GEOTHERMAL INJECTION MONITORING IN KLAMATH FALLS, OR

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ABSTRACT

Klamath Falls has nearly a 150-year history of geothermal utilization. The geothermal aquifer has been the subject of many studies and is probably the most tested direct use reservoir in the world. This provides good background data for increased monitoring needed as new injection wells are drilled. Prior to July 1990, few injection wells existed. A city ordinance requires injection after July 1990. The city and major injectors have initiated a monitoring system.

INTRODUCTION

Klamath Falls has a long history of direct use of geothermal energy. The Indians used local boiling springs for perhaps thousands of years for scalding water foul and cooking meat. Mid-19th century pioneers developed the springs for bathing, heating and cooking. On August 10, 1876, an account in the Ashland Tidings provides an interesting account of a visit to a ranch and use for a bathhouse. "Eggs and meat are cooked by placing a vessel containing them under a flowing hydrant", and adds a bit of humor, "We congratulated Mr. Brooks on the favorable location of his place when he comes to die, for it is evident that the distance to that other country must be very short, and he would, therefore, be saved a long and perhaps tedious journey."

Until the mid-1970s, geothermal use was characterized by American pioneer individualism. Use occurred through individual initiative and although some impressive uses had been developed such as the four story brick White Pelican Hotel, built in 1911 which was supplied with geothermal water through a 2,000 ft plus wooden pipeline, geothermal wells typically supplied only one house or business. Today there are over 550 wells, most of which utilize downhole heat exchangers and supply only one use, although some are fairly large.

In 1977, the first district heating system was proposed and with demonstration project funds from the U.S. Department of Energy, construction was started in 1979 and completed in early

1982. The system consisted of two production wells, an injection well, heat exchange facilities, a 0.7 mile geothermal pipeline and closed loop piping serving government buildings.

Meanwhile, although by this time there were operating injection systems, there had been no long-term large pump and inject tests, and citizens became concerned about the effects of the district system on individual wells. Also, it had become fairly evident that water levels had started dropping in about 1973 and were continuing at the rate of about one foot per year (Figure 1). The district system production wells were near residential wells and the injection well was near downtown over 3,000 feet away. Concerns became so great that an initiative petition and city ordinance were passed which prohibited extraction of geothermal water from a well unless it was returned undiminished in quantity to the same well. The ordinance effectively blocked any use except downhole heat exchangers which do not extract water, and blocked use of the already constructed system.

