

# A Tracer Test at the Beowawe Geothermal Field, Nevada, Using Fluorescein and Tinopal CBS

Peter E. Rose, Michael C. Adams  
Earth Sciences and Resources, Inc.  
University of Utah, Salt Lake City, UT 84108  
and  
Dick Benoit  
Oxbow Power Services, Inc.  
5250 South Virginia Street  
Reno, Nevada 89502

## ABSTRACT

An interwell tracer test using fluorescein and tinopal CBS was performed at the Beowawe geothermal field in north-central Nevada in order to assess the effects of recent changes to the injection strategy. Fluorescein return curves established injection-production flow patterns and verified that produced water is being reinjected into a region of the reservoir that is in excellent communication with the production wells. Tinopal CBS was apparently strongly adsorbed onto the reservoir rock. The fluorescein return curves were used to estimate the overall (fractures and matrix) reservoir volume.

## INTRODUCTION

The Beowawe geothermal field in north-central Nevada, shown in Figure 1, is a viable steam-production and electrical generation facility. With 2 wells initially on line, the power plant at Beowawe began producing electricity at a peak capacity of 16.7 MW in late 1985. Subsequent temperature declines required the drilling of a third production well that went on line in July, 1991. The addition of that third well resulted in excessive pressure declines, which lead to significant changes to the injection approach. As a result of those changes, an interwell tracer test was conducted in order to characterize flow processes along the newly established injection-production pathways. A complete account of the geology, exploration, and production history at

the Beowawe geothermal field has been presented elsewhere.<sup>1</sup>

## TRACER TEST

On July 13, 1994, 91 kg (200 lb) of the fluorescent dye, uranine (sodium salt of fluorescein), and 100 kg (220 lb) of a second fluorescent compound, tinopal CBS, were mixed with approximately 23 m<sup>3</sup> (6000 gal) of reservoir water. The solution was then injected as a slug into the injection well, 85-18, at the rate of 0.22 m<sup>3</sup>/sec (3500 gpm). Samples of produced reservoir water were collected at each of the three production wells, Ginn 1-13, Ginn 2-13 and 77-13, over the subsequent 9 months. The water samples were analyzed for both fluorescein and tinopal CBS using a Perkin/Elmer LS30 luminescence spectrometer.

Plots of fluorescein concentration vs time are shown in Figure 2 for each of the three production wells monitored during the 1994 field test. The first well in which the dyes were observed was Ginn 2, where the maximum concentration was detected only 17 days after tracer injection. In contrast, peak concentrations were detected in wells Ginn 1 and 77-13 at 30 days and 35 days, respectively, or about twice as long as the peak return time for Ginn 2. It is evident that a much shorter and/or direct path exists between injection well 85-18 and production well Ginn 2 than between the injector and the other two producers.

Also shown in Figure 2 are the tinopal CBS concentrations measured at each of the three production wells. It is evident from this figure that tinopal CBS was detected only in well Ginn 2. Tinopal CBS has been shown to be resistant to thermal decomposition under laboratory conditions that simulate the reservoir conditions at Beowawe. Based upon the shape of the return curve, as well as the fact that only 1.6% of the tinopal CBS was returned (in contrast to a 38% return to date for the nonadsorbent fluorescein), it is believed that tinopal CBS was adsorbed upon the reservoir rock. Adsorption would also serve to explain the fact that tinopal CBS was detected only at producer Ginn 2 and not at producers Ginn 1 or 77-13, since the longer, more tortuous path between the injector and these latter two producers would expose the tinopal CBS to a greater rock-surface area and, consequently, a greater opportunity for adsorption.

A plot of cumulative fluorescein return vs time for the three producers used in the 1994 tracer test is shown as the upper curve in Figure 3. This curve was calculated by summing the flow rate of each production well multiplied by its measured concentration and then dividing that sum by the overall flow rate. That curve represents the fluorescein concentration that would have been measured if the three produced flow streams had been completely mixed before being sampled. The lower curve represents the fluorescein concentration after accounting for the effects of recycling the produced water. Failure to consider the quantity of reinjected fluorescein would result in an overcalculation of the amount of produced tracer. The lower plot reveals the shape of the fluorescein return curve if all of the fluorescein had been removed from the produced water before reinjection. By numerically integrating the lower curve in Figure 3, a tracer return of 38% was calculated.

In 1990, a previous tracer test was conducted at Beowawe.<sup>1</sup> On April 6, 175 kg (375 lb) of uranine was mixed with 64 m<sup>3</sup> (17000 gal) of produced reservoir water and injected as a slug into well Batz 1. Samples were collected over the subsequent 14 months at the two production

wells, Ginn 1-13 and Ginn 2-13. The samples were analyzed using a Turner filter fluorometer.

Figure 4 shows plots of the fluorescein return curves for the two production wells, Ginn 1 and Ginn 2, from the 1990 test, along with the fluorescein return curves for the three production wells in production during the 1994 test. It is evident that the tracer was produced at a much lower concentration and at much longer peak-concentration times during the 1990 test than during the 1994 test. As noted above, nearly twice as much tracer was used in the 1990 test as was used in the 1994 test. The injector used in the 1990 test was Batz 1, which had been shown through interference testing to be unconnected to either of the two producers.<sup>1</sup> Since Batz 1 was completed in a high permeability zone, the use of this well as an injector represented a rare opportunity to reinject produced reservoir water without the risk of prematurely cooling the reservoir. In spite of the fact that no pressure connection had been detected between Batz 1 and the production wells, a minor flow path evidently existed, as shown by the return curves in Figure 4. About 8% of the tracer was returned to wells Ginn 1 and Ginn 2 during the 1990 test.

## RESERVOIR VOLUME

Shown in Figure 5 are the fluorescein return curves to 5 wells, measured during a recent tracer test at Steamboat Hills, Nevada.<sup>2</sup> It is evident from this figure that towards the end of the tracer test the return-curve concentrations were approaching a common value of about 2.5 ppb. Due to the process of recirculating the produced water, the fluorescein was becoming thoroughly mixed throughout the reservoir.

If the amount of fluorescein initially added to the reservoir is known, then it is possible to determine the overall (fractures and matrix) reservoir volume through the expression:<sup>3,4</sup>

$$V = m_i / C_i \quad (1)$$

where V is the overall reservoir volume, m<sub>i</sub> is the

mass of tracer injected and  $C_t$  is the final tracer concentration. Since the mass of fluorescein injected at Steamboat Hills was 100 kg, equation 1 becomes:

$$V = 100 \text{ kg} / 2.5 \text{ ppb} = 40 * 10^9 \text{ kg} \quad (2)$$

or, approximately, 40 million  $\text{m}^3$  (10 billion gal).

From the horizontal shape of the return curves at long times, it is evident that the reservoir at Steamboat Hills behaves like a closed system. The only path for water to leave the reservoir is through the production wells, and, likewise, the only path for water to enter the system is through the injection wells.

As shown in Figure 3 for the Beowawe system, the shape of the cumulative (3-well average) return curve at long times is not horizontal, but continuously sloped downward. With reservoir temperatures too cool to produce a measurable thermal decay of fluorescein<sup>5</sup>, the fluorescein concentration continues nevertheless to diminish.

