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CROW™ FIELD DEMONSTRATION WITH BELL LUMBER AND POLE

Final Report

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By
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DISCLAIMER

ABSTRACT

In 1990, efforts were initiated to implement an in-situ remediation project for the contaminated aquifer at the Bell Lumber and Pole Company (Bell Pole) site in New Brighton, Minnesota. The remediation project involves the application of the Contained Recovery of Oily Waste (CROW™) process, which consists of hot-water injection to displace and recover nonaqueous phase liquids.

While reviewing the site evaluation information, it became apparent that better site characterization would enhance the outcome of the project. Additional coring indicated that the areal extent of the contaminated soils was approximately eight times greater than initially believed. Because of the uncertainties, in 1993, a pilot test was conducted that provided containment and organic recovery information that assisted in the design of the full-scale CROW process demonstration.

After reviewing the cost ramifications of implementing the full-scale CROW field demonstration, Bell Pole approached Western Research Institute (WRI) with a request for a staged, sequential site remediation. Bell Pole's request for the change in the project scope was prompted by budgetary constraints. Bell Pole felt that although a longer project might be more costly, by extending the length of the project, the yearly cost burden would be more manageable.

After considering several options, WRI recommended implementing a phased approach to remediate the contaminated area. Phase 1 involves a CROW process demonstration to remediate the upgradient one-third of the contaminated area, which contains the largest amount of free organic material.

The Bell Pole Phase 1 CROW demonstration began in mid-1995 and was operated until January 2001. The operation of the demonstration was satisfactory, although at less than the design conditions. During the demonstration, 25,502,902 gal of hot water was injected and 83,155 gal of organics was transferred to the storage tank. During operations more than 65% of the produced organic material was used in Bell Pole’s treating operation. Additional quantities of the material have been used since termination of the Phase 1 injection. Recycling the produced organic material has partially offset the cost of remediation.

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INTRODUCTION

Beginning in 1990, efforts were initiated by Western Research Institute (WRI) to implement an in-situ remediation project for the contaminated aquifer at the Bell Lumber and Pole Company (Bell Pole) site in New Brighton, Minnesota. The remediation project involves the application of the Contained Recovery of Oily Waste (CROW™) process (Johnson and Sudduth 1989), which consists of hot-water injection to displace and recover nonaqueous phase liquids (NAPLs).

Wood treating activities began at the Bell Pole site in 1923 and have included the use of creosote and pentachlorophenol (PCP) in a fuel-oil carrier. Creosote was used as a wood preservative from 1923 to 1958. Provalene 4-A, a nonsludging fuel-oil-type carrier for PCP, was used from 1952 until 1968, when it was no longer commercially available. A 5–6% mixture of PCP in fuel oil has been used as a wood preservative since 1952, and a fuel-oil-type carrier, P-9, has been used since 1968.

While reviewing the site evaluation information, it became apparent that better site characterization would enhance the outcome of the project. Additional coring indicated that the areal extent of the contaminated soils was more than two acres, approximately eight times greater than initially believed. Because of the uncertainties, a pilot test was conducted that provided containment and organic recovery information that assisted in the design of the full-scale CROW process demonstration (Fahy and Johnson 1992). Based on the results from the pilot test, a full-scale CROW process demonstration was implemented in 1995. Results from the pilot test and the full-scale CROW process demonstration through 1997 were summarized in a report to the Department of Energy (Fahy and Johnson 1998).

SITE CHARACTERIZATION

Characterization of the contaminated area at the Bell Pole site has been conducted for several years by Conestoga-Rovers & Associates Limited (CRA) and other consultants. The contaminated soil is contained in the New Brighton Formation (Stone 1966). It has been described as a relatively uniform, silty, fine- to medium-grain sand, 23–47 ft thick (CRA 1986). The contaminated soil is underlain by the Twin Cities Formation, which is a silty to sandy clay till. The New Brighton Formation is highly permeable, with hydraulic conductivities in the range of 3.1×10^{-3} to 9.5×10^{-3} cm/sec. Conversely, the underlying Twin Cities Formation has low permeability, with a conductivity on the order of 1.0×10^{-7} cm/sec (CRA 1986). The underlying clay till has provided an effective lower boundary to fluid migration and has been responsible for limiting the downward migration of the organic material.

A continuous aquifer lies at a depth of 10–20 ft below the ground surface. Groundwater flows radially at a velocity of 0.1–0.6 ft/day from a pond located to the northeast. Across the Bell

Pole site the groundwater gradient is 0.004 ft/ft toward the southwest, where the water appears to discharge into a drainage ditch.

In early 1990, 22 boreholes were drilled to define the extent of the contamination. Later, in preparation for the two-well pilot test, one new injection well and three monitor wells were also drilled and cored. Based on the evaluation of the coring data, it appears that the contaminated or saturated interval has an elongated, teardrop shape and dips toward the northeast (Figure 1). The maximum thickness in the center of the zone is approximately 25 ft, while the edge of the contaminated zone is between 1 and 2 ft thick. The horizontal extent of the contaminated area is more than two acres.

PROJECT OPERATION

Based on the results from the pilot test, conditions and procedures were developed for implementing a full-scale CROW process demonstration to remediate the remaining contaminated soil at the Bell Pole site. After reviewing the cost of implementing the full-scale CROW field demonstration, Bell Pole approached WRI and the Minnesota Pollution Control Agency (MPCA) with a request for a staged, sequential site remediation (CRA 1990). Bell Pole's request for the change in the project scope was prompted by budgetary constraints. Bell Pole felt that although a longer project might be more costly, by extending the length of the project, the yearly cost burden would be more manageable.

To address Bell Pole's request for a staged, sequential remediation plan, WRI designed a phased approach to remediate the contaminated area. Phase 1 involves a CROW process demonstration to remediate the upgradient one-third of the contaminated area, which contains the largest amount of free organic material. The phased approach is not expected to cause any adverse effects except for extending the time required to complete the entire project.