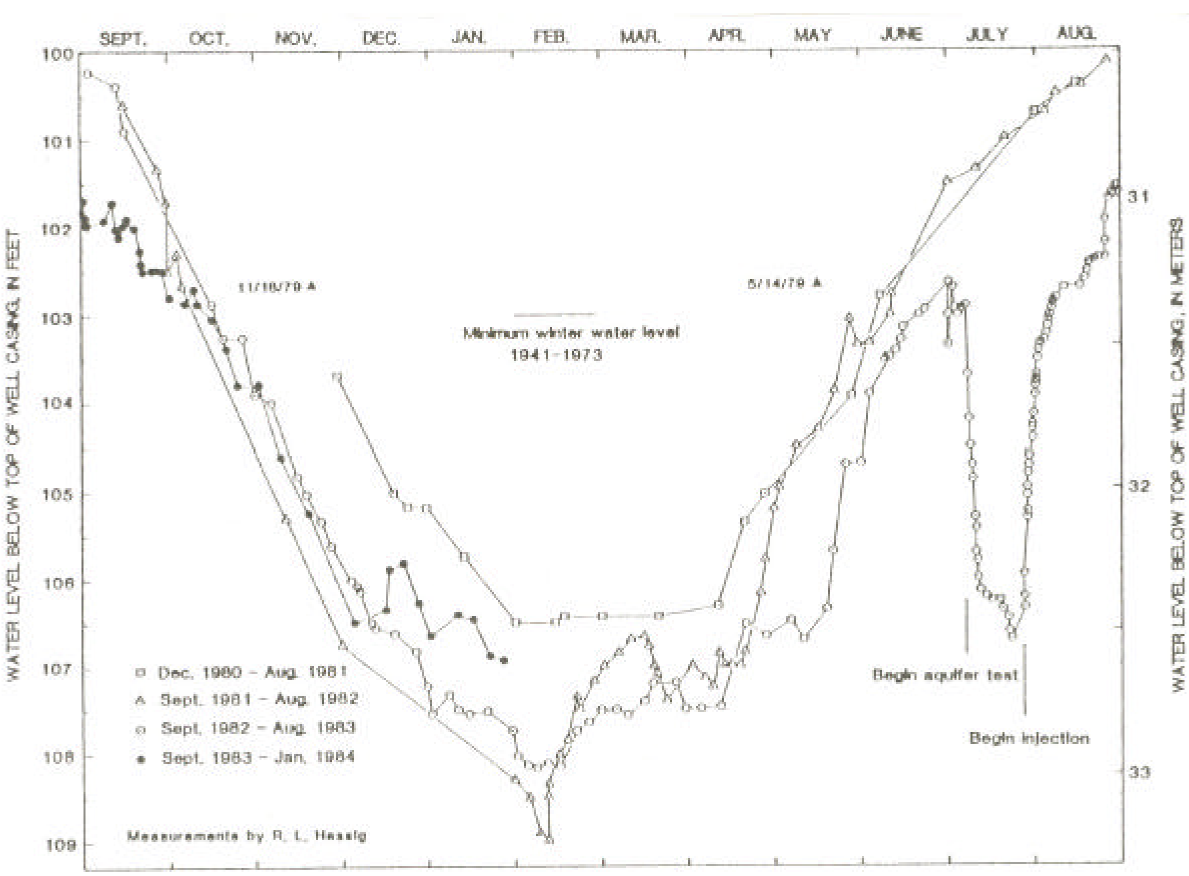

Figure 1. Annual water-level fluctuations in well 181 (Hessig) for the years 1981-1984.

In January 1983, the County Chamber of Commerce and a well owners group, Citizens for Responsible Geothermal Development (CRGD), initiated efforts to gather data and by March aquifer monitoring was under way largely by volunteers. The objectives of the program were to gather historical data, and to monitor water levels and temperatures. However, this effort ultimately led to a large scale aquifer test which included long-term pumping and injection and tracer testing.

At this point, it might be worth noting that a great deal of background data existed--but was not all readily available. This included very early personal diaries; tintypes and photographs; drillers, plumbers and pump installers' records; notes on floor joists and posts in basements, etc. Also, the State Water Resources Department had started monitoring water levels and temperature of a few wells in the late 1950s. This effort was expanded by OIT in 1962, before construction of the geothermally heated campus and carried on for several years afterward. Starting in 1973, the Geo-Heat Center completed several projects including documenting well temperatures, water chemistry, water levels, well depths, etc., in the urban area, and at the same time, USGS did similar work and completed reports on the geology and hydrology of the Klamath Basin. All of these bits and pieces contributed to the history, baseline data and understanding of the resource, which is a prerequisite to monitoring.

During the summer of 1983, investigators from Lawrence Berkeley Laboratory (LBL), Stanford University and Oregon Institute of Technology (OIT), funded largely by USDOE, were co-investigators with the U.S. Geological Service in an intensive study of the Klamath Falls Geothermal Aquifer. This work included tracer studies by Stanford; a pumping and injection test by LBL; temperature, discharge and utilization studies by OIT, and sampling for chemical and isotopic analysis by USGS.

Very briefly, the geology is that of a fault controlled lateral leakage geothermal reservoir. Rocks are primarily volcanic and much of the fluid movement occurs in layers of scoria and brecia that may be one to a few feet thick. Overall thickness of the reservoir is estimated to be at least 1,500 feet. The hot well area is complexly faulted and well lithology often cannot be correlated over distances as short as 100 feet. Much of the fluid rises along a major northwest trending fault along the east side of the hot well area (Sammel, 1984). Based on the results of the 1983 aquifer test and more recent analysis of aerial photos and well lithologies, there appears to be at least two sub-parallel faults west of the major fault and several northeast trending faults crossing the area. Figure 2 shows the major fault at the east side of the hot well area and well temperature isotherms.