One explanation for such behavior is that, in contrast to the reservoir at Steamboat Hills, the Beowawe system is open. Water not only enters the reservoir through underground aquifers, but exits by aquifers as well. Figure 6 depicts this open-reservoir behavior, where the arrows represent aquifer flow both into and out of the reservoir. Of course, some water is lost through evaporation due to fluid flashing during power production, but, since fluorescein partitions exclusively to the liquid phase, it is all returned to the reservoir through produced-fluid reinjection. Although it accounts for some water loss, flashing does not result in fluorescein loss.

Another explanation for the sloped tail of the cumulative return curve results from the fact that the reservoir liquid-phase saturation is increasing. Shown in Figure 7 is the pressure history of the reservoir monitored at the Vulcan 2 observation well. It reveals not only the recent pressure decline resulting from the addition of well 77-13, but the significant pressure increase resulting

from injection into well 85-18. The increase in pressure results from an increase in the hydrostatic head of water that has collected within the reservoir. As shown in Figure 7, the tracer test began shortly after injection was initiated into well 85-18, during the rapidly increasing portion of the pressure curve. A continuous increase in liquid saturation would undoubtedly result in the steady dilution of the fluorescein tracer, which could account, at least in part, for the continuously decreasing slope of the fluorescein concentration at long times. Figure 8 depicts a reservoir that is open only to aquifers delivering water to the system, but closed to aquifers that remove water from the system.

If the downward slope of the return curve at long times results from the effect of dilution, as opposed to aquifer outflow, it is expected that the curve will eventually become horizontal as the pressure approaches a plateau, and, concomitantly, as the reservoir becomes more "closed". Monitoring of the production wells will continue until sufficient data have been collected to quantify the flow processes that are responsible for the shape of the return curve at long times.

In spite of the fact that fluorescein return curves do not approach a common constant value at long times, it is nevertheless possible to estimate the overall reservoir-fluid (fractures and matrix) volume. As explained above, if the concentration of a nondecaying and nonadsorbing dye such as fluorescein is observed to diminish at long times, such a process results from dilution due either to aquifer flow through the reservoir or to aquifer flow into the system in excess of net withdrawal. An extrapolation of the linear, constantly sloping portion of the cumulative return curve indicates the dye concentration that would have resulted if the fluorescein had been perfectly mixed throughout the reservoir immediately after injection. As shown in Figure 9, this extrapolation to initial time indicates a dye concentration of approximately 10 ppb. Application of Equation 1 indicates an effective reservoir volume of approximately 9 million  $\text{m}^3$  (2.4 billion gal). Thus, 9 million  $\text{m}^3$  of water would be required to dilute 91 kg of fluorescein to 10 ppb.

## SUMMARY AND CONCLUSIONS

Results of tracer tests conducted in 1990 and 1994 at Beowawe have revealed the effects of distinctly different injection strategies. In 1990, injection was into Batz 1, which had been shown through interference testing to be unconnected to the main reservoir. The return curves were broad and flat, with only 8% of the tracer being returned. The second tracer test was conducted after moving the injection to well 85-18, which, in contrast to Batz 1, had been shown through interference testing to be strongly connected to the main reservoir. Likewise, the tracer return curves for the 1994 test revealed strong conductivity between the injector and the producers.

An analysis of the cumulative tracer return curve at long times can be used to estimate the overall (fractures and matrix) reservoir volume. This method was applied using the Beowawe tracer test data to determine a volume of 9 million m<sup>3</sup> (2.4 billion gal). The constantly sloped tail of the fluorescein return curve results from either the effect of aquifers flowing through the reservoir or from the diluting effect of net increases in the liquid-phase saturation, as evidenced by the significant recent increase in reservoir pressure.

## ACKNOWLEDGEMENTS

This work was supported by the U.S. Department of Energy under contract number DE-HC07-90ID12929. Such support does not constitute an endorsement by the U.S. Department of Energy of the views expressed in this publication.

## REFERENCES

1. Benoit, W. R., Stock, D., 1993, A case history of injection at the Beowawe, Nevada, geothermal reservoir. Geothermal Resources Council Transactions, vol. 17, p. 473-480.
2. Rose, P. E., Adams, M. C., 1994, The application of rhodamine WT as a geothermal

tracer: Geothermal Resources Council Transactions, vol. 18, p. 237-240.

3. Ito, J., Kubota, Y., and Kurosawa, M., 1977, On the geothermal water flow of the Onuma Geothermal Reservoir: Chinetsu (Geothermal Energy), v. 14, p. 15-20.

4. Ito, J., Kubota, Y., and Kurosawa, M., 1978, Tracer tests of the geothermal hot water at Onuma Geothermal Field: Japan Geothermal Energy Association Journal, v. 15, p.87-93.

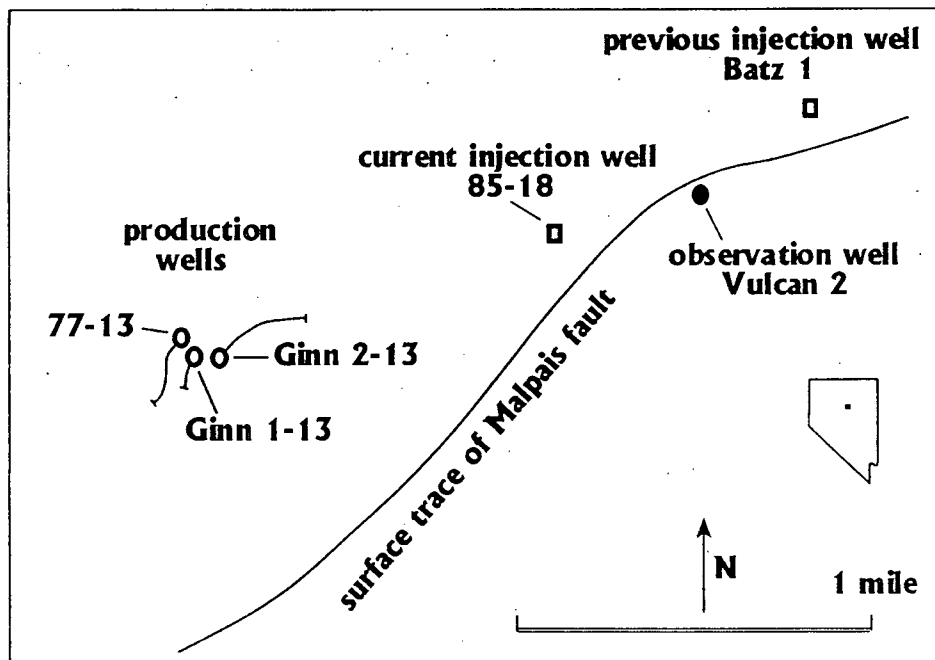


Figure 1. Location map of the Beowawe geothermal system.