In 1993, WRI drilled four Phase 1 injection wells, three monitoring wells, and two Phase 2 injection wells, which are being used as downgradient monitoring wells during the first phase. By using the existing extraction well, PW1, and the new injection wells, a 0.6-acre, inverted, five-spot pattern was installed (Figure 1). Injection-to-extraction well spacings ranged from 88 to 145 ft, which is approximately twice the spacing used during the pilot test.

Initially, more patterns were planned to remediate the Bell Pole contaminated area, which would have provided injection-to-extraction well spacings similar to those of the pilot test. When the phased approach was implemented, a larger pattern with larger injection-to-extraction well spacings was implemented to lower up-front drilling and equipment costs. The larger well spacings, the lower pattern injection rate, and low temperature have combined to make heating the aquifer slower than initially planned.

Because of the high volume of traffic in the contaminated pattern area, all wells were completed with at-grade installations. Surface piping was buried below frost level, which also reduces heat loss. All surface tanks, equipment, and instrumentation are contained in a building.

A produced-fluid treatment system based on results from the pilot test (Fahy and Johnson 1992) and bench-scale tests conducted by Bell Pole and various vendors was designed and installed. During the pilot test, it was observed that a significant amount of oil/water separation was occurring in the 40,000-gal tank where all produced organic material and water was being pumped. To capitalize on this occurrence, sulfuric acid was added to lower the pH to approximately 3.5, and all produced water and organic material was pumped into a 40,000-gal process tank. Organic material skimmed from the top and pumped from the bottom of the tank was routed to an oil storage tank. This batch operation was performed daily.

Water was continuously pumped from the 40,000-gal process tank to an air flotation unit where the oily water was aerated and most of the remaining oil and grease, PCP, and organic carbon were removed and recycled back to the 40,000-gal process tank.

The treated water leaving the air flotation unit was further treated with sodium hydroxide, then pumped to a 10,000-gal equalization tank. From this tank, excess produced water, approximately 3–4 gpm, was pumped to an ozonation unit that removed residual PCP. The water was then disposed of in the sewer. The conceptual design of the water treatment system is shown in Figure 2.

Prior to installing the CROW process system, Bell Pole installed a two-well, pump-and-treat system downgradient from the area of mobile organic contamination. The water produced from the pump-and-treat wells entered the 10,000-gal equalization tank and was either treated for disposal or reinjected.

Water that was not pumped to the ozonation unit was recycled through a hot-oil boiler/heat exchanger system, where it was heated and reinjected. A stainless steel, tube-and-shell heat exchanger was installed during 1999. This heat exchanger gave better reliability and resulted in a higher injection water temperature. Heat exchangers were a problem throughout the project. Four different units were placed in operation. These units, in addition to tube and plate failure, experienced tube organic coating that resulted in poor heat transfer and lower injection water temperatures. The hot-oil boiler used to heat the injection water also presented problems. This type of heating system is not ideal for this application, but was used because of its availability and because it met operational code requirements that could not be achieved as easily with a high-pressure steam boiler.

Results of the water treatment system are shown in Table 1. Water organic concentration measurements have been taken throughout the operation of the pilot test and the Phase 1 full-scale

CROW field demonstration. The air flotation unit provided lower oil and grease values than a coalescing separator used during the pilot test. The March 1996, PW1, effluent, oil and grease measurements were uncharacteristically low; however, the September 1998 oil and grease measurements were more typical of what was expected from the pilot test. The oil and grease values for injected water were lower in the 1998 sampling than in the 1996 sample values. Injection water and discharge water organic limits are shown in Table 1 for comparison.

To enhance the operation of the water treatment system, a secondary oil skimmer tank was added downstream of the air flotation unit. This unit removed additional organic material and improved the quality of the reinjected water. During 1998 and 1999 two tests were conducted in an attempt to improve the organic/water separation and the water quality of the reinjected water. The first test involved running the reinjected water through resin beds after it left the air flotation unit. In the second test, the water was treated with a polymer. The resin beds did not remove significant amounts of organic material and proved to be very costly. The polymer also did not remove enough organic material to make it worthwhile. The MPCA and the Minnesota Department of Health have stringent requirements, making many polymer materials unacceptable for use. If better polymers that are acceptable in Minnesota had been found, additional polymer injection testing would have been undertaken.

After intermittent operation in 1995, continuous groundwater extraction was established in late February 1996, and continuous hot-water injection began a week later in March. In July 1996, hot-water injection was terminated because of the first heat exchanger failure. Ambient-temperature water injection and extraction continued. The entire system was shut down in November 1996 because of organic/water emulsion problems. After treating the emulsion, hot-water injection began again in April 1997 and continued until late September 1997, when after 194 days of continuous operation, the system was shut down for maintenance, equipment modifications, and additional emulsion treatment. The system was restarted in January 1998 and operated until January 2001 with only short periods of downtime for maintenance.

Since starting hot-water injection in March 1996, the Bell Pole CROW system has operated for 59 months with a 78% on-line rate.

RESULTS

The Bell Pole Phase 1 CROW demonstration operated satisfactorily, although at less than the original design conditions. The Bell Pole CROW test summaries are shown in Table 2. The original target flow rates and temperatures are included for comparison.

Injection and extraction flow rates, injection water temperatures, and average aquifer temperatures for monitoring well BP27 are shown in Figure 3. For the first 40+ months of operation, it was impossible to achieve injection water temperatures higher than 160 °F (71 °C). But, since the changes in the heat exchange were made, injection temperatures of 179 ºF (81.6 ºC) were realized.