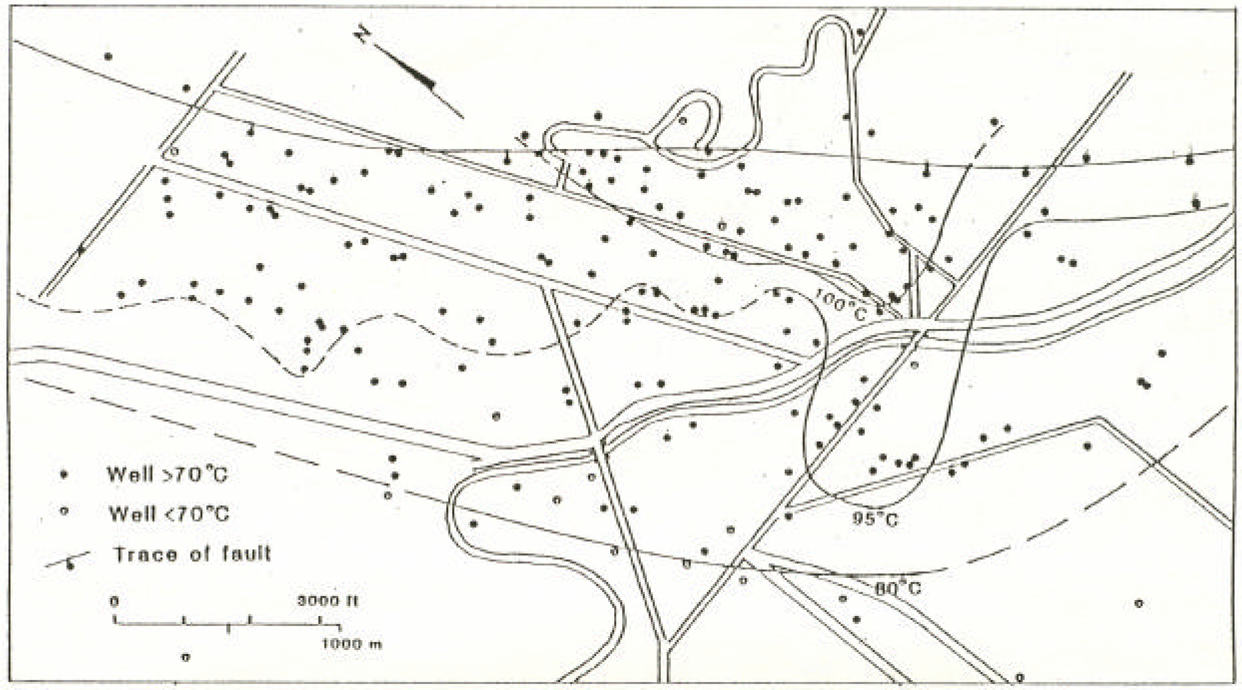

Figure 2. Lines of equal temperature based on reported maximum temperatures measured in wells or in well discharges, in °C. The isotherm define regions in which most wells have reported temperatures in the ranges indicated.

TRACER TESTS

Klamath Union High School Doublet

In 1983, there were four doublet systems in Klamath Falls, i.e. systems that pump from one well and inject into another with no wells in between. Klamath Union High School (KU) was chosen for the test since it has a high constant flow rate, is near the city injection well, near the main hot well area and has several other wells nearby suitable for monitoring for tracer breakthrough.

The KU production well is 257 feet deep and the lower 25 feet has perforated casing. The injection well is 250 feet away, 240 feet deep and cased to 120 feet. At the start of the heating system, the production well pump is turned on and pumps 305 gpm to the high school until spring. Produced water is 165°F at startup, but falls to 160°F in 3 to 10 days after startup. During the heating season, water enters the high school heat exchangers at 160°F and leaves at 150 - 152°F depending on heat load. Output is typically 0.3 MWt.

Both chemical and fluorescent tracers were used in the KU test. Potassium iodide was the chemical tracer, and rhodamine WT and fluorescein as fluorescent tracers. The purpose of using several tracers was to evaluate their performance in low temperature geothermal systems. Tracers were injected at the injection well head.