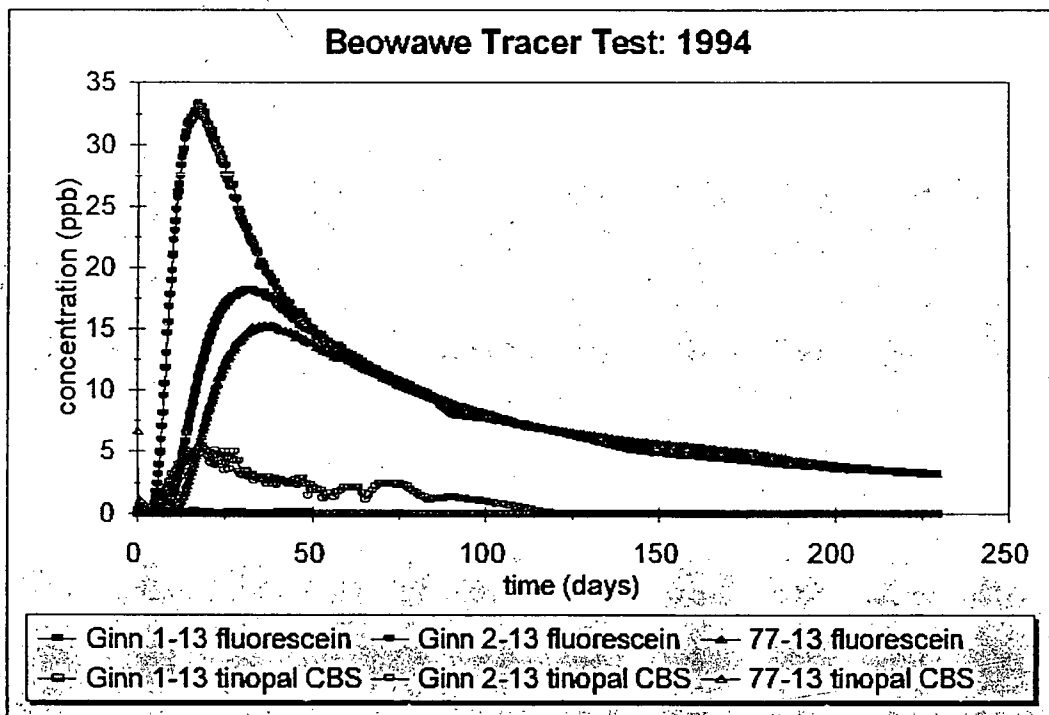
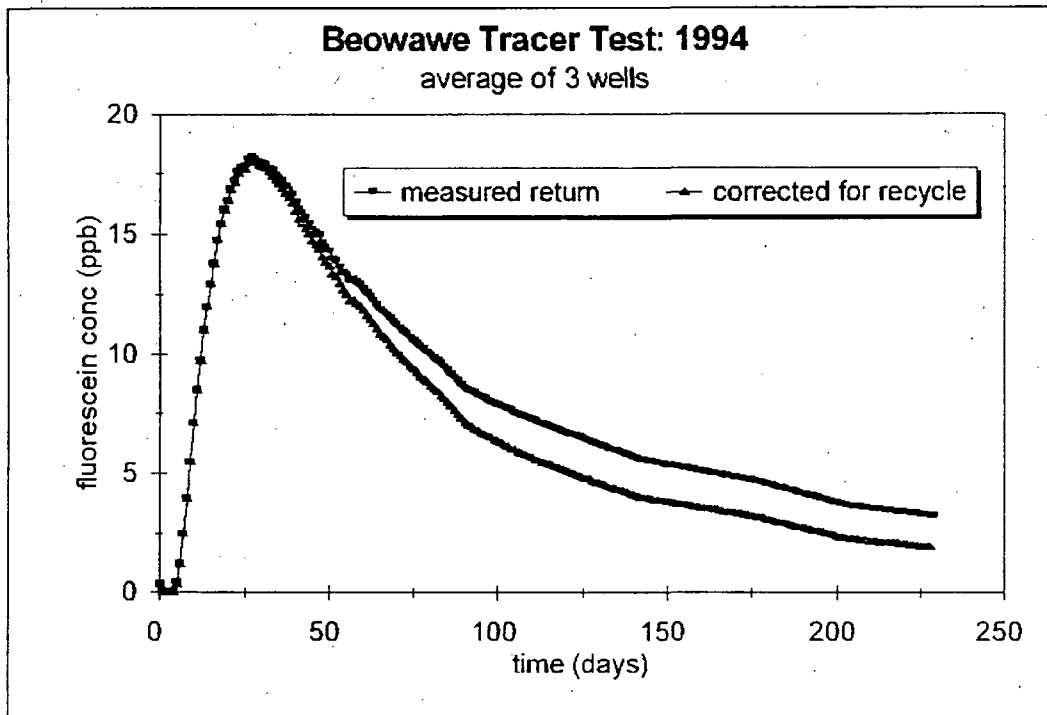
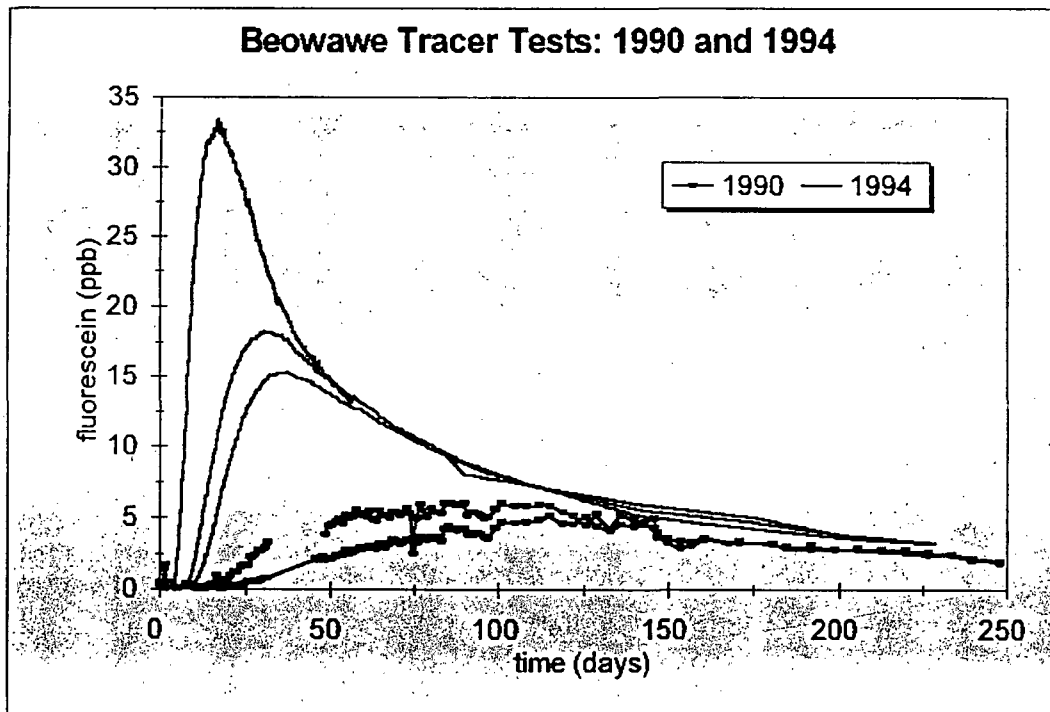


Figure 2. Return curves for the 1994 Beowawe tracer test.