Monthly aquifer temperature measurements were taken throughout the life of the project. Aquifer temperature measurements were contoured a month after the system was shut down at the end of October 1997 (Figure 4). Similar measurements were taken in December 1998 and February 2000 (Figures 5 and 6). In 1997, the hot-water injection appeared to establish an interconnected hot-water front, especially in the upgradient direction. The highest temperatures in the pattern occurred in the area of monitoring well BP27, and appeared to be influenced by injection into IW10. The extraction well, PW1, did not see a high-temperature response. The downgradient part of the pattern in the area of monitoring well BP25 did not respond as fast as the upgradient part. From the temperature measurements taken in late 1998, a similar heating profile was seen. However, higher temperatures were being achieved, and most of the pattern approached the target temperature range of 120–140 ºF (49–60 ºC). Unfortunately, beginning in early 1999, aquifer temperatures began to decline. Figure 6, the latest temperature contour map, maintains the same shape of the earlier figures, but is twenty degrees cooler overall than in December 1998.

Monitoring wells BP27 and BP29, located on a line between wells IW10 and PW1, experienced the greatest temperature response, although less than earlier in the project. Monitoring well BP28, which is also on a line between IW10 and PW1, experienced temperature increases during 1998, but was significantly cooler than nearby BP29, a trend that was noted since the pilot test. Downgradient, monitoring well BP25 temperatures continue to be colder than at BP27 and BP29, but similar to BP28. The extraction well, PW1, aquifer temperature has been approximately 95 ºF (35 ºC) for the last 24 months. Fairly uniform vertical temperature distributions occurred at all monitoring wells, suggesting that acceptable vertical sweep efficiency was being achieved (Fahy and Johnson 1999).

The Bell Pole aquifer was overpumped by an average of 21%, 2–4 gpm more than was injected. This was done for containment purposes. By pumping more water from the center of the pattern, injected water was drawn toward the extraction well. Aquifer temperature measurements confirmed the containment of the reinjected water.

Organic production was estimated from the daily transfer of organic material from the process tank to the oil storage tank. Organic material was typically drained from the process tank until water appeared. Unfortunately, it was impossible to know if all the organic material had been drained from the tank at that time. This tends to make production rates somewhat erratic, and often it was not known for some time whether increases or decreases in the organic production rates were real. The monthly organic production tank transfers are shown in Figure 7. A seven-month rolling average was applied to smooth the data and provide a better estimation of the actual organic material production rate for comparison with the modeling results. By shutdown in January 2001, 83,155 gal of organic material was produced and transferred (Figure 8).

Figure 7 also contains the average aquifer temperature at monitoring well BP27, the hottest upgradient aquifer temperature. During a 14-month period, 23 to 37 months into the test, there was a clear trend of increased organic production, which followed a six-month period of declining production. The increased organic production corresponded to an increased aquifer temperature in the upgradient part of the pattern. As the aquifer temperature declined, so did the organic production. Reduced organic production was obviously affected by the declining aquifer temperature, but also by a declining organic content in the upgradient part of the pattern.

The produced organic material is a usable product in the Bell Pole operation and is partially offsetting the cost of remediation. More than 65% of the produced organic material was used in Bell Pole's treating operation by the end of hot-water injection. Additional quantities of the material have been used since termination of injection.

As the organic production decreased, consideration was given to expanding the Phase 1 pattern to begin producing and remediating the remaining part of the contaminated area. Two scenarios were considered. The first scenario involved producing a centrally located extraction well in the vicinity of well IW8. The second scenario was similar, but two downgradient injectors would also be added to develop two interconnected, inverted, five-spot patterns. These expansion efforts will begin when the Bell Pole management authorizes the necessary expenditures.

Modeling

A three-dimensional thermal simulator developed by WRI was used to model the CROW field demonstration at Bell Pole (Mones et al. 1996). Relative permeability curves were developed from the Bell Pole Phase 1 production data. With these relative permeability curves, an acceptable match between predicted and actual cumulative organic material recovery results was achieved (Figure 8). Details of the Bell Pole data matching are contained in an earlier final report (Fahy and Johnson 1998).

Applying heat to a contaminated aquifer through the CROW process can aid organic recovery through viscosity reduction, reduction in the residual organic saturation, thermal expansion effects, and improvement in the mobility ratio (Farouq Ali 1974). Numerous studies have also reported temperature effects on two-phase relative permeability in porous media, which is another important effect for improved remediation with the CROW process. Early thermal modeling suggested that temperature dependence of relative permeability must be incorporated into the model to reproduce experimental results (Coats et al. 1974). Review of the early literature on the effects of temperature on relative permeability (Nakornthap and Evans 1986) suggests the following:

- Relative permeability can be expressed in terms of water saturation and irreducible water saturation.

- Relative permeability can be related to temperature if the irreducible water saturation has been found to increase with temperature.

- Relative permeability to oil increases and relative permeability to water decreases as temperature increases.

- Ignoring the temperature-dependent relative permeability may lead to pessimistic organic recovery results.

- Residual oil saturation decreases as temperature increases.

At this time, temperature-dependent relative permeability effects have not been addressed with the simulator. The data were not available for the Bell Pole project, and acceptable substitutions have not been found in the literature. However, the Phase 1 pattern aquifer did experience an increase in organic production with an increase in temperature, as achieved during the pilot test and in the laboratory.

Without adjusting the relative permeability curves, the model predicts less additional recovery at elevated temperature than was achieved. The findings summarized from Nakornthap (1986) suggest that the residual organic saturation will decrease, and the elevated-temperature, irreducible water saturation will increase until the excess organic production, achieved from month 35 until the present, is matched. In addition to the ambient-temperature relative permeability curves now in use, this procedure provided calculated relative permeability curves for the Bell Pole project at elevated temperatures.

CONCLUSIONS

Based on the Bell Pole Phase 1 results, the following conclusions and comments can be made:

- The project did not achieve the design flow rates and temperature; however, organic production exceeded expectations.

- Injection water was contained by overpumping the extraction well.

- The produced organic material was a usable product in the Bell Pole operation and partially offset the cost of remediation.