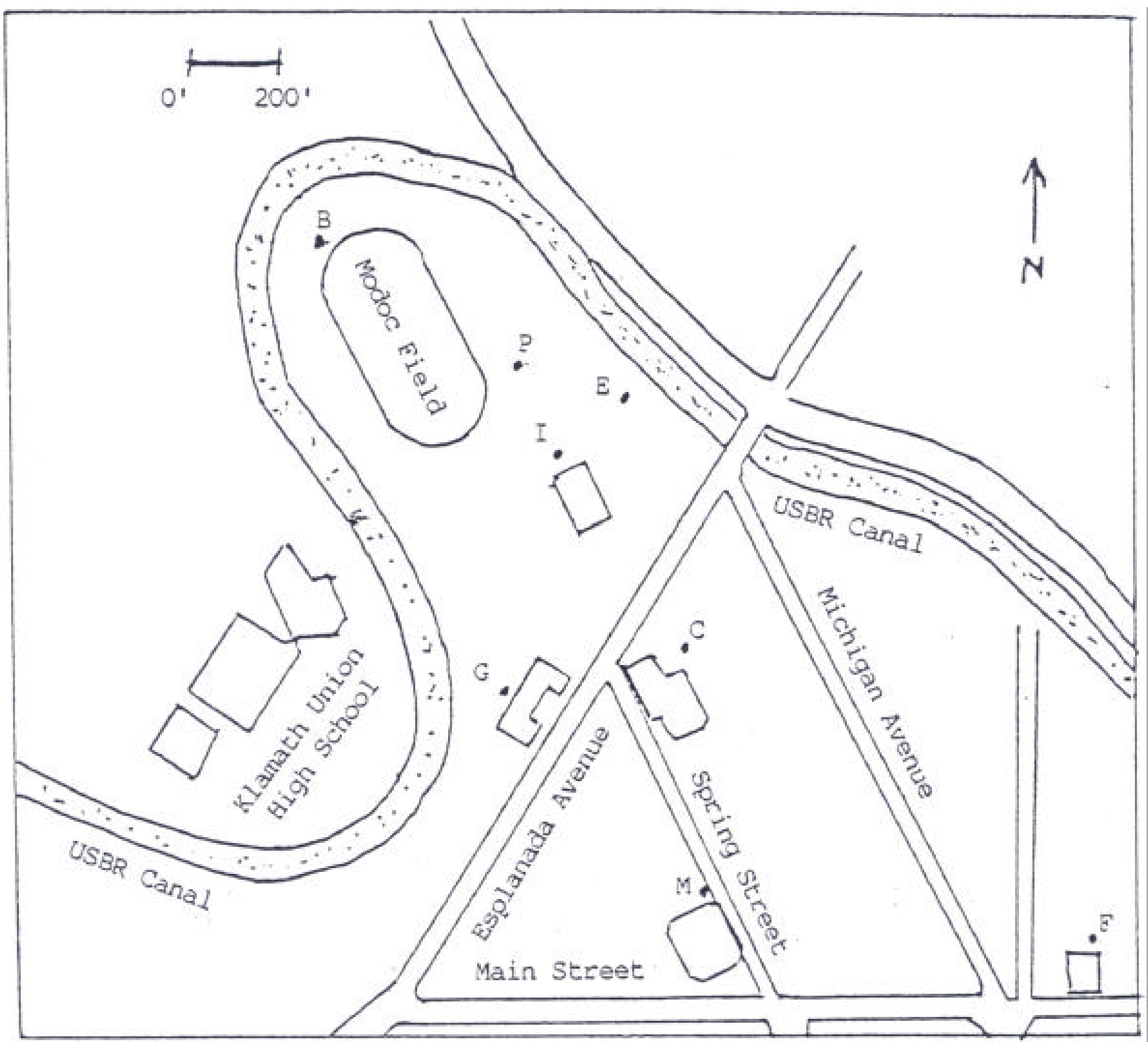

Figure 3. Locations of wells for the Klamath Union High School tracer test. P, production well; I, injection well; B, Balsiger well; C, Medo-Bel well; E, Eccles well; G, Garrison well; F, Friesen well; M, County Museum well. Not shown, Jones well 1,120 ft - 15 ft/day.

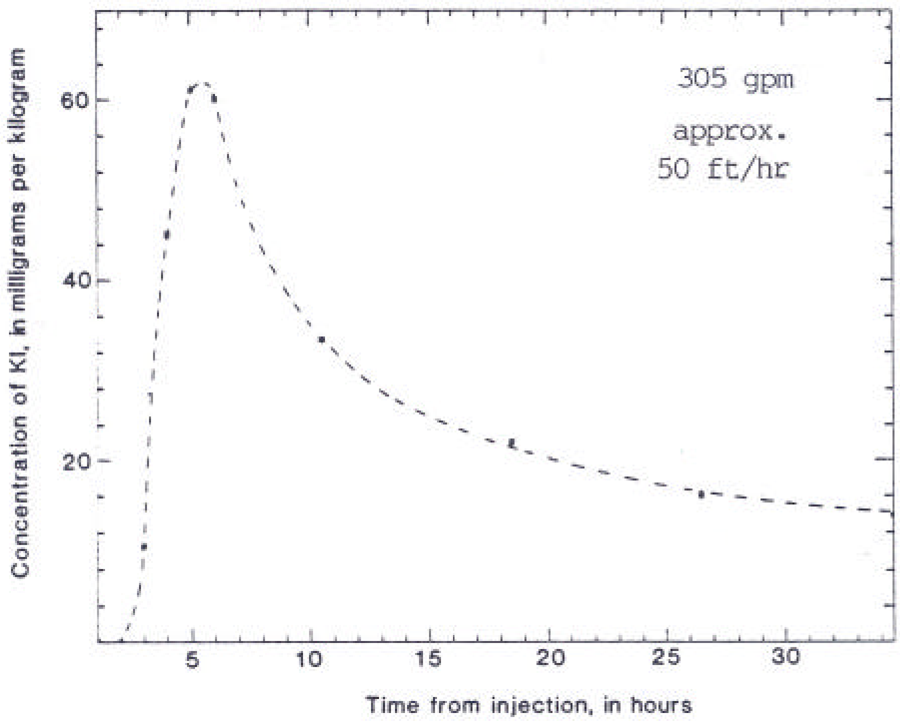

Figure 4. Breakthrough curve in production well, KUHS doublet test.