**Figure 3.** Cumulative fluorescein return curves with and without a correction for recycle.



**Figure 4.** Fluorescein return curves for the 1990 and 1994 tracer tests

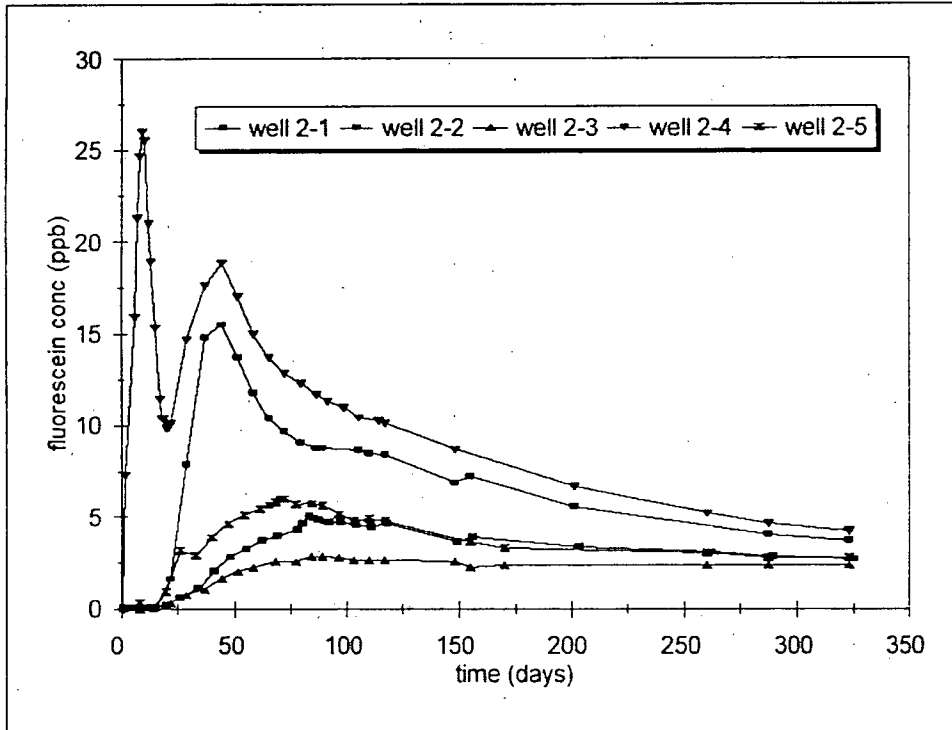


Figure 5. Return curves for 5 wells from a 1992 Steamboat Hills tracer test showing the even mixing of fluorescein throughout the reservoir.

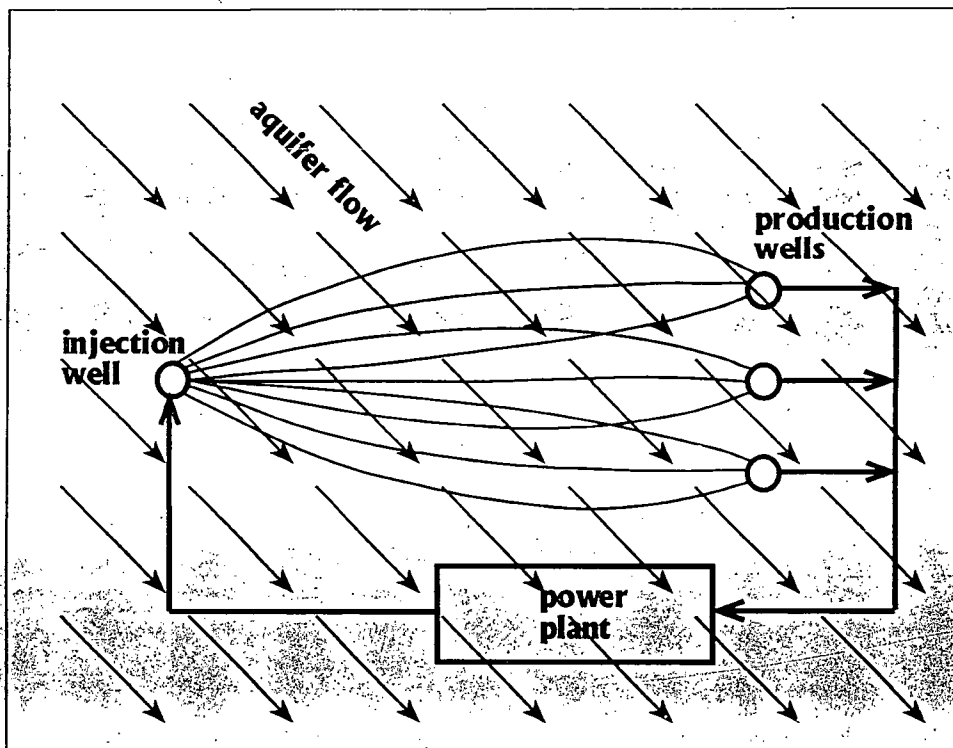
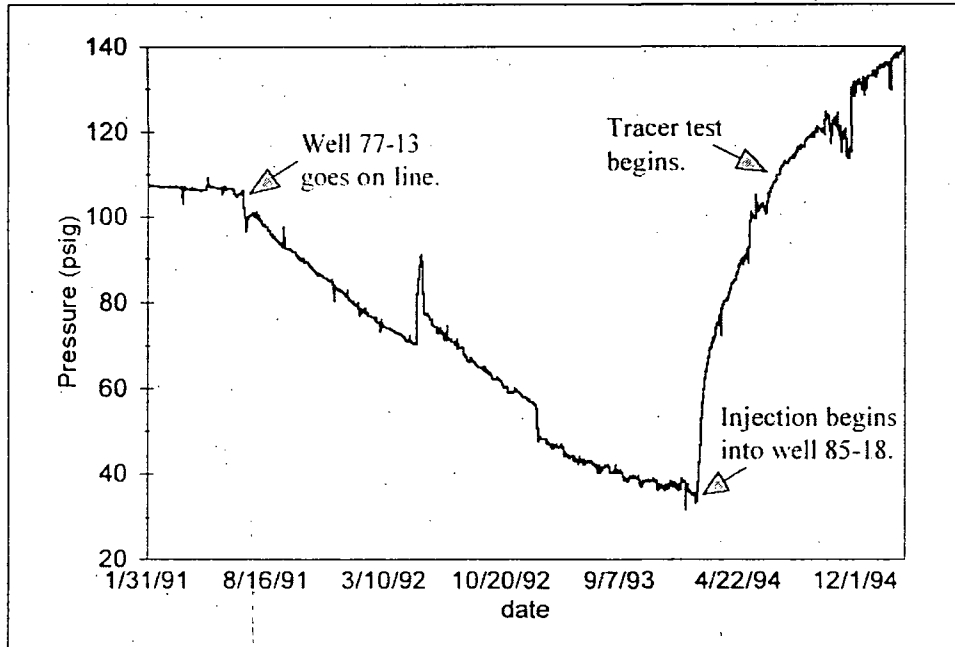
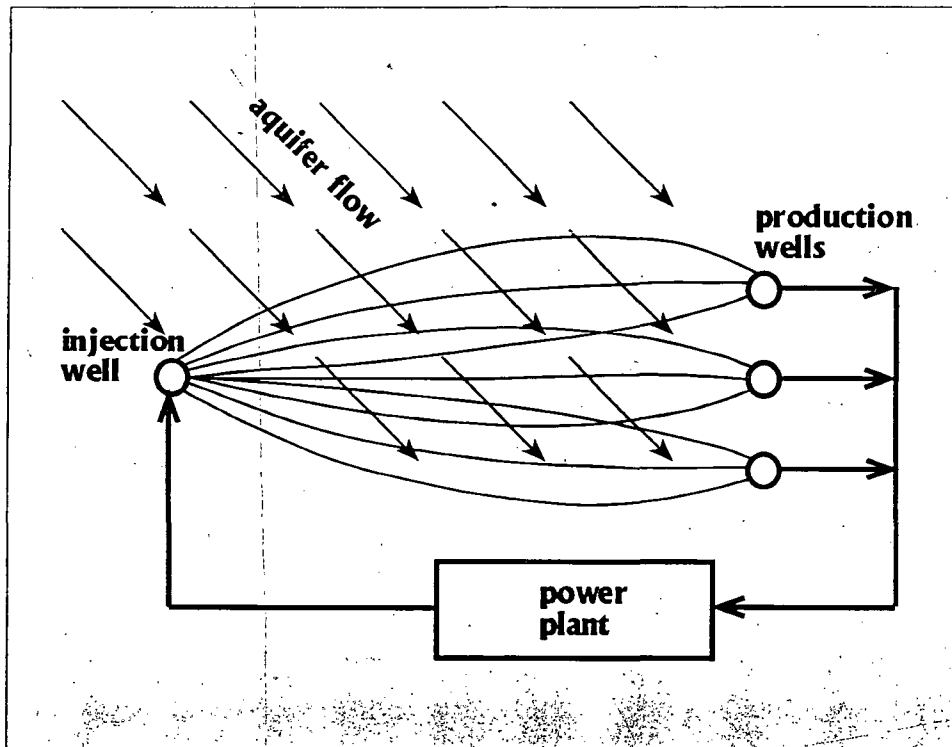


