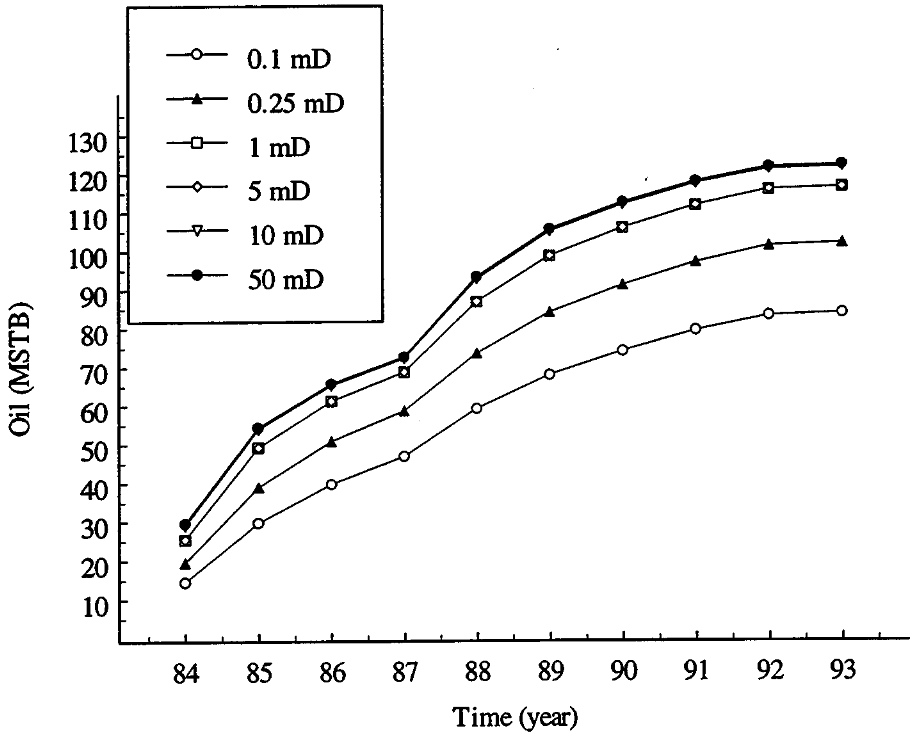


Figure 5: Effect of fracture frequency on cumulative production for Michelle Ute well: a) oil, b) gas.
a)



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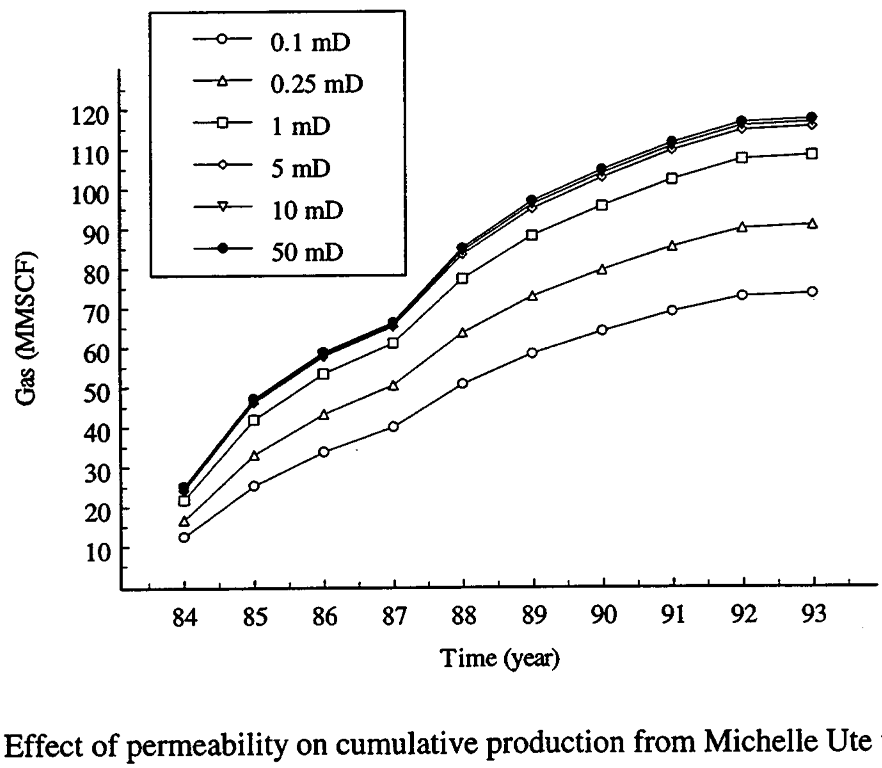

Figure 6: Effect of permeability on cumulative production from Michelle Ute well: a) oil, b) gas.