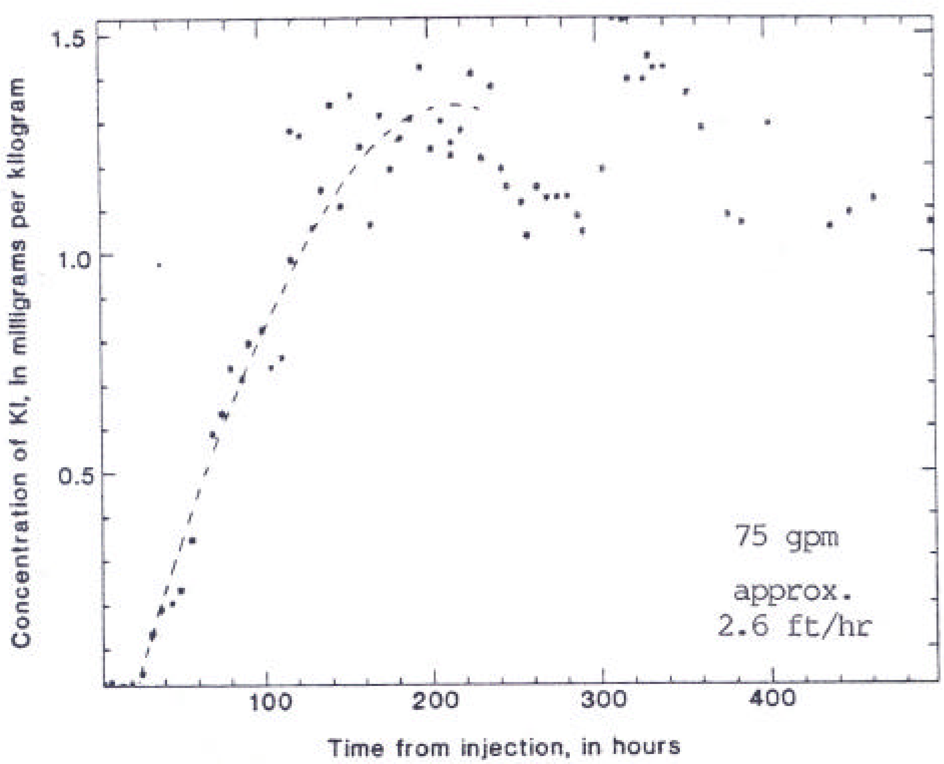

Figure 5. Breakthrough curve in Medo-Bel, KUHS doublet test.

An automatic sampling apparatus was set up at the KU production well. Five other wells were sampled by hand: Balsiger, 250 ft deep 30 gpm; Medo-Bel, 765 ft deep 75 gpm; Eccles, 787 ft deep 20 gpm; Friesen, 563 ft deep 20 gpm, and Garrison, 240 ft deep 10 gpm. Other wells in the area were shut off during the test (Figure 3).

Tracer breakthrough to the KU production well was detected about two hours after injection. Concentration peaked at about 5 -6 hours, fell off rapidly at first then more slowly (Figure 4). Chemical and dye tracers showed the same behavior. The flow pattern in the KU doublet is affected by other wells. Tracers were detected in the Medo-Bel well 450 feet away in 26 - 27 hours and peaked at 180 - 200 hours (Figure 5). Tracers were not detected in other wells in 500 hours.

The average flow velocity in the KU doublet is 43 - 49 feet per hour. Average velocity to the Medo-Bel well was 2.3 - 2.6 feet per hour.

City District Heating System

An aquifer test utilizing one of the city system production wells and the injection well was started June 29, 1983. The test consisted of: background monitoring, June 29 - July 5; pumping with no injection, July 5 - July 26 (21 days); pumping with injection, July 26 - August 24 (30 days); recovery monitoring, August 24 - September 1. A tracer test was conducted in conjunction with the pumping with injection segment.

The production well and injection well are about 3,000 feet apart with a natural hydraulic gradient of 0.5% from the production well to the injection well. The injection well is slightly artesian and the total head difference is 15 feet. Pressure at the injection well head was 39 psi rising to 43 psi at the end of the test. The production well was pumped at 720 gpm without injection; but, injection back pressure reduced this to 690 - 675 during injection. There are a large number of DHEs, pumped and flowing wells between the production wells and injection well. Five flowing and pumped wells were initially selected for tracer collection and four were added after the test started.

Of the five wells initially selected, tracer was detected in only one, the Friesen well, about 1,000 ft from the injection well and on a direct line between injection and production. Tracer detection occurred about 16 days after injection peaking at 36 days, 8 days after injection stopped. The well is pumped at about 20 gpm (Figure 6).