Figure 6. Representative "open" geothermal reservoir showing possible aquifer flow paths.

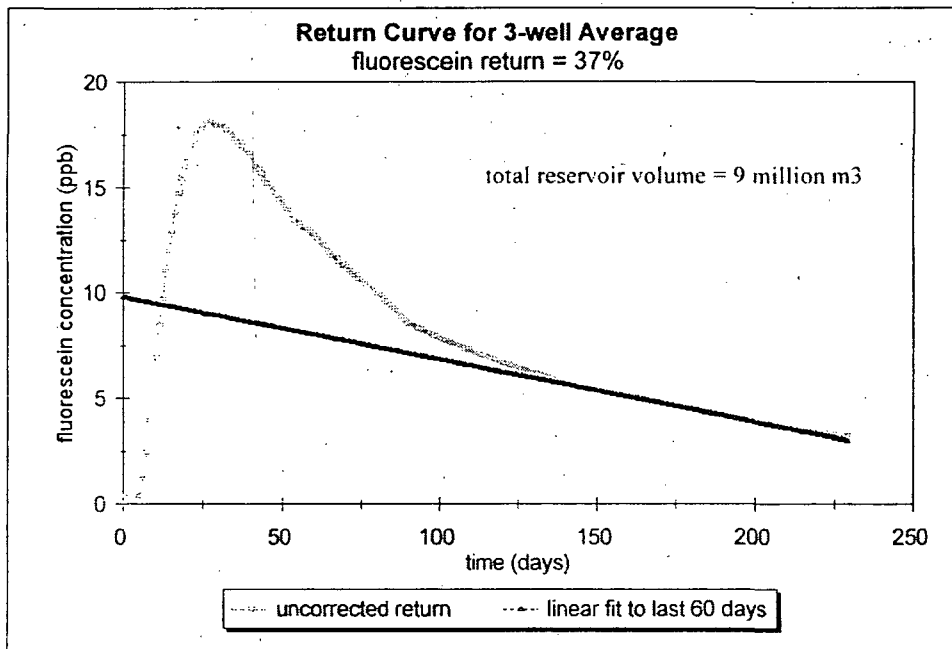


**Figure 7.** Pressure readings between January, 1991, and February, 1995, at the Vulcan 2 observation well.



**Figure 8.** Representation of a geothermal reservoir that is open to aquifer flow into to the system, but closed to aquifer flow out of the system.





**Figure 9.** A linear extrapolation from the return curve at long times to determine an “initial” fluorescein concentration.

## A TRACER TEST AT THE BEOWAWE GEOTHERMAL FIELD, NEVADA, USING FLUORESCHEIN AND TINOPAL CBS

Peter E. Rose, Michael C. Adams  
Earth Sciences and Resources Institute  
Department of Civil and Environmental Engineering  
University of Utah, Salt Lake City, UT 84108

Dick Benoit  
Oxbow Power Services, Inc.  
5250 South Virginia Street  
Reno, Nevada 89502

### ABSTRACT

An interwell tracer test using fluorescein and tinopal CBS was performed at the Beowawe geothermal field in north-central Nevada in order to assess the effects of recent changes to the injection strategy. Fluorescein return curves established injection-production flow patterns and verified that produced water is being reinjected into a region of the reservoir that is in excellent communication with the production wells. An analysis of the tinopal CBS return curves indicated that tinopal CBS was apparently strongly adsorbed onto the reservoir rock. The fluorescein return curves were used to estimate the overall (fractures and matrix) reservoir volume.

### INTRODUCTION

The Beowawe geothermal system in north-central Nevada (see Figure 1) has been described as an inclined thermal plume within the Malpais fault zone (Layman, 1984). The Malpais fault, with a constant northwest dip of 65-70° and an ENE strike trend, cuts through Miocene volcanic rock and the underlying Valmy Formation. It is the major conduit for hot geothermal fluids to rise from a deeper underlying carbonate reservoir, the presence of which is assumed based upon brine geochemical analyses (Hoang et al, 1987).

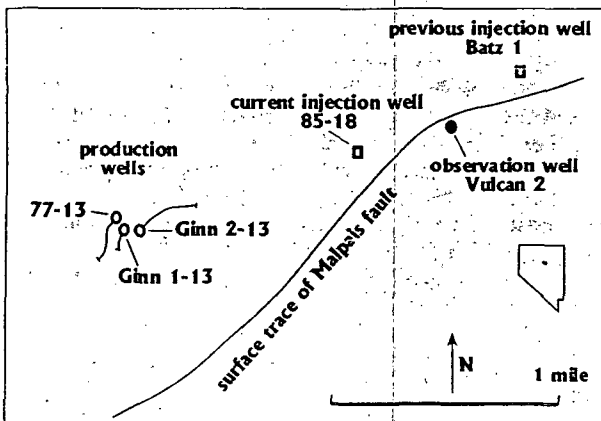


Figure 1. Location map of the Beowawe geothermal system.

The first deep exploration well into the Beowawe reservoir was drilled in 1974 and completed at a depth of 2900 m (9500 ft) in the highly permeable Malpais fault zone.

Fluid temperatures as high as 215°C (420°F) were measured. Since that initial well, seven additional production wells have been drilled, of which only two have been commercially viable, well Ginn 2-13 and well 77-13 (Benoit and Stock, 1993). Both wells were located in close proximity to well Ginn 1-13. Currently, the three wells produce water in the temperature range of 180°C-200°C (356°F - 392°F) at a combined flow rate of 450,000 kg/hr (1,000,000 lb/hr). A recent publication summarizes the geology as well as the exploration and production history at the Beowawe geothermal field (Benoit and Stock, 1993).