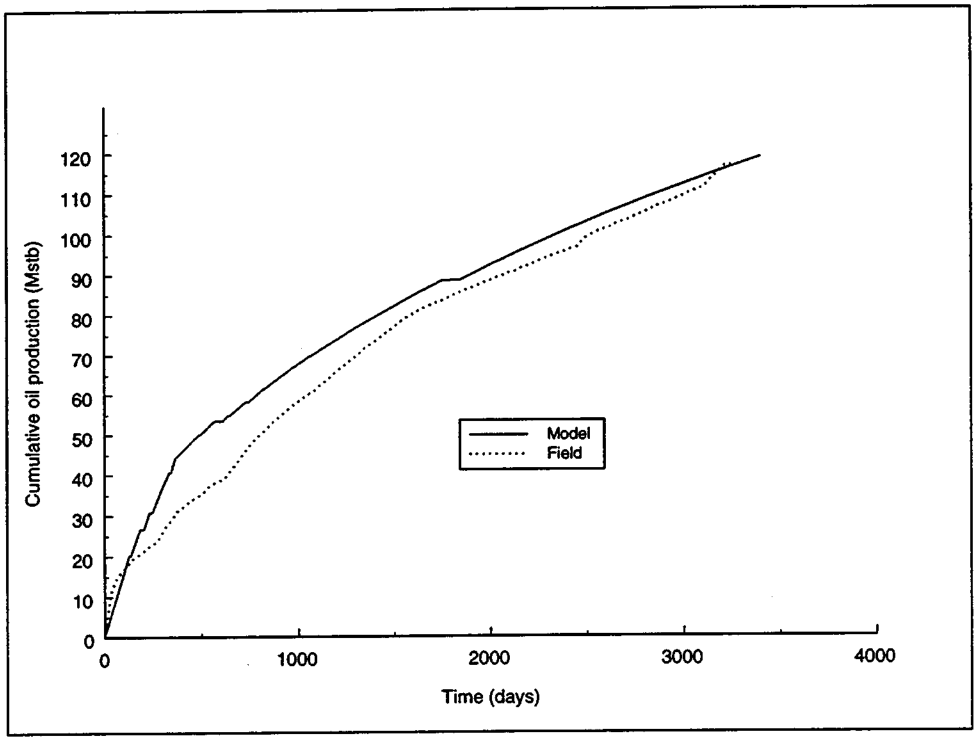

Figure 7: Comparison of oil cumulative production in Malnar Pike with the modified model predictions

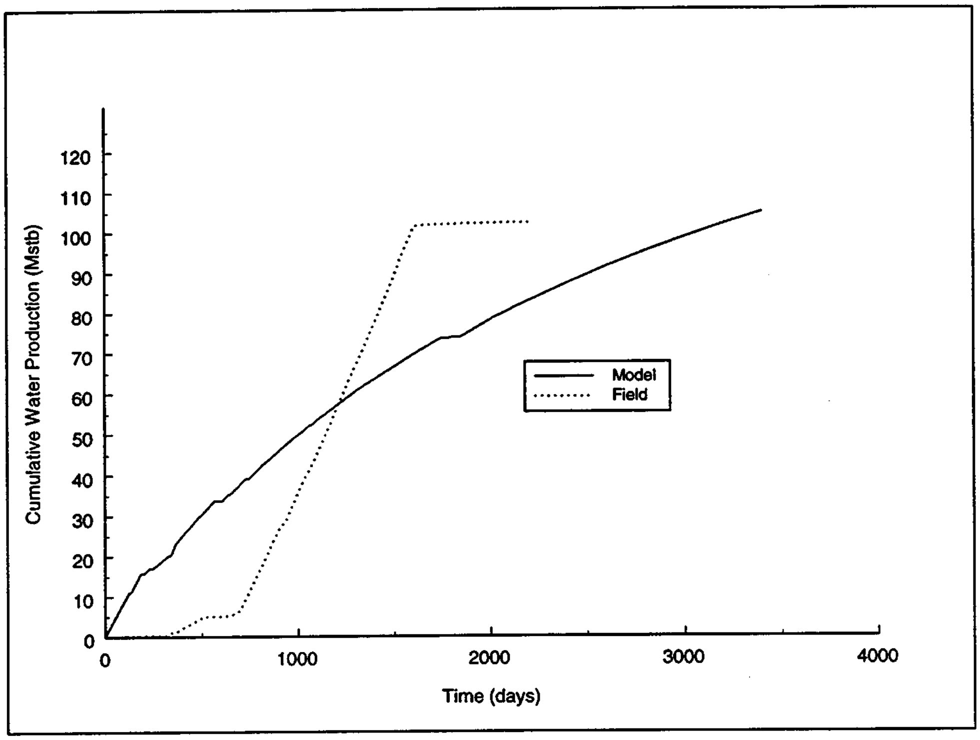

Figure 8: Comparison of water cumulative production in Malnar Pike with the modified model predictions