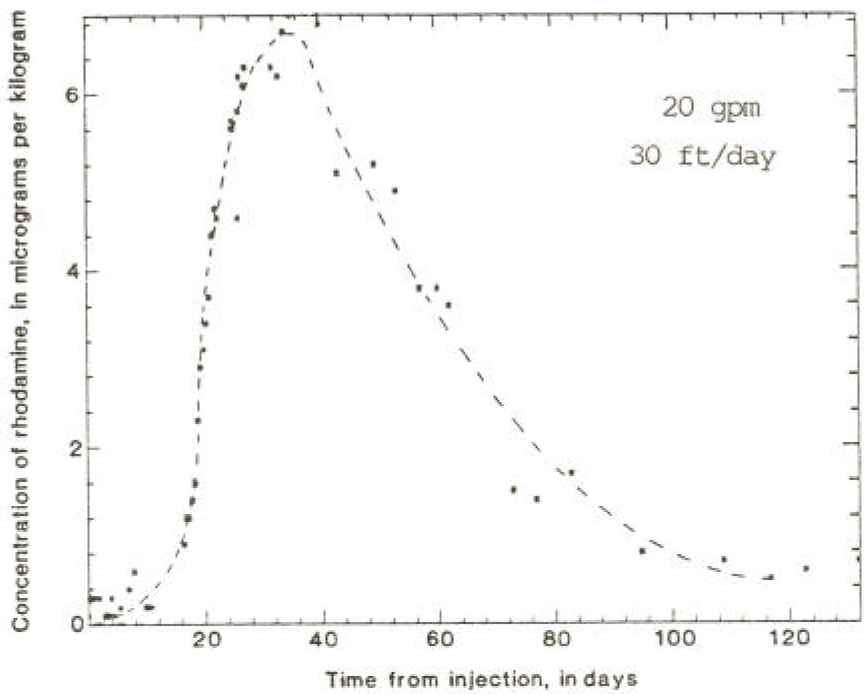

Figure 6. Breakthrough curve in Friesen well, County Museum well injection test.

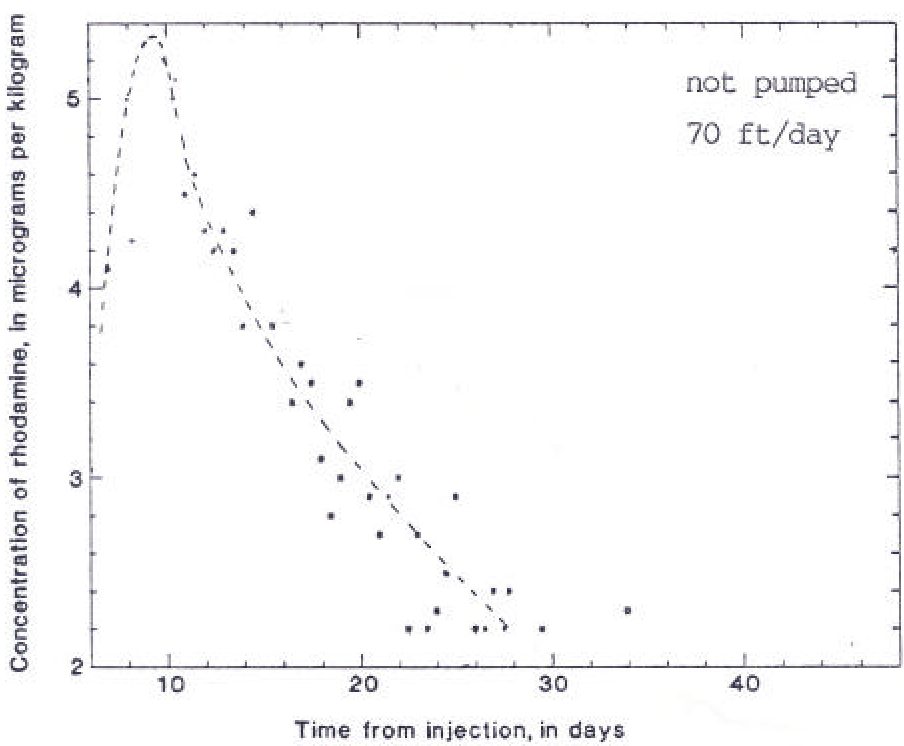

Figure 7. Breakthrough curve in Medo-Bel well, County Museum well injection test.

Between 3 and 5 days after injection, it was discovered the Medo-Bell well had started flowing. Tracer was evident from the start of sampling (Figure 7). The well is 1,200 feet north of the injection well almost perpendicular to a line between injection and production. There was no major pumping in that direction, the high school wells being shut in.

Two other wells started flowing during the injection test. The Fire Station well 130 feet from the injection well started flowing about the same time as the Medo-Bel well. Tracer was evident from the start of sampling, but did not show a maximum. The Spires and Meist well flowed intermittently during injection. Tracer breakthrough was before September 9; but, it was not possible to determine when the maximum occurred. This well is about 1,000 feet from the injection well and about 300 feet south of a line between injection and production. Highest tracer concentration was 40 ug/kg; higher than either Friesen or Medo-Bel.

The Jones well 1,120 feet south, southeast of the injection well was intermittently pumped at about 20 gpm for space heat. A September 23 sample showed no tracer, but the October 9 sample indicated 12 ug/kg and decreased after that.

When the 1983 Klamath Falls tracer tests were conducted, tracer testing of geothermal reservoirs was in its infancy (it may be young adolescence now) and not much can be said about the results. The Klamath Falls tests were done to provide field data for use in developing interpretive methods and to compliment the aquifer stress test (Gudmundsson, 1983).

We did, however, succeed in estimating flow velocities between several wells and these velocities are fast relative to normal groundwater movement. The flow velocities indicate that thermal breakthrough will occur. The relatively high velocities along the line of the city injection well, the Medo-Bel well and the KU injection and production wells further confirmed a suspected fault there resulting in fracture flow along the fault. The slower but still high velocities noted between other wells seems to indicate radial flow in zones of high permeability but limited thickness--a fact already known from well lithology.