- A reasonable match of the Bell Pole Phase 1 results was achieved with the WRI thermal simulator without considering the effect of temperature on relative permeability.

- The Bell Pole aquifer temperatures finally approached the desired temperature range and an increase in organic production occurred because of the increased temperature. Unfortunately, since early 1999, aquifer temperatures and organic production have both declined.

- The decline in organic production is also affected by the declining organic saturation in the upgradient part of the pattern. This effort will be conducted entirely by Bell Lumber and Pole without any U.S. Department of Energy involvement.

- Modeling efforts to evaluate the effect of temperature on recovery by the CROW process are ongoing.

- Design efforts are also under way to prepare for remediation of the remaining contaminated area.

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Table 1. Bell Pole CROW Hydrocarbon Sampling, mg/l

	Pilot Test	March 1996	September 1998	Discharge Limit
PW1 Effluent				
Oil and Grease	810-6300	300	1300	—
PCP		190-300		
PAH		38-1390		
After Process Tank				
Oil and Grease	522-570	—	730	—
PCP				
PAH				
Coalescing/Air Flotation Unit				
Oil and Grease	130-390	71	93	—
PCP		33-64		
PAH		12-15		
Injection Water				
Oil and Grease	—	96	70	100
PCP		10		
PAH				
Discharge Water				
Oil and Grease	—	—	—	—
PCP		0.05	<1	2
PAH		—	<4	10

Table 2. CROW Operations Summary, Bell Lumber and Pole

Year	Operating	Injection	Extraction		Sewer Discharge	Flow Temperature	
			Fluids	Organics		Extraction	Injection
	Days	gal/yr	gal/yr	gal/yr	gal/yr	deg F	deg F
1995	NA	222,811	642,269	536	544,018	NA	NA
1996	250	4,103,856	5,288,544	18,943	1,601,148	Amb	Amb
1997	194	4,025,088	4,951,296	22,484	1,491,779	73	135
1998	330	6,883,056	8,180,352	20,610	1,876,755	94	158
1999	316	6,368,688	7,175,952	15,365	1,273,043	95	160
2000	196	3,532,896	4,277,520	5,273	1,038,441	90	170
2001	29	589,318	693,520	480	126,580	86	172
96-02 Total	**1,315**	**25,502,902**	**30,567,184**	**83,155**	**7,407,746**		
96-02 Average, gpd		19,393	23,245	63.2	5,633		
96-02 Average, gpm		13.5	16.1	0.04	39		
Target Rate		20-40	30-50		5-10		200