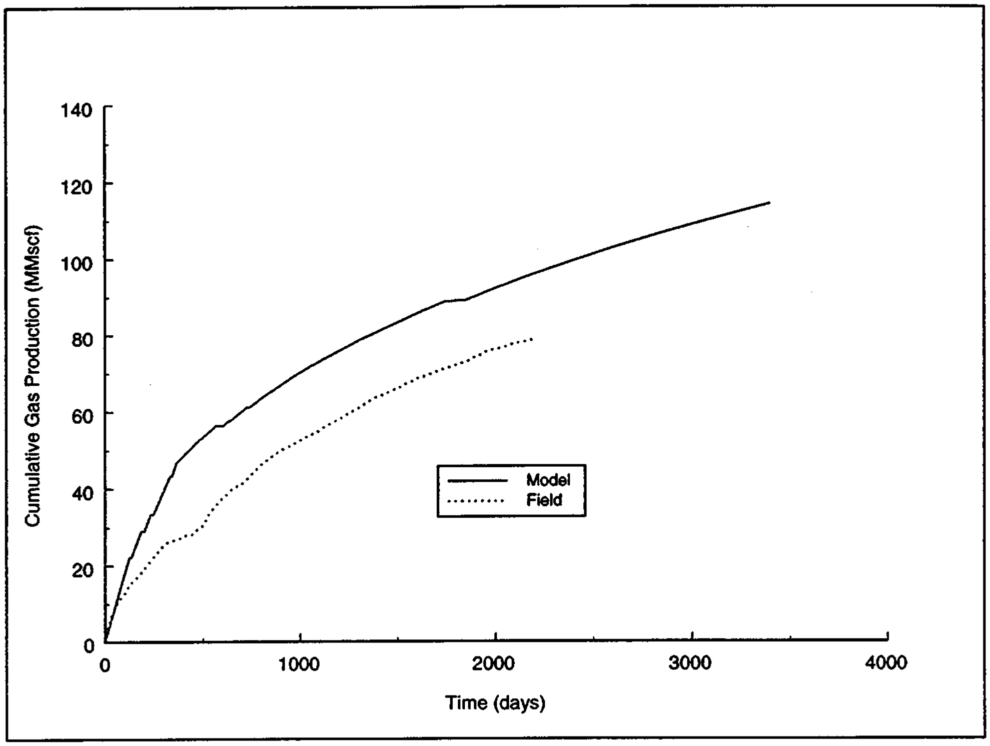

Figure 9: Comparison of gas cumulative production in Malnar Pike with the modified model predictions

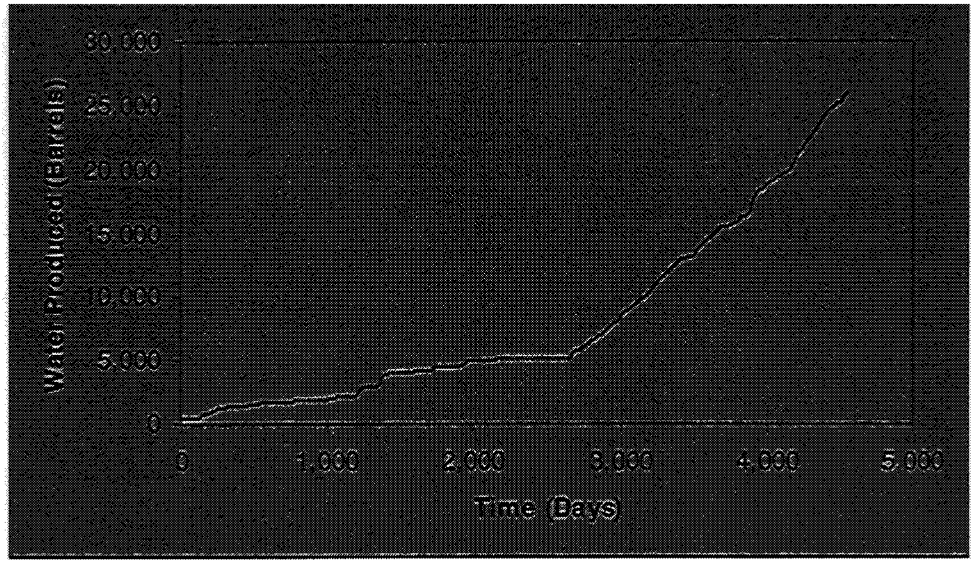

Figure 10: Water produced from the Michele-Ute; observe the sharp transition at around 2700 days.