### PRODUCTION HISTORY

At the start-up of the Beowawe power plant in late 1985, two production wells, Ginn 1-13 and Ginn 2-13, provided for full-capacity production of 16.7 MW. As shown in Figure 2, the fluid temperatures in these two wells declined gradually but continuously over the next several years. In order to maintain full-capacity production at the lower temperatures, a third production well, 77-13, was drilled and placed on line in May, 1991.

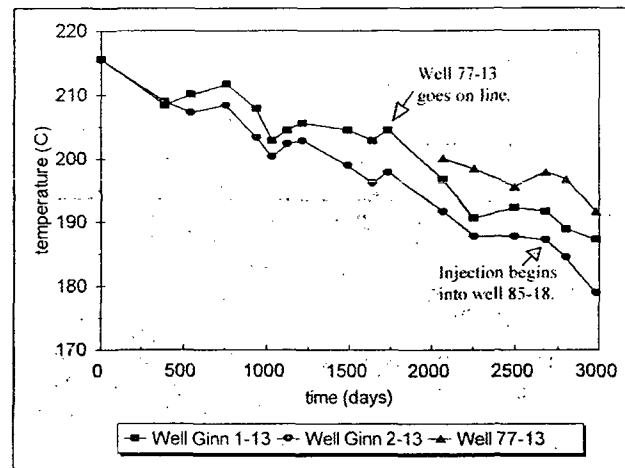


Figure 2. Production-well temperatures for the 3 wells between September, 1986, and October, 1994.

Although providing for a significantly higher production flow rate, the addition of well 77-13 resulted in a long period of reservoir-pressure decline, as shown in Figure 3. Whereas the pressure had been quite constant at a value of about 7.5 atm (110 psig), for the first five years of plant oper-

ation, it dropped significantly over the subsequent 3 years to a value of about 2.7 atm (40 psig). In addition to the pressure decline, a slight increase in the rate of temperature decline accompanied the addition of well 77-13, as shown in Figure 2.

From the initiation of production, produced fluid had been injected into well Batz 1, which had been shown through interference testing to be unconnected to any of the producers (Benoit and Stock, 1993). Since Batz 1 had been completed in a high-permeability zone, the use of this well as an injector represented a rare opportunity to reinject produced reservoir water without the risk of prematurely cooling the reservoir. However, temperature declines occurred anyway. With the reduction of reservoir pressure, cool ground water was evidently entering the reservoir through underground aquifers. Thus, a new injection strategy was devised and initiated.

In February, 1994, injection was moved from well Batz 1 to well 85-18, which had been shown to be strongly connected to the production wells. With injection into the main reservoir, the reservoir pressure began to increase rapidly, as shown in Figure 3. A tracer test was conducted in order to determine the newly established injection-production flow patterns and to assess the risk of short-circuiting between the injector and producers.

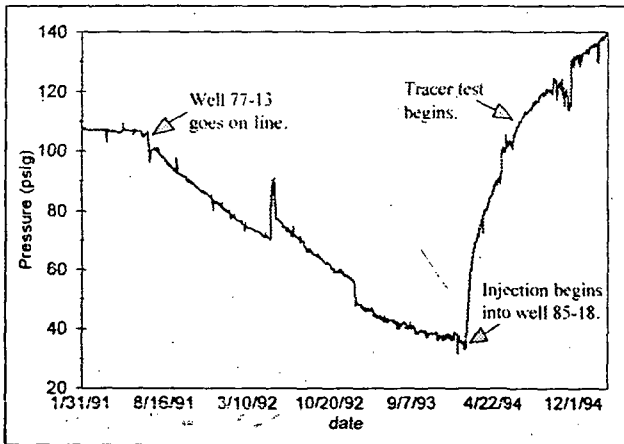


Figure 3. Pressure readings at observation well Vulcan 2.

**TRACER TEST**

On July 13, 1994, 91 kg (200 lb) of the fluorescent dye, uranine (sodium salt of fluorescein), and 100 kg (220 lb) of a second fluorescent compound, tinopal CBS, were mixed with approximately 23 m<sup>3</sup> (6000 gal) of reservoir water. The solution was then injected as a slug into the injection well, 85-18, at the rate of 0.22 m<sup>3</sup>/sec (3500 gpm). Samples of produced reservoir water were collected at each of the three production wells, Ginn 1-13, Ginn 2-13 and 77-13, over the subsequent 9 months. The water samples were analyzed for both fluorescein and tinopal CBS using a Perkin/Elmer LS30 luminescence spectrometer.

Plots of fluorescein concentration vs time are shown in Figure 4 for each of the three production wells monitored during the 1994 field test. The first well in which the dyes were observed was Ginn 2, where the maximum concentration was detected only 17 days after tracer injection. In contrast, peak concentrations were detected in wells Ginn 1 and 77-13 at 30 days and 35 days, respectively, or about twice as long as the peak return time for Ginn 2. It is evident that a much shorter and/or direct path exists between injection well 85-18 and production well Ginn 2 than between the injector and the other two producers.

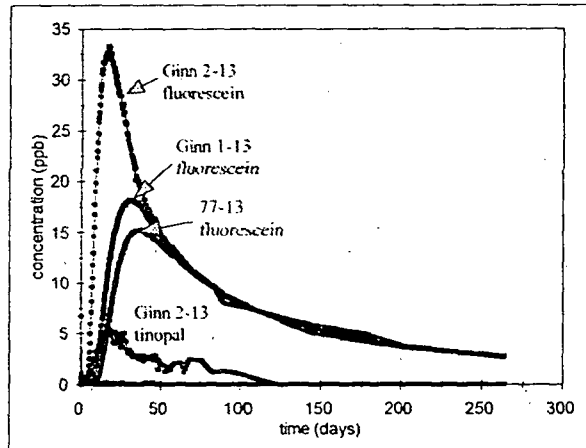


Figure 4. Fluorescein and tinopal CBS return curves for three wells.

Also shown in Figure 4 are the tinopal CBS concentrations measured at each of the three production wells. It is evident from this figure that tinopal CBS was detected only in well Ginn 2-13. Tinopal CBS has been shown to be resistant to thermal decomposition under laboratory conditions that simulate the reservoir conditions at Beowawe. Based upon the shape of the return curve, as well as the fact that only 1.6% of the tinopal CBS was returned (in contrast to a 38% return-to-date for the nonadsorbent fluorescein), it is believed that tinopal CBS was adsorbed upon the reservoir rock. Adsorption would also serve to explain the fact that tinopal CBS was detected only at producer Ginn 2 and not at producers Ginn 1 or 77-13, since the longer, more tortuous path between the injector and these latter two producers would expose the tinopal CBS to a greater rock-surface area and, consequently, a greater opportunity for adsorption.

A plot of fluorescein return vs time for the three producers used in the 1994 tracer test is shown as the upper curve in Figure 5. This curve was calculated by summing the flow rate of each production well multiplied by its measured concentration and then dividing that sum by the overall flow rate. That curve represents the fluorescein concentration that would have been measured if the three produced flow streams had been completely mixed before being sampled. The lower curve represents the fluorescein concentration after accounting for the effects of recycling the produced water. Failure to

consider the quantity of reinjected fluorescein would result in an overcalculation of the amount of produced tracer. The lower plot reveals the shape of the fluorescein return curve if all of the fluorescein had been removed from the produced water before reinjection. By numerically integrating the lower curve in Figure 5, a tracer return of 38% was calculated.