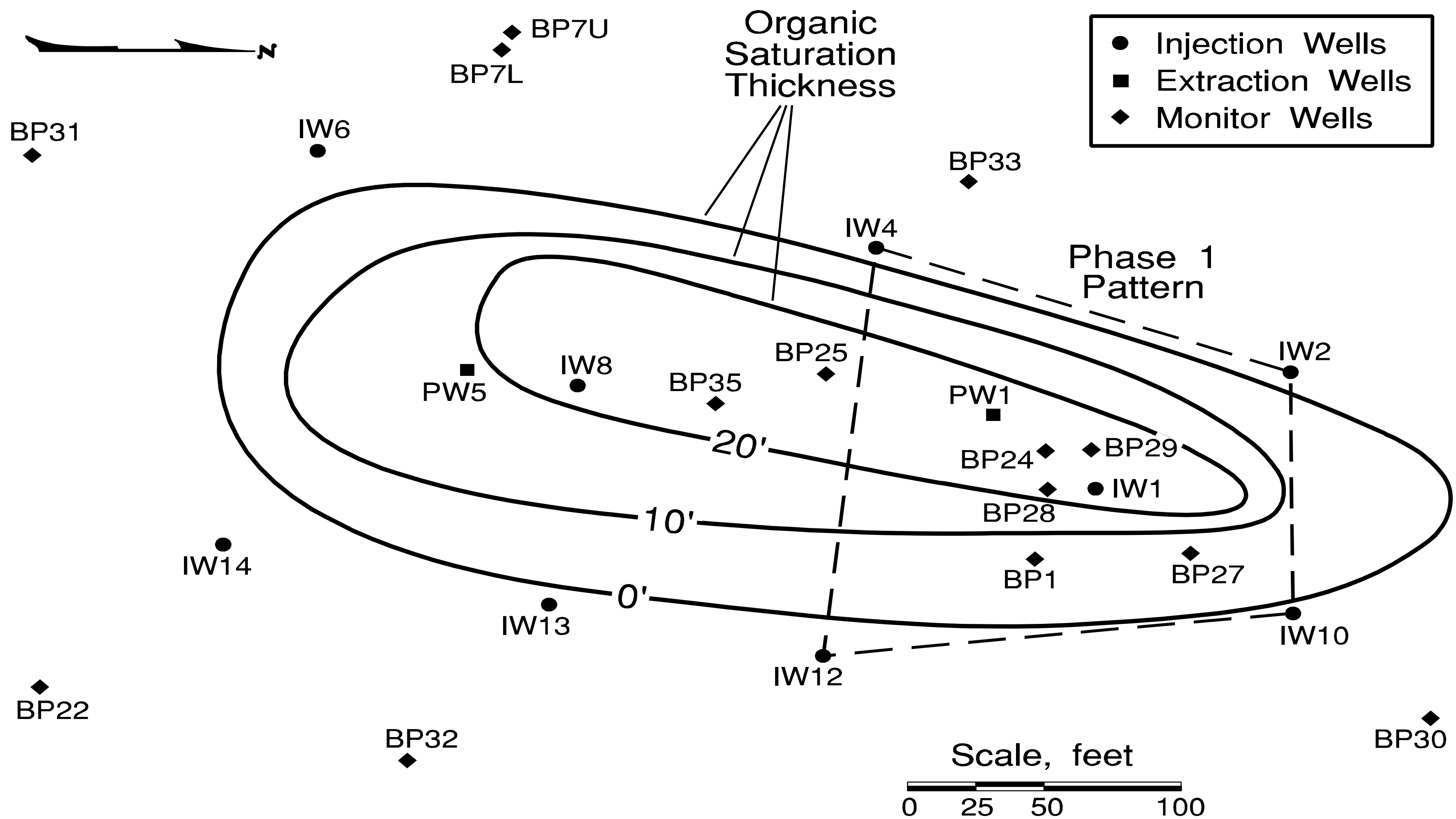


Figure 1. Phase One Well Pattern

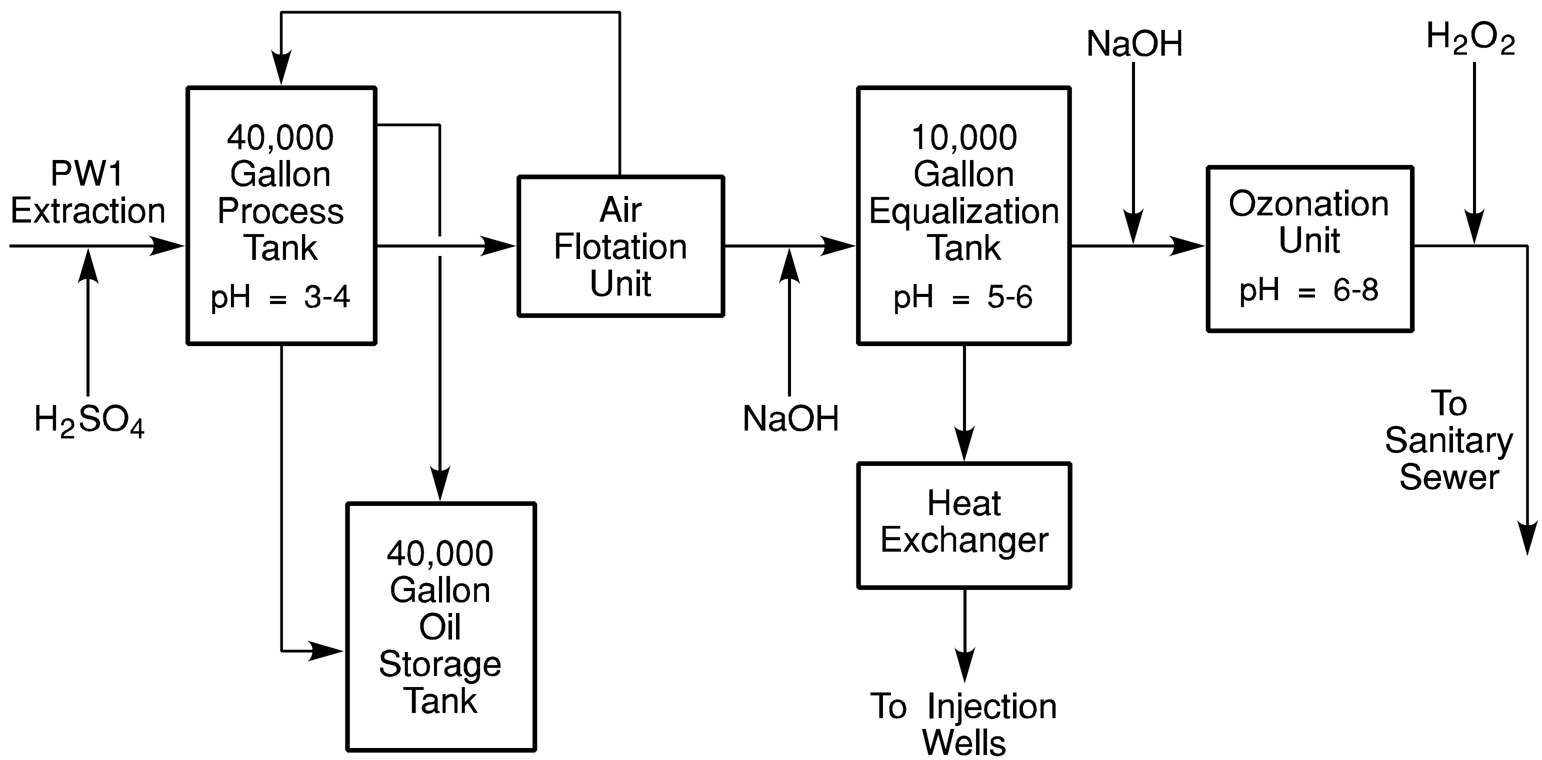


Figure 2. Bell Pole Water Treatment System

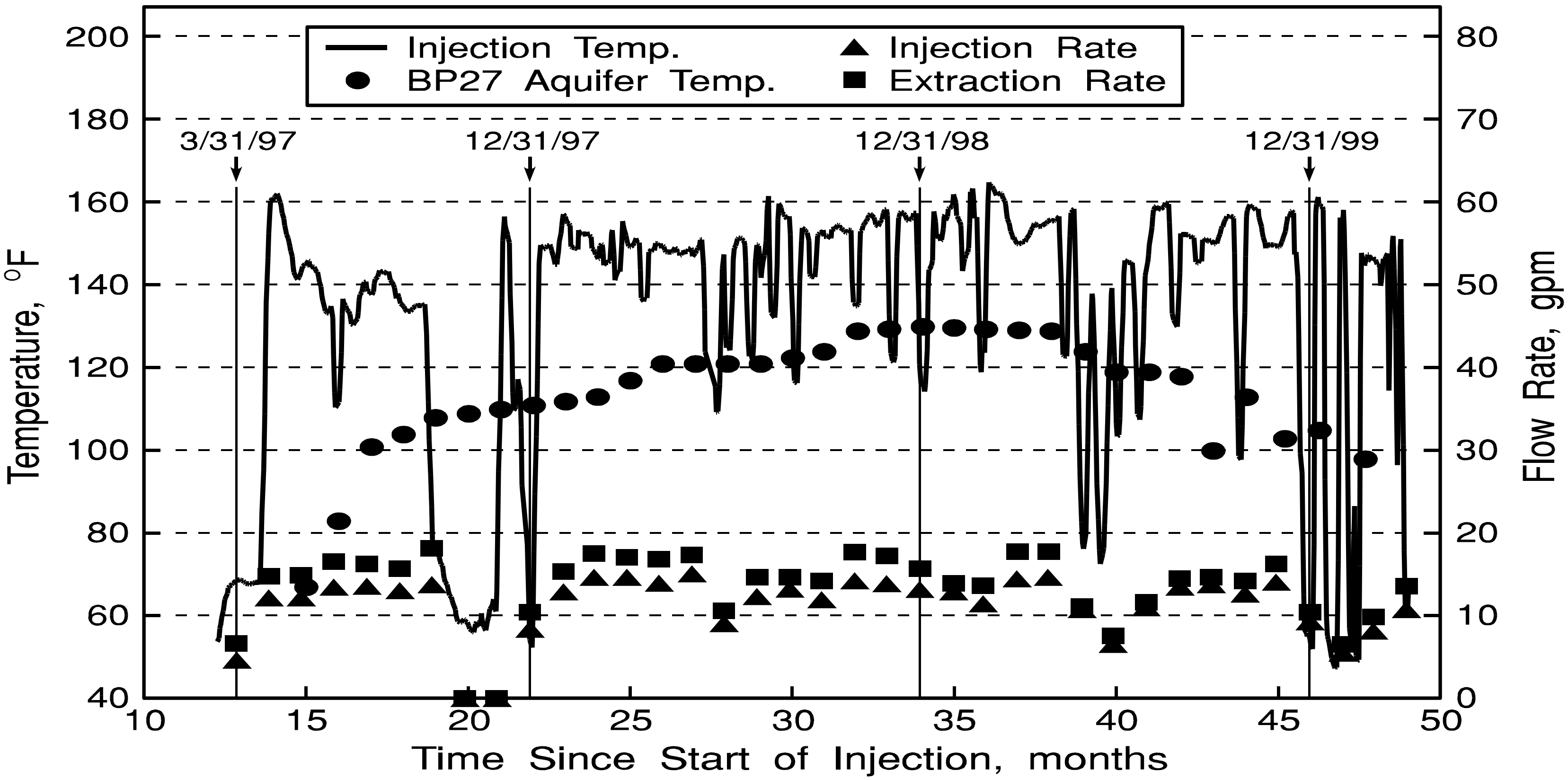