Pumping and Injection Test

During the pumping and injection test conducted June 29 through September 1, 1983, 52 wells were regularly monitored. Eleven wells were fitted with pressure transducers supplied by LBL. These wells were all connected via temporary wiring to a central data logger center where all pressures and temperatures were simultaneously recorded. Eight wells were fitted with float-type continuous chart recorders. An additional 33 wells were monitored by hand with electric level sensors, or steel tapes where the level was near or above ground level. Specific wells were regularly temperature profiled, atmospheric pressure monitored and two wells fitted with downhole seismographs. Three wells outside the hot well area were monitored with continuous recorders. Water samples for chemical analysis were taken from the pumped well periodically throughout the duration of the test.

Briefly, the results of the test showed:

1. Despite the heterogeneous geology, the system behaves hydrogeologically as a homogenous aquifer. Permeability thickness was determined to be 1.5 x 10^6 md/ft. If the aquifer is an average of 1,000 feet thick, the average permeability is 1.5 darcy (Benson, 1984). Considering that the flows occur in zones one to a few feet thick and the hydraulic gradient is about 1.5%, the transmissivity of these zones is very high.

2. No hydrogeologic boundaries were detected; although the fault is very close to the production well. The radius of investigation is estimated to be 3.5 miles. This implies that either the fault has permeability at least as great as the shallow aquifer and at the tested pump rates acts as an infinite source, or the fractured zone is of considerable width and cannot be detected (Benson, 1984).

3. At the shallow depths tested, the geothermal aquifer is separate from the cold water aquifer. There was no response in cold wells located just east of the fault zone nor west of the hot well area.

4. Based on chemistry and isotopic analysis, the water in the shallow reservoir is a mixture of 44% high temperature at 365 - 378°F and 56% cold water. Carbon and tritium dating puts the age of the high temperature water at 11,400 years and the cold member has greater than a 30-yr storage life (Truesdell, 1984).

5. Both the aquifer tests and tracer tests indicate the aquifer behaves as a double-porosity reservoir. Pressure changes are transmitted rapidly and flow velocity is high; thus, the system behaves more like a network of pipes than an unconfined reservoir. Injection brings with it significant risk, and injection wells must be carefully designed and located (Sammel, 1984).

Extrapolation to other resources of the minimal temperature breakthrough experienced in the Klamath Union High School doublet despite the fast tracer breakthrough must be done with great care. The Klamath Falls aquifer has a high hydraulic gradient and very high permeability in the permeable zones. The hydraulic gradient to the southeast and the fact that during the overall aquifer test tracer was detected only on a line between injection and production, and to the south and east of that line indicate a large volume of water moving in that direction. A large volume of water flowing in the direction from KU production to KU injection would provide a continuous source of water and heat that would wash out the thermal breakthrough.

Both of the KU doublet wells apparently lie along the same fault zone. This zone is concealed by superficial lake deposits but has been perceived in results of several well tests. This fault provides a vertical path for cool injected water to sink and be replaced by hotter water. This is indicated by the fact that significant tracer was detected in the Medo-Bel well which is 525 ft deeper than either the KU production or injection wells.

If the above conditions did not exist, thermal breakthrough undoubtedly would be greater. How much greater is unknown.

CURRENT MONITORING

Since the 1983 test, the city has continuously monitored static water levels in three wells: one near the production wells, one near the injection well and one in a cold well area. Injection pressure is continuously monitored at the injection well; but, during very low flow periods, the well accepts injectate by gravity. One continuous recorder is used in areas where residents suspect trouble--thus has seen considerable use but in several different areas. Additionally, CRGD members monitor 12 wells either daily or weekly using electric water level detectors. The city production well chemistry is analyzed yearly per Oregon Water Resource Department (OWRD) permit.

As noted earlier, there is a city ordinance prohibiting surface disposal after July 1, 1990. Surface disposal after that date could carry up to a $500 per day fine. When it was agreed to present this paper, it had been assumed there would be at least several injectors with at least some records--eight applications for injection wells were filed between July 1 and mid-August, and at least nine more were planning injection. With one exception, this has not happened. The application form to actual injection process is fairly lengthy, and although several wells have been drilled and three are currently being drilled (October 19, 1990), none have been fully approved. Part of the process is submittal of injection well construction, and a plan for pump testing and monitoring for approval by OWRD. This has proven to be a bottleneck and the city has been forced to grant extensions for surface disposal.

The one exception is the OIT injection well. This is perhaps worth some discussion since some aspects of its construction and chemistry might be counter to what might be approved in other states.

OIT Injection Well Monitoring

In the fall of 1988, OIT permitted and contracted the drilling of a 1,500 ft injection well with the option of drilling to 2,500 ft. The intent was to drill a well with a capacity of 1,000 gpm since the campus system currently has a peak capacity of 800 gpm. The well was drilled using the bentonite mud rotary method.