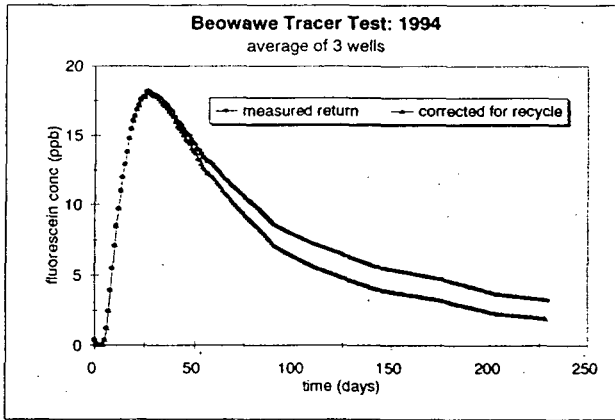


Figure 5. Fluorescein return curves with and without a correction for recycle.

In 1990, a previous tracer test was conducted at Beowawe (Benoit and Stock, 1993). On April 6, 175 kg (375 lb) of uranine was mixed with 64 m<sup>3</sup> (17000 gal) of produced reservoir water and injected as a slug into well Batz 1. Samples were collected over the subsequent 14 months at the two production wells, Ginn 1-13 and Ginn 2-13. The samples were analyzed using a Turner filter fluorometer.

Figure 6 shows plots of the fluorescein return curves for the two production wells, Ginn 1 and Ginn 2, from the 1990 test along with the fluorescein return curves for the three production wells in production during the 1994 test. It is evident that the tracer was produced at a much lower concentration and at much longer peak-concentration times during the 1990 test than during the 1994 test. As noted above, nearly twice as much tracer was used in the 1990 test as was used in the 1994 test. The injector used in the 1990 test was Batz 1, which had been shown through interference testing to be unconnected to either of the two producers, as explained above. In spite of the fact that no pressure connection had been detected between Batz 1 and the production wells, a minor flow path evidently existed, as shown by the return curves in Figure 6. About 8% of the tracer was returned to wells Ginn1 and Ginn 2 during the 1990 test.

**RESERVOIR VOLUME**

Shown in Figure 7 are the fluorescein return curves to 5 wells, measured during a recent tracer test at Steamboat Hills, Nevada (Rose and Adams, 1994). It is evident from this figure that towards the end of the tracer test the return-curve concentrations were approaching a common value of about 2.5 ppb. Due to the process of recirculating the produced water, the fluorescein was becoming thoroughly mixed throughout the reservoir.

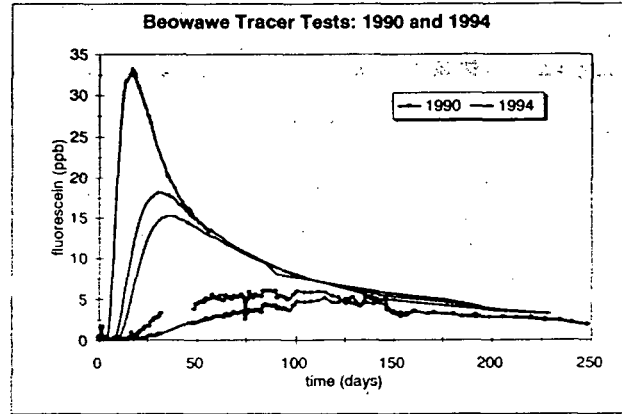


Figure 6. Fluorescein return curves for the 1990 and 1994 tracer tests.

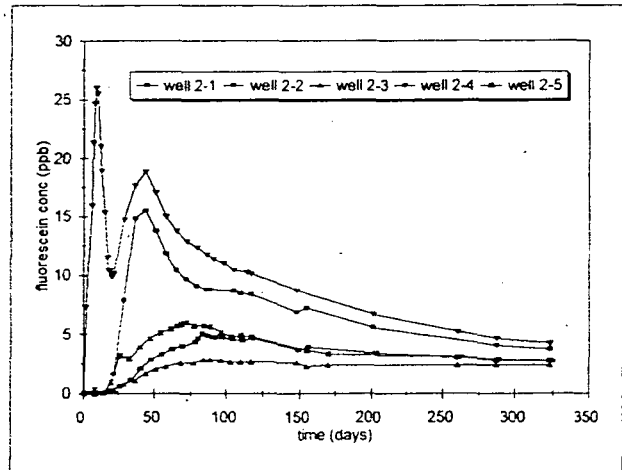


Figure 7. Return curves for 5 wells from a 1992 Steamboat Hills tracer test showing the even mixing of fluorescein throughout the reservoir.

If the amount of fluorescein initially added to the reservoir is known, then it is possible to determine the overall volume of the fluid contained within the reservoir through the expression (Ito et al, 1977; Ito et al, 1978):

$$V = m_t / C_t \tag{1}$$

where V is the overall reservoir-fluid mass, m<sub>t</sub> is the mass of tracer injected and C<sub>t</sub> is the final tracer concentration. Since the concentrations are known in units of ppb, expression 1 becomes:

$$M = m_t / C_t \tag{2}$$

where M is the overall mass of liquid in the reservoir, and, as before, m<sub>t</sub> is the mass of tracer injected and c<sub>t</sub> is the concentration of tracer. Since the mass of fluorescein injected at Steamboat Hills was 100 kg, equation 2 becomes:

$$M = 100\text{kg} / 2.5\text{ppb} = 40 \cdot 10^9\text{kg} \tag{3}$$

or, approximately, 40 million m<sup>3</sup> (10 billion gal).

From the horizontal shape of the return curves at long times, it is evident that the reservoir at Steamboat Hills behaves like a closed system. The only path for water to leave the reservoir is through the production wells, and, likewise, the only path for water to enter the system is through the injection wells.

As shown in Figure 5 for the Beowawe system, the shape of the cumulative (3-well average) return curve at long times is not horizontal, but continuously sloped downward. With reservoir temperatures too cool to produce a measurable thermal decay of fluorescein (Adams and Davis, 1991), the fluorescein concentration continued nevertheless to diminish.

One explanation for such behavior is that, in contrast to the reservoir at Steamboat Hills, the Beowawe system is open. Water not only enters the reservoir through underground aquifers, but exits by aquifers as well. Figure 8 depicts this open-reservoir behavior, where the arrows represent aquifer flow both into and out of the reservoir. Of course, some water is lost through evaporation due to fluid flashing during power production, but, since fluorescein partitions exclusively to the liquid phase, it is all returned to the reservoir through produced-fluid reinjection. Although it accounts for some water loss, flashing does not result in fluorescein loss.

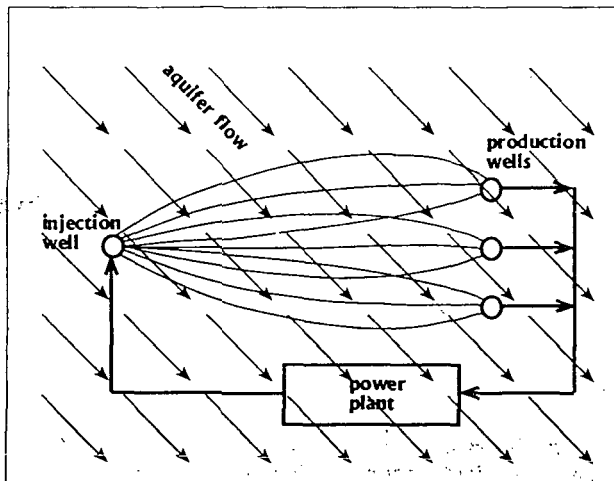


Figure 8. Representative "open" geothermal reservoir showing possible aquifer flow paths.