Figure 3. Bell Pole Temperature and Flow Rate Profile

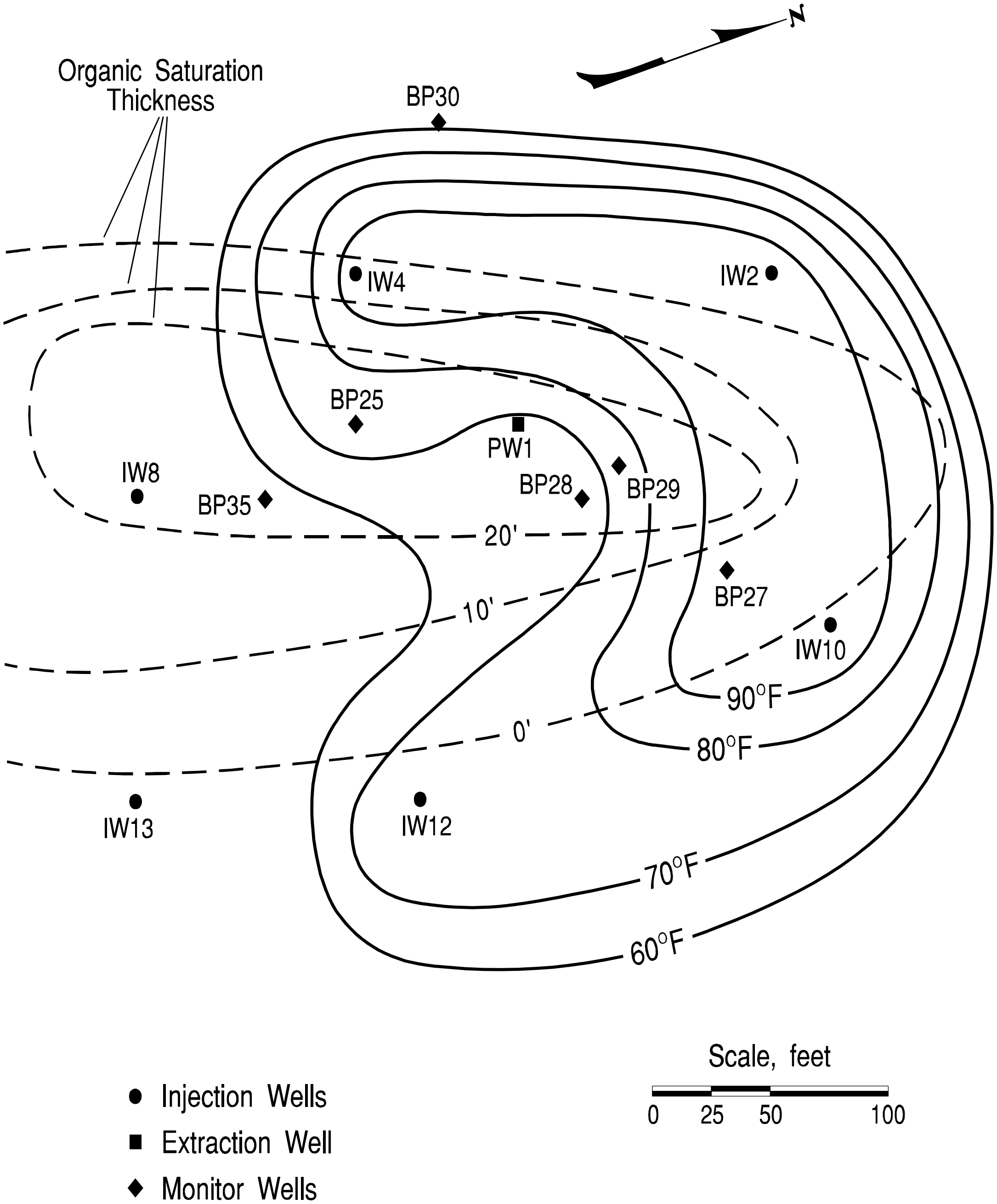


Figure 4. Bell Pole Temperature Profile, October 1997 (System Shut Down)

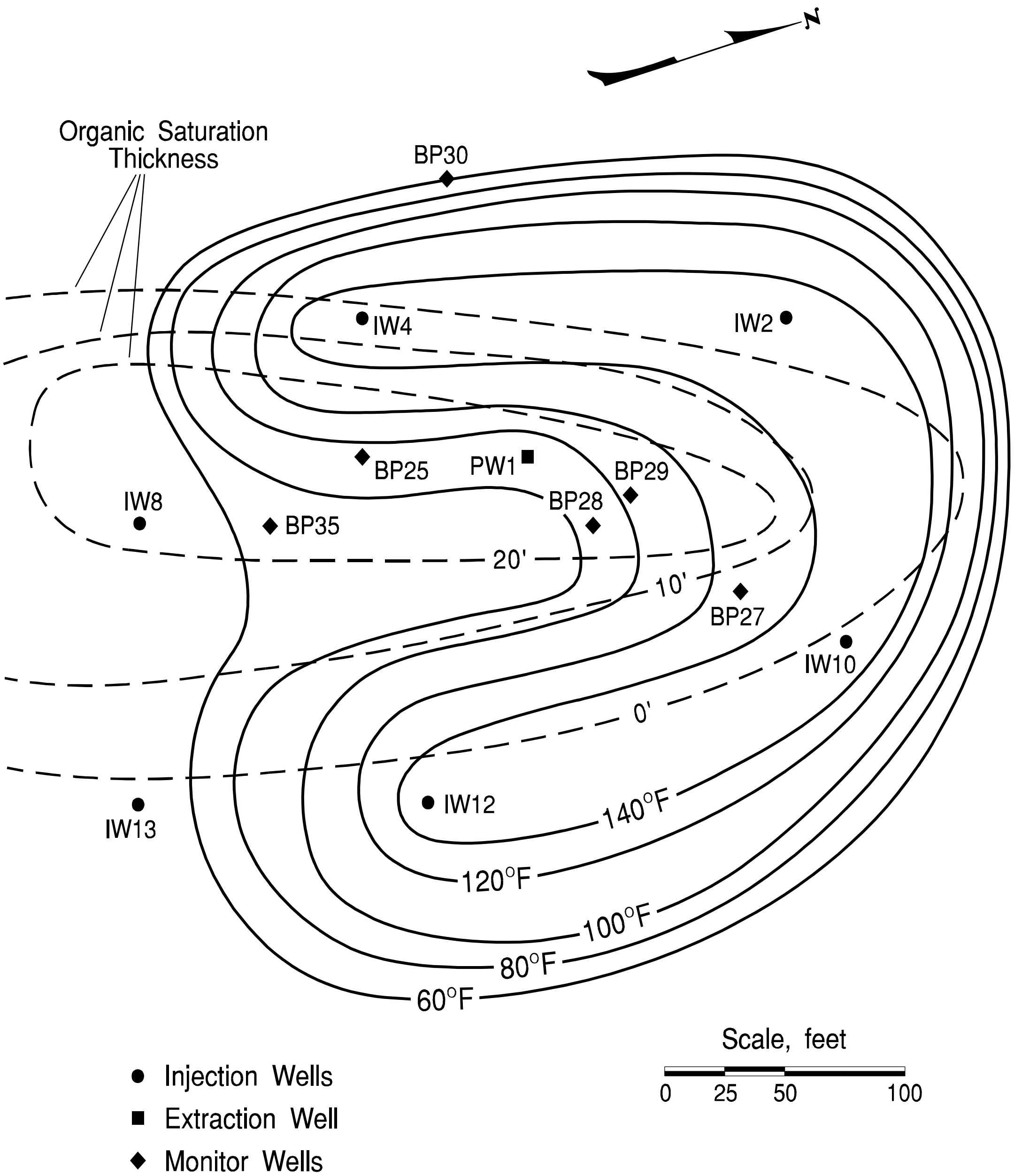
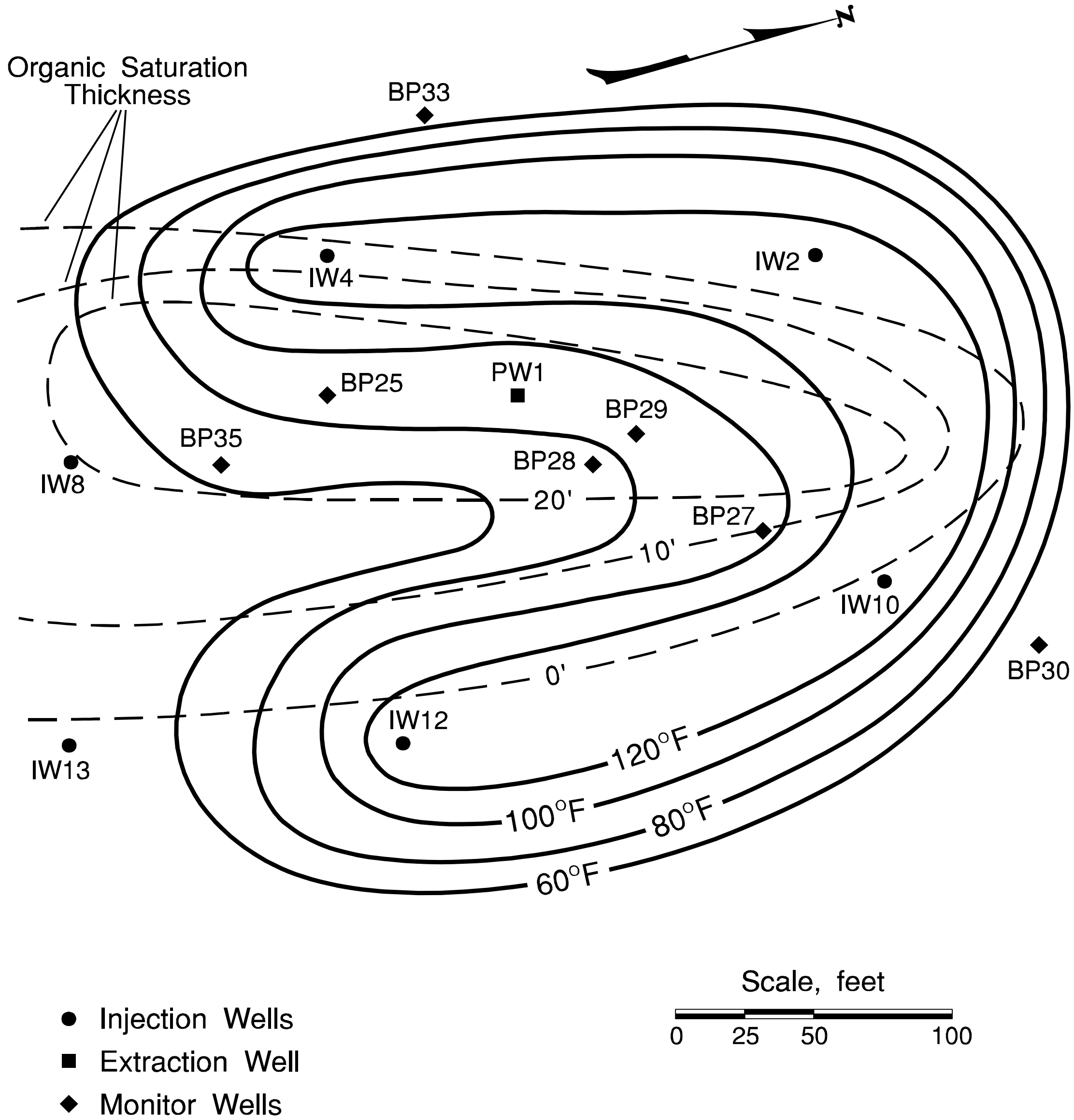


Figure 5. Bell Pole Temperature Profile, December 1998 (System Operating)



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Temperature Profile, February 2000 (System Operating)

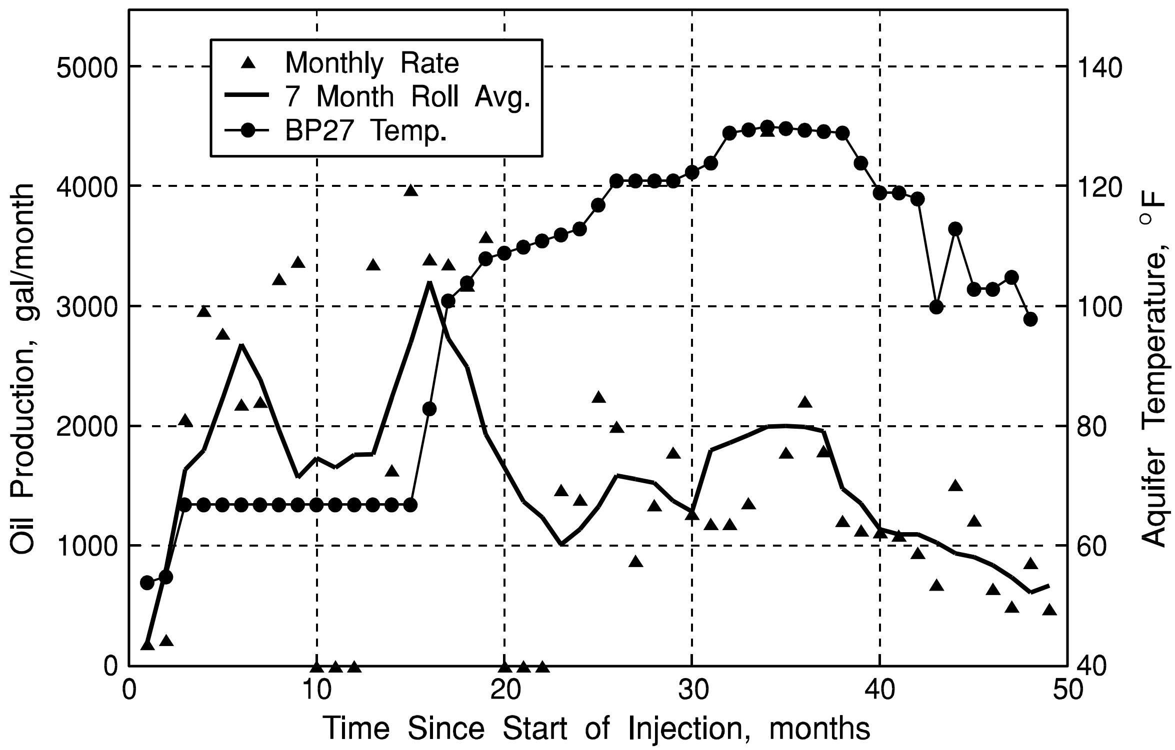

Figure 7. Bell Pole Monthly Organic Production Rate

Figure 8. Bell Pole Cumulative Organic Production Comparison