At a depth of 1,500 ft, a temperature profile indicated an increase in temperature near the bottom and drilling was continued. At about 1,548 to 1,565 ft, considerable loss of circulation was encountered but estimated to be not enough for the 1,000 gpm. Drilling was continued through impermeable basalt to 2,005 ft. The well was completed by hanging casing perforated at the loss zone to 1,675 ft, back filling to 1,695 ft, cementing to 1,675 ft (20 ft between backfill and casing shoe) below the perforations, and 1,409 to 1350 (59 ft) above the perforations. The remainder of the annulus was filled with bentonite pellets (Figure 8).

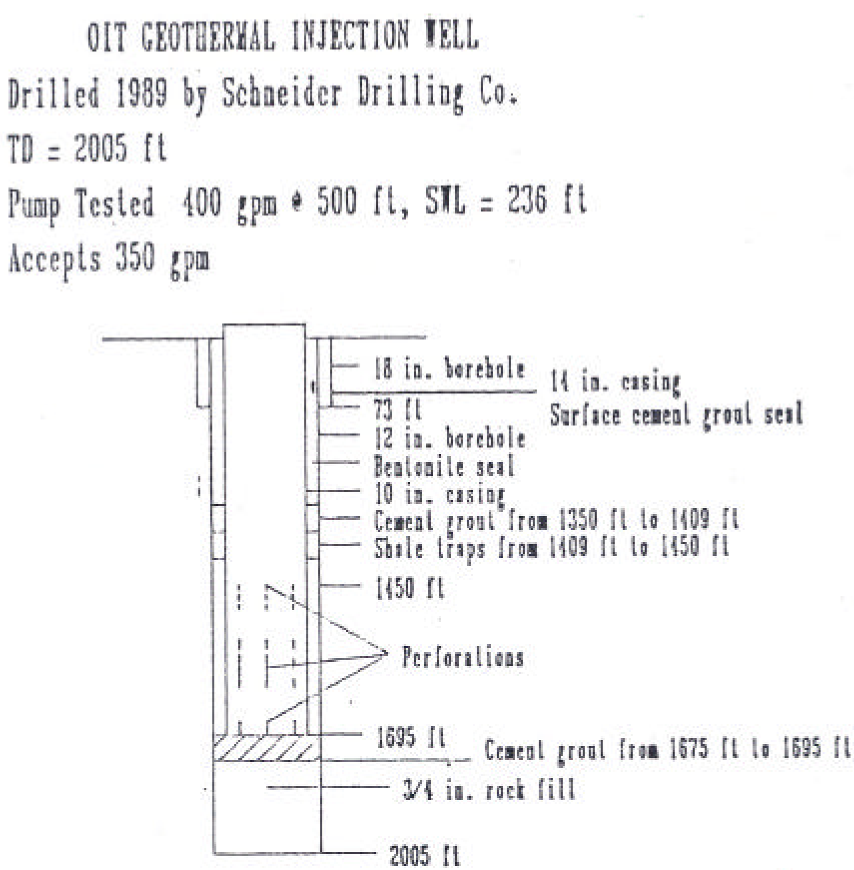

Figure 8. OIT geothermal injection well.

The engineers' reasoning for this completion was:

> Space heating injection wells are subject to variable flows, and in summer in Klamath Falls, accept low flows by gravity with water level approaching static water level. Experience with other wells has shown that even though cemented to the surface, temperature variations in the casing eventually break the cement bond with unconsolidated formations, and the casing lengthens and contracts. This has the potential for leakage.
>
> This particular well will be subject to conditions varying from no flow when the casing will be at normal earth temperature to 180°F at peak air conditioning when using the absorption chiller--a temperature swing greater than most in Klamath Falls.
>
> The cement seal above the perforations will prevent injected fluid from rising and the bentonite seal will allow casing expansion while maintaining a seal to prevent any inter-zonal migration.
>
> This completion has been successful in Klamath Falls in the past (Bomar, 1989).

After completion, the well was pump tested yielding 200 gpm with 280 ft of drawdown. It was suspected the lost circulation zones were plugged with bentonite, and the well was acidized with 13% hydrochloric and 3% hydrofluoric acid and swabed. After two acidizing treatments, yield was increased to 400 gpm with 280 ft drawdown--much less than hoped for. Subsequent step and constant rate pump tests indicate the well has a large skin factor and may be plugged with mud to 25 times the effective well radius. Practical maximum injection rate was estimated at less than 600 gpm (Nork, 1989).

In anticipation of the pump tests, an observation well network had been selected (Figure 9) and chemistry of several of the wells analyzed, including a sample taken at the end of pumping after acidizing the injection well (Table 1). Note the elevated chloride concentration. All cold water in the Klamath Basin is low in chloride indicating water in the injection well is at least partially derived from thermal water. Other constituents normally found at elevated concentrations in thermal waters, given sufficient time, would have equilibrated to the lower temperature (95°F) of this well. This provided an argument for injection testing to determine if the injection well is connected to the hot or cold aquifer. Elevated chloride was believed not to be an artifact of acidizing since the well was extensively pumped after the pH was reduced to its pre-acidizing level.