Another explanation for the sloped tail of the cumulative return curve results from the fact that the reservoir liquid-phase saturation is increasing. Shown in Figure 3 is the pressure history of the reservoir monitored at the Vulcan 2 observation well. It reveals not only the recent pressure decline resulting from the addition of well 77-13, but the significant pressure increase resulting from injection into well 85-18. The increase in pressure results from an increase in the hydrostatic head of water that has collected within the reservoir. As shown in Figure 3, the tracer test began shortly after injection was initiated in well 85-18, during the rapidly increasing portion of the pressure curve. A continuous increase in liquid saturation would undoubtedly result in the steady dilution of the fluorescein tracer, which could account,

at least in part, for the continuously decreasing slope of the fluorescein concentration at long times. Figure 9 depicts a reservoir that is open only to aquifers delivering water to the system, but closed to aquifers that remove water from the system.

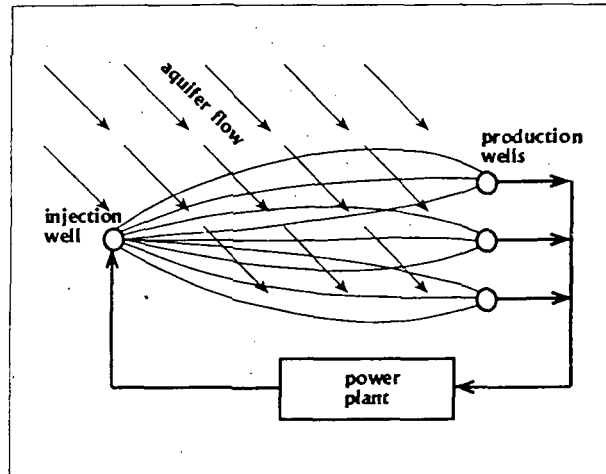


Figure 9. Representation of a geothermal reservoir that is open to aquifer flow into to the system, but closed to aquifer flow out of the system.

If the downward slope of the return curve at long times results from the effect of dilution, as opposed to aquifer outflow, it is expected that the curve will eventually become horizontal as the pressure approaches a plateau, and, concomitantly, as the reservoir becomes more "closed". Monitoring of the production wells will continue until sufficient data have been collected to quantify the flow processes that are responsible for the shape of the return curve at long times.

In spite of the fact that fluorescein return curves do not approach a common constant value at long times, it is nevertheless possible to estimate the overall reservoir-fluid (fractures and matrix) volume. As explained above, if the concentration of a nondecaying and nonadsorbing dye such as fluorescein is observed to diminish at long times, such a process results from dilution due either to aquifer flow through the reservoir or to aquifer flow into the system in excess of net withdrawal. An extrapolation of the linear, constantly sloping portion of the cumulative return curve indicates the dye concentration that would have resulted if the fluorescein had been perfectly mixed throughout the reservoir immediately after injection. As shown in Figure 10, this extrapolation to initial time indicates a dye concentration of approximately 10 ppb. Application of Equation 1 indicates an effective reservoir volume of approximately 9 million  $m^3$  (2.4 billion gal). Thus, 9 million  $m^3$  of water would be required to dilute 91 kg of fluorescein to 10 ppb.

## SUMMARY AND CONCLUSIONS

Results of tracer tests conducted in 1990 and 1994 at Beowawe have revealed the effects of distinctly different injection strategies. In 1990, injection was into Batz 1, which had been shown through interference testing to be unconnect-

ed to the main reservoir. The return curves were broad and flat, with only 8% of the tracer being returned. The second tracer test was conducted after moving the injection to well 85-18, which, in contrast to Batz 1, had been shown through interference testing to be strongly connected to the main reservoir. Likewise, the tracer return curves for the 1994 test revealed strong conductivity between the injector and the producers.

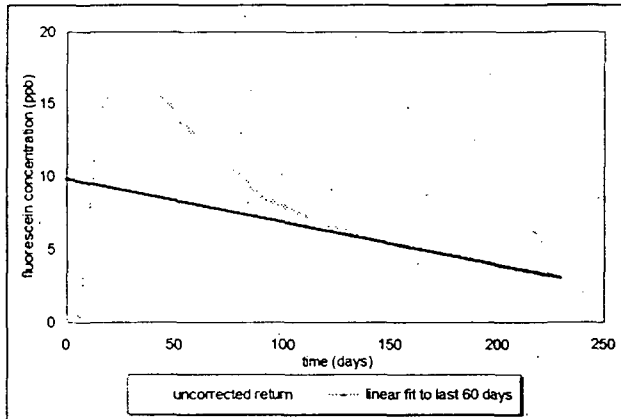


Figure 10. A linear extrapolation from the return curve at long times to determine an "initial" fluorescein concentration.

An analysis of the cumulative tracer return curve at long times can be used to estimate the overall (fractures and matrix) reservoir volume. This method was applied using the Beowawe tracer test data to determine a volume of 9 million  $m^3$  (2.4 billion gal). The constantly sloped tail of the fluorescein return curve results from either the effect of aquifers flowing through the reservoir or from the diluting effect of net increases in the liquid-phase saturation, as evidenced by the significant recent increase in reservoir pressure.

#### ACKNOWLEDGEMENTS

This work was supported by the U.S. Department of Energy under contract number DE-HC07-90ID12929. Such support does not constitute an endorsement by the U.S. Department of Energy of the views expressed in this publication.

#### REFERENCES

- Adams, M. C., Davis, J., 1991, Kinetics of fluorescein decay and its application as a geothermal tracer: *Geothermics*, vol. 20, no.1/2, p. 53-66.
- Benoit, W. R., Stock, D., 1993, A case history of injection at the Beowawe, Nevada, geothermal reservoir: *Geothermal Resources Council Transactions*, vol. 17, p. 473-480.
- Hoang, V.T., James, E.D., Epperson, I.J., 1987, Development drilling, testing and initial production of the Beowawe geothermal field: *Proceedings of the Twelfth Workshop on Geothermal Reservoir Engineering*, Stanford University, SGP-TR-109, p. 159-162.
- Ito, J., Kubota, Y., and Kurosawa, M., 1977, On the geothermal water flow of the Onuma Geothermal Reservoir: *Chinetsu (Geothermal Energy)*, v. 14, p. 15-20.
- Ito, J., Kubota, Y., and Kurosawa, M., 1978, Tracer tests of the geothermal hot water at Onuma Geothermal Field: *Japan Geothermal Energy Association Journal*, v. 15, p.87-93.
- Layman, E. B., 1984, A simple basin and range fault model for the Beowawe geothermal system, Nevada: *Geothermal Resources Council Transactions*, vol 8, p. 451-456.
- Rose, P. E., Adams, M. C., 1994, The application of rhodamine WT as a geothermal tracer: *Geothermal Resources Council Transactions*, vol. 18, p. 237-240.