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'GAS BREAKTHROUGH' DURING DRILLING AT DARAJAT AND IMPLICATIONS FOR STEAMFIELD MANAGEMENT

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ABSTRACT

While drilling two production wells without circulation in the Darajat Geothermal Field, West Java, Indonesia, significant changes occurred in gas chemistry of adjacent wells. The drilling of well DRJ-23, without circulation, caused gas/steam ratios in some wells in the southern production area to increase. Whereas, drilling of well DRJ-24 affected wells in the north area. The change in chemistry was presumed to be due to permeable connectivity within the reservoir. Intensive monitoring of well chemistry, wellhead pressure and temperature and power plant performance, was performed to acquire sufficient data for interpretation.

A numerical model was used to analyze the transient gas concentrations, with respect to water volumes injected during drilling without circulation of the subject wells. The increased gas to steam ratios and water volumes injected were used to estimate the steam condensation within the reservoir and likely fracture sizes. The assessment of reservoir steam condensation was done using the ratios obtained from the gas analyses.

The changes in chemistry of the affected wells were employed to support the interpretation of the numerical model. Isotopic samples, taken during the breakthrough, were useful in confirming the source of water causing the breakthrough. Additional data obtained from a tracer study, utilizing SF_6 and Freon-134a tracers, has contributed significantly to understanding the phenomena and validating the interpretation.

The results have possible implications for future steamfield management, including condensate injection strategy, potential negative impacts on power plant output and a general steam production strategy.

1. INTRODUCTION

The connectivity among wells within a fractured vapor-dominated reservoir is an important consideration in the development of a conceptual reservoir model, and an appropriate production and injection strategy. Methods have been developed to calculate well connectivity including pressure interference and tracer testing. The term 'gas breakthrough' refers to an occurrence of increased gas/steam ratios resulting from water being injected into the reservoir. This gas/steam ratio change is a method to infer inter-well connectivity. This paper analyzes the unusual 'gas breakthrough' in the vapor-dominated Darajat geothermal field during development drilling and its possible implications for future steamfield management.

The Darajat geothermal field is located in rugged terrain in the Kendang Volcanic Complex, at an average elevation of 1750 – 2000 masl. The field is located in the Garut Regency, approximately 35 km SE of Bandung, the capital city of West Java, Indonesia and about 12 km SW of the Kamojang geothermal field (Figure 1).

Amoseas Indonesia Inc., a jointly held affiliate of Chevron and Texaco, operates the Darajat steamfield under a 42-year joint operation contract with Pertamina (The State Oil and Gas Company). The recent production testing of 18 new highly successful production wells has indicated that the field is capable of producing 630 kg/s of dry saturated steam at a wellhead pressure of 15 bara, equivalent to approximately 365 MWe. Of these 18 new wells, DRJ-21 is the world's largest dry steam producing well (13 3/8" production casing and 9-5/8" perforated liner). DRJ-21 is capable of delivering 67 kg/s of dry saturated steam at a wellhead pressure of 15 bara, an equivalent of 40 MWe. The field currently supplies a 55 MWe generating facility owned by P.T. PLN (The State Electricity Company). In addition, Amoseas has successfully completed testing its new 77 MWe geothermal power plant in May 1999.

2. BRIEF DESCRIPTION OF THE OCCURRENCE

Drilling without circulation has been a normal practice at Darajat, once significant steam entries have been encountered within the reservoir. Amoseas has routinely been able to drill more than 500 m, and on occasion as much as 1700 m, without circulation. This was achieved by a careful balance of sufficient water down the drilling assembly, for bit cooling and cuttings lift, and additional water down the annulus between the production casing and the drilling assembly for well control. This allowed for the drill cuttings to be lifted up the wellbore and out into the major fractured zones in the surrounding rock formations. This process has not been excessively detrimental to the wells' deliverability.

Unusual gas breakthrough due to this practice was first noted near the completion of drilling well DRJ-23. A rapid increase in gas/steam ratio occurred in the adjacent wells, in particular DRJ-4 and DRJ-13. DRJ-23's major loss of circulation was encountered at a depth of 1315 m on January 18, 1998. Major loss of circulation in DRJ-24 was encountered at a depth of 1508 m on May 15, 1998 and drilling without circulation continued at a pumping rate of about 30 barrels per minute. Adjacent wells in the northern area were frequently monitored for gas/steam ratio changes resulting from the losses of these drilling fluids to the reservoir. Well DRJ-7 appeared to show the strongest effects. Other wells were on bleed and the effect may not have been as evident. It was also necessary, due to increased condenser pressure in the plant caused by the elevated gas content, for some wells to be throttled, while others were opened, to correct this problem. These flowrate changes resulted in a poorer quality of gas data collected from the north wells. The location map and N-S cross section of wells DRJ-4, DRJ-7, DRJ-13, DRJ-23 and DRJ-24 are shown in Figures 2 and 3. Figures 4 and 5 illustrate the wellhead gas/steam ratios and mass of water injected during the drilling without circulation.

3. NUMERICAL APPROACH IN ANALYZING THE GAS TRANSIENT

The produced gas/steam ratio increased when water was injected into the reservoir. This indicated condensation of steam within the reservoir. A numerical model explaining this relationship of water injection and steam condensation was suggested by Grant (1998). Steam condensation within the reservoir formation resulting from drilling water injection is calculated by the model. It correlates the steam and water masses to changes in gas ratios and likely fracture sizes. The model is derived by using mass and heat balance and a simple dynamic gas balance, to yield a differential equation to solve for the mass of steam within the mixing volume. Figure 6 illustrates the basic model. The unit for the mass flowrate (**W**) is kg/s.

The model assumes mixing occurs within the highly permeable or fractured zone of the reservoir. Neither, the pressure and temperature of the mixing volume change significantly, nor does the mass of steam within it. Figure 7 illustrates the wellhead pressure and temperature of DRJ-4, DRJ-13 and DRJ-7 during the breakthrough. Relative to the saturation line, the figure indicates that the pressure and temperature relationship of steam in the reservoir did not change during the mixing process, validating the assumptions.

According to the model, $\mathbf{W}_{rech}$ is equal to $\mathbf{W}_{disch}$, if there are no drilling fluid losses. If drilling fluid losses occur, the cold water enters the mixing volume and condenses some steam, resulting in heated drilling fluids and steam condensate ($\mathbf{W}_{drain}$).

The temperature of the Darajat steam reservoir is 240°C. A simple enthalpy balance using water at 40° C, suggests that the drilling fluid losses would result in the condensation of reservoir steam at approximately a 2 to 1 ratio by mass.

$$\mathbf{W}_{cond} = 0.497\ \mathbf{W}_{loss} \qquad (1)$$

Taking the initial gas/steam ratio of the reservoir steam, $\boldsymbol{x}_{rech}$, and the gas/steam ratio measured at the wellhead, $\boldsymbol{x}_{disch}$, with a known water loss, the following gas balance equation can be derived:

$$\boldsymbol{x}_{disch} = \boldsymbol{x}_{rech}\,(1 + 0.497\ \mathbf{W}_{loss}/\mathbf{W}_{disch}) \qquad (2)$$

DRJ-4 and DRJ-13's average combined production during the breakthrough was about 19 kg/s, and the average water loss while drilling DRJ-23 was 100 kg/s. Substituting these figures into the equation indicated an increase of about 3.5 fold in the gas/steam ratio, approximately what was measured in the field.

If the gas/steam ratio of the steam in the mixing volume, $\boldsymbol{x}$, is changing with time, a simple dynamic gas balance can be applied.

$$W\frac{dx}{dt} = \mathbf{W}_{rech}\,\boldsymbol{x}_{rech} - \mathbf{W}_{disch}\boldsymbol{x}_{disch} \qquad (3)$$

When the steam is produced from the mixing volume, the equation can be re-arranged to yield:

$$W\frac{dx}{dt} = (\mathbf{W}_{disch} + 0.497\ \mathbf{W}_{loss})\boldsymbol{x}_{rech} - \boldsymbol{x}\mathbf{W}_{disch} \qquad (4)$$

Figure 8 shows the data and the model fits for gas/steam ratios for both gas breakthrough occurrences. The gas data used for model fit is the normalized gas/steam ratio with respect to mass flowrates. The response of DRJ-4 and DRJ-13 gas/steam ratio to DRJ-23 drilling fluid losses, fitted the model best for 10,000 tons mixing volume. The undisturbed gas/steam ratio was taken at 1.2%, which approximated the gas/steam ratio measured at 1% in March 1998.

The 10,000 tons of steam at 240°C occupies a volume of about 600,000 m^3. The major steam entry of DRJ-23 lies 500 m from DRJ-4 and DRJ-13. If this volume is a cylinder of 250m radius, its height is 3m, or if the radius is 500m, then the height is 0.76m. This suggests the size of a fracture zone that could include DRJ-4, DRJ-13 and DRJ-23.

The response of DRJ-7 gas/steam ratio to drilling fluid losses of DRJ-24, on the other hand, fitted the model for 1,000 tons mixing volume. This relatively small mixing volume indicated a very narrow fractured zone or fault and hence resulted in the much quicker response to losses, as seen in Figure 8. The rate of drilling fluid losses changed continuously, while the gas/steam ratio was measured only daily. This explained why the modeled gas/steam ratio does not fit the field data as closely as the DRJ-4 and DRJ-13 model.

Nevertheless, the gas/steam ratio increase in the production wells suggested the mixing of fluid in the reservoir.

4. CHEMISTRY OF GAS VERIFYING METEORIC BREAKTHROUGH

Condensation of the steam phase within a reservoir, either due to the cooling of steam ascending towards the surface or breakthrough of meteoric water into the reservoir, will increase the gas/steam ratios remaining in the vapor phase. The steam condensate will dissolve some of the more soluble gases, and the proportion of less soluble gases in the remaining steam will increase (Nicholson, 1993). This process has been demonstrated by the events previously described here.

Collections of non-condensable gas and steam condensate samples were undertaken to provide sufficient data for analyses. The discussion on chemistry focuses on the verification of reservoir steam condensation, which involves examination of the N_2 and Ar concentration, gas ratios (CO_2/N_2 and CO_2/NH_3) and the isotopic composition ($\delta^{18}O$ and $\delta^{2}H$).

Nitrogen, as the principal atmospheric gas, and Argon, which is dominantly contributed to geothermal fluid by meteoric recharge (Nicholson, 1993), are used to verify the source of water during the breakthrough. Both constituents increased in concentration during the breakthrough and returned to normal after injection ceased (Figure 9). The N_2/Ar ratio was calculated at 70 – 90, which did not change. Sample contamination was unlikely since oxygen was found, either below detection limit or the N_2/O_2 ratio was much greater than the ratio in free air in all samples.

Another approach to deduce the presence of meteoric water in the mixing volume from which the gas was produced, is to observe the ratio of several gases. The following discussion on gas ratios refers to Nicholson (1993).

The CO_2/N_2 ratio will decrease if the N_2 saturated meteoric water enters the mixing volume, whereas the CO_2/NH_3 ratio will increase due to the higher solubility of NH_3. Figure 10 shows the ratios of these gases. DRJ-4, DRJ-13 and DRJ-7 CO_2/N_2 ratios decreased as the drilling fluid losses entered the mixing volume. The CO_2/NH_3 ratio on the other hand increased when breakthrough occurred, but DRJ-4 and DRJ-13 CO_2/NH_3 ratios increased on May 5, 1998, before the gas breakthrough at DRJ-7 occurred. This change may be explained by the tracer test result, which confirmed connectivity among wells DRJ-7, DRJ-24, DRJ-4 and DRJ-13.

In addition to gas analyses, the isotopic composition of the steam indicated the presence of meteoric water during breakthrough. The rapid mixing of steam with meteoric water caused the ^{18}O and ^{2}H isotopic compositions of the steam to shift towards less negative values, since the meteoric waters have lower ^{18}O and ^{2}H content than the reservoir steam. Figure 11 shows the isotopic compositions shifts.

The isotopic plot clearly indicated the presence of meteoric water. The parallel lines connecting the shift in the isotopic composition of DRJ-4 and DRJ-13 before, during and after the breakthrough suggested that these two wells received a fluid from the same source, DRJ-23 drilling fluid losses. The greater shift in isotopic composition of DRJ-7 may be due to the larger amount of drilling fluid losses and the smaller fracture size connecting DRJ-7 and DRJ-24, which resulted in more intense mixing.

5. TRACER TEST VERIFYING NUMERICAL MODEL

A tracer test at the Darajat geothermal field was performed after the 'gas breakthrough' observations. This test was aimed at providing a controlled study for understanding the communication among wells within the reservoir. SF_6 and R-134a, which are commonly used in vapor-dominated reservoirs, were used as chemical tracers. The tracers were injected into DRJ-7.

Figure 12 illustrates the results of the test at wells under discussion. The figure shows that the concentration peak for SF_6 was only detected at DRJ-13, after 15 days. The other peaks were attained in a shorter than expected period and arrival times cannot be seen, as no early samples were taken. However, the results have demonstrated the connectivity among DRJ-4, DRJ-13, and DRJ-7. In addition, the back flow analyses at DRJ-24 detected both tracers in this well, which confirms that there is connectivity with DRJ-24. No tracer samples were analyzed from DRJ-23 since the well was on bleed at extremely low flowrates during the survey. However, DRJ-4, DRJ-13 and DRJ-23's numerical model results, discussed earlier in Section 3, have already provided sufficient proof as to the connectivity among these wells.

The variance in the model fit for DRJ-7 and DRJ-24 can be explained using the tracer test result. The assumption that all drilling fluid losses went into the loss zone at 1508 m may not be valid. Pressure and temperature surveys taken in DRJ-24 during heat recovery indicated other loss zones located below the 1508 m loss zone. The multiple zones in DRJ-24 may be connected not only to DRJ-7, but also to other wells such as DRJ-4 and DRJ-13. This was demonstrated by the tracer test, which showed that DRJ-4 and DRJ-13 are in communication with DRJ-7. Changes in production flowrates during the breakthrough occurrences to reduce non-condensable gases flowing to the power plant may have caused some disturbances to the model fits. The numerical model appears valid only for a single loss zone and fixed number of wells. A more complex model and use of a numerical simulator would be required to explain all the likely variables.

The tracer test has shown that the tracer concentration profiles were similar to the gas/steam ratio profiles. The arrival times for the peaks are highly dependent on the rate of fluid injection, the distance of wells, and the permeability of the fracture zones or faults connecting the wells.

It can be concluded, that the variable rate of drilling fluid losses during breakthrough in DRJ-7, along with the small fracture size connecting DRJ-24 and DRJ-7, account for the variation in gas/steam ratios and poorer numerical model fit. Other contributing factors are the presence of multiple loss zones, which appear from the gas chemistry ratios, to have effected other wells, even if to a lesser degree.

6. IMPLICATIONS FOR STEAMFIELD MANAGEMENT

As the effect of gas breakthrough during drilling had not previously been experienced at Darajat, no plans were in place to deal with the potential impacts. The resulting loss of power generation capacity and other potential impacts, that fortunately did not arise, have led to strategy changes for management of the steamfield. In addition, new standard operating procedures to mitigate negative impacts in the future have been established. The gas breakthrough has also given valuable insight into the field's connectivity and is assisting in the development of an injection strategy that will have the least impact on the field's long term productivity.

6.1 Impact on Power Plant Output

The gas/steam ratio increases during the gas breakthrough were first noted by a measurable decline in power plant output. The reduced output was a direct consequence of increased non-condensable gas flows to the plant, resulting in an elevated condenser pressure on the turbine discharge. The P. T. PLN Darajat power plant has a design inlet gas/steam ratio of 1.5% by weight. Normal mass average gas/steam ratios at the plant interface vary from 0.5 - 1.2%, depending on the combination of wells in use. Peak measured gas loading during the DRJ-23 gas breakthrough, saw the mass-average gas rise to 2.22%. This resulted in a reduction in power output of approximately 2.5 MWe per hour. Subsequent operational actions to lessen the effect included reduction of the flowrate from the affected wells and introduction of other unaffected wells. Similarly, the breakthrough from DRJ-24 increased the mass-average gas to 2.06%, with a resulting output loss of 1.5 MWe per hour. This was mitigated quickly as the increased gas content was expected.

The reservoir steam condensation did not cause a measurable reduction in reservoir temperature, pressure or calculated enthalpy. The water from drilling fluid losses was injected over a relatively short time period, and below the major steam entries of the affected wells. However, if a temperature reduction had occurred and the losses were above the productive zones of the surrounding wells, in all likelihood the wells would have produced a combination of steam and water. The wellhead equipment of a vapor-dominated steamfield is not commonly furnished with steam/water separators and the steam transmission piping is only designed for a single gaseous phase. If any significant water had been produced and the normal condensate rejection system of low point drains and steam traps had been unable to cope with the water volume, it could have resulted in liquid carry-over to the power plant. A failure on the part of the plant separator and demister to remove any excess wetness could have had adverse effects on the turbine. First, it could have caused turbine blade erosion, due to water impingement, and secondly, it could have potentially caused turbine blade scaling, due to the deposition of chemical constituents such as silica. Both cases would result in reduced turbine efficiency. To prevent such an occurrence, steam quality testing should be done frequently, anytime there is a potential for production wells to produce water in a vapor-dominated field.

6.2 Field Management During Infield Drilling

Lessons learned from DRJ-23 and DRJ-24, show that well drilling programs should include, in the geologic prognosis, the structures to be intersected, that may potentially result in increased gas/steam ratios in the production wells. The incorporation of this information will allow for better planning and management of the production wells during infield drilling. With prior knowledge, wells with feed zones that are predicted to have high connectivity to wells being drilled, should be throttled to reduce the impact of rising gas/steam ratios on power plant output. Ideally the wells should be taken out of production and vented to atmosphere. This would purge the non-condensable gases from the reservoir. Venting the wells would also allow representative gas samples to be collected to aid the interpretation of the degree of interference and connectivity between wells.

As can be seen from the DRJ-24 and DRJ-7 breakthrough occurrence, the rate of water loss can have a significant impact on gas/steam ratios. Drilling supervisors should be aware of this fact, and limit water injection rates to that necessary to maintain well control and drill cuttings removal. In the highly permeable and productive Darajat reservoir wells, the rate of losses for well control will be difficult to minimize. This is especially true, when drilling without circulation.

6.3 Future Injection Strategy

The main issues for a future injection strategy are the placement of injection wells and the rate of injection. The placement of wells includes not only its well location within the field, but also its structural target.

As shown by the tracer study results, properly regulated injection rates can minimize negative impacts and may allow for longer contact with the reservoir bulk rock. It appears high injection rates will only result in pushing water through the fracture zones, condensing steam within the fractures.

Special efforts must be taken to get injection fluid into less permeable areas within the reservoir to increase retention time with the hot reservoir rock to produce steam recharge, rather than condensing existing steam. As seen at Darajat and in other vapor-dominated fields, careful monitoring of the surrounding wells must accompany wells being drilled for injection. This is to ensure that the target will have minimal effects on production and result in positive recharge to the reservoir.

The gas breakthrough and the tracer test have provided a better understanding of connectivity and fluid flow within the Darajat reservoir and have enhanced our understanding of the field and future strategies to ensure long field life.

ACKNOWLEDGEMENTS

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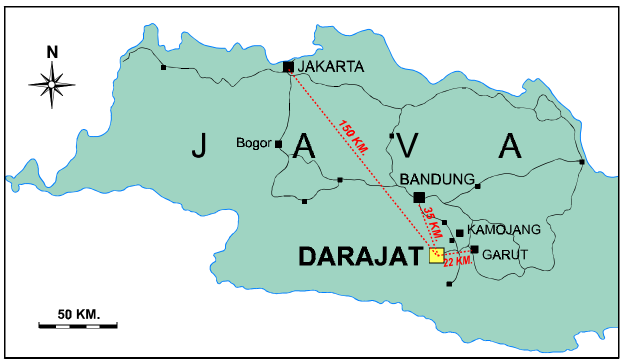

Figure 1. Location of the Darajat Geothermal Field, Indonesia

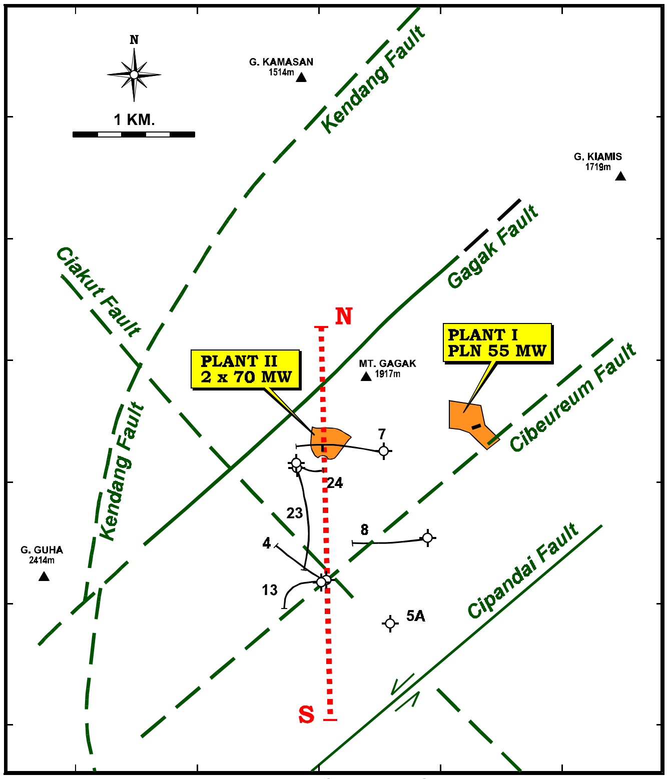

Figure 2. Map location of Darajat Contract Area

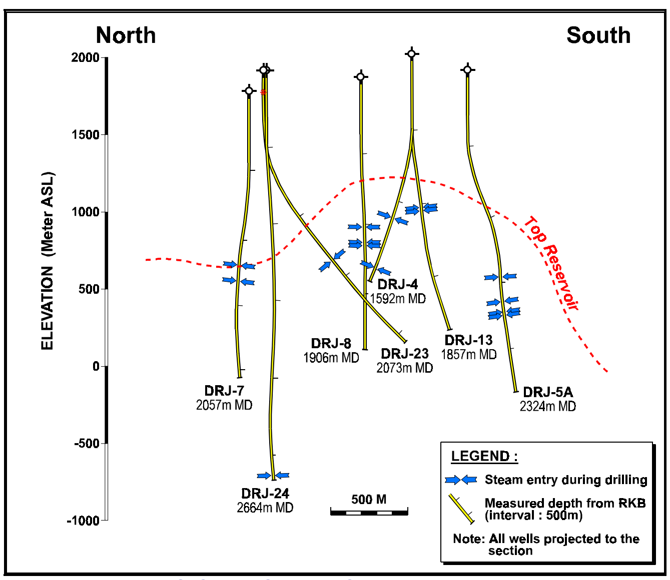

Figure 3. N-S Cross Section Showing DRJ-4, DRJ-7, DRJ- 13, DRJ-23 and DRJ-24

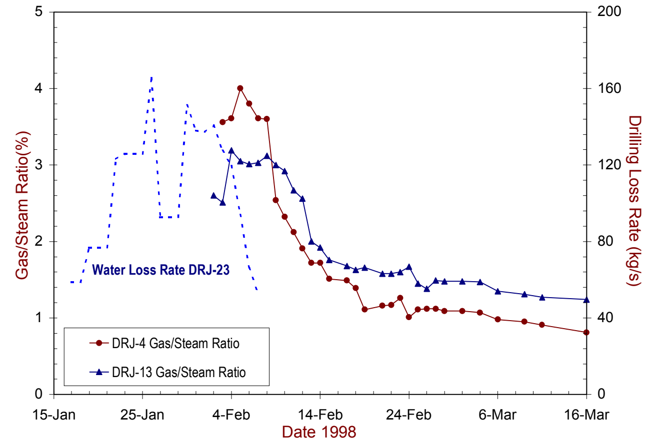

Figure 4. DRJ-4 and DRJ-13 Gas/Steam ratio

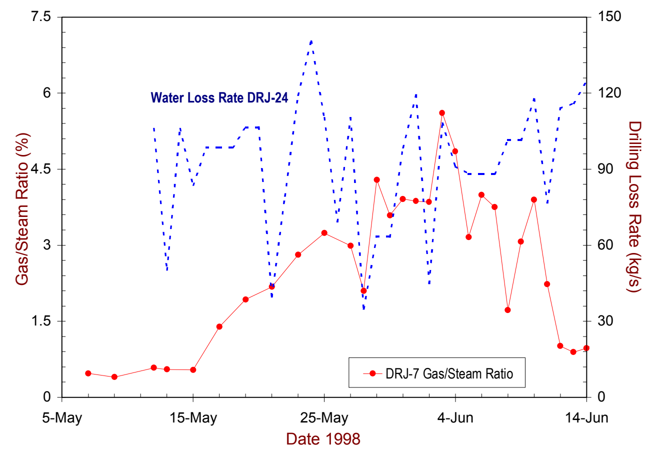

Figure 5. DRJ-7 Gas/Steam ratio

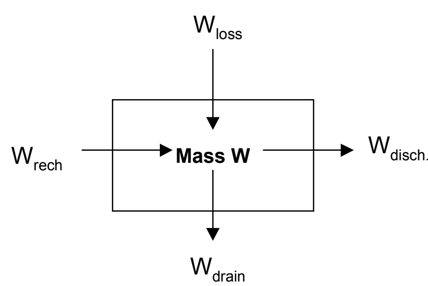

Figure 6. Basic Model for Reservoir Steam Condensation

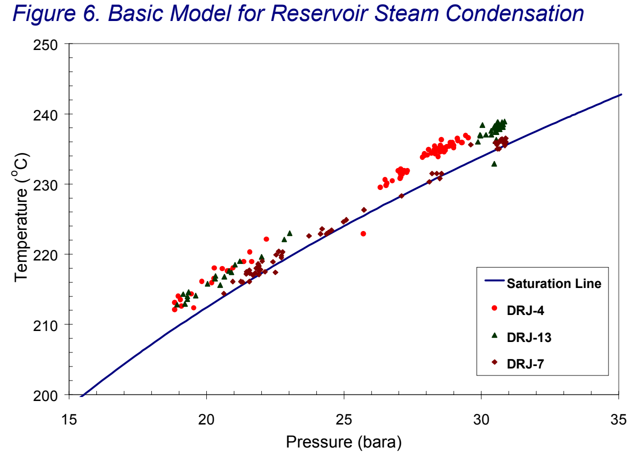

Figure 7. DRJ-4, DRJ-7 and DRJ-13 Daily Averaged Wellhead Pressure & Temperature

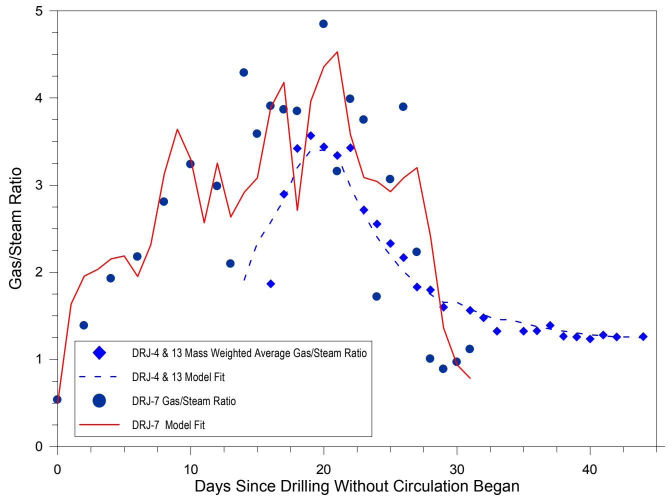

Figure 8. DRJ-4 & 13 and DRJ-7 Gas/Steam Ratio Model Fit

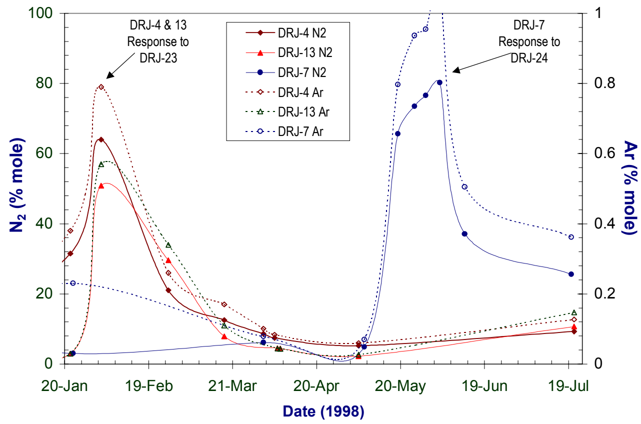

Figure 9. N_2 and Ar Concentration

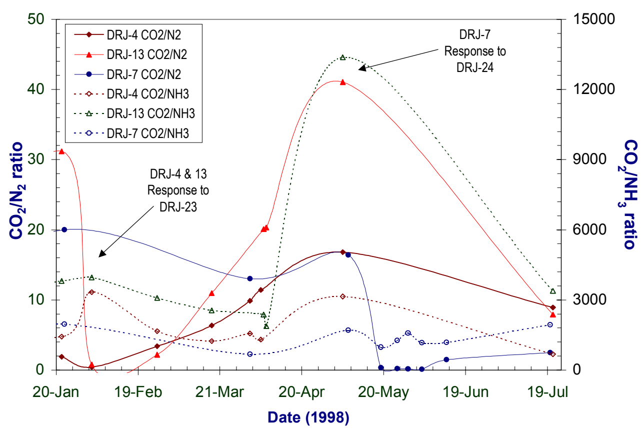

Figure 10. CO_2/N_2 ratio and CO_2/NH_3 ratio

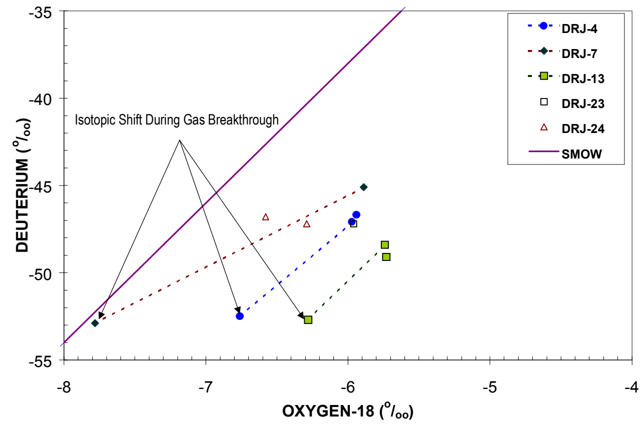

Figure 11. Isotopic Composition during Breakthrough

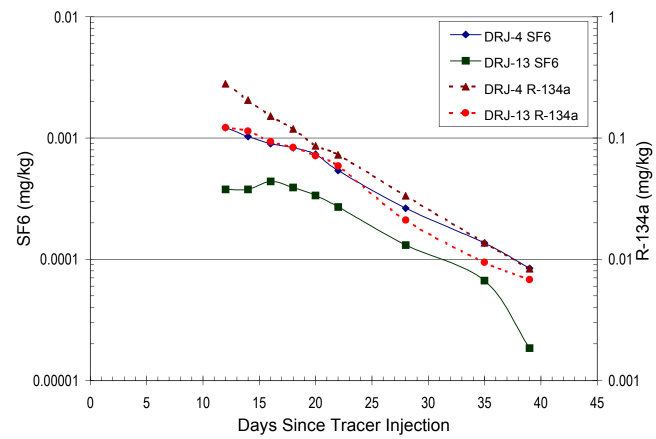

Figure 12. SF6 and R-134a Concentration during Tracer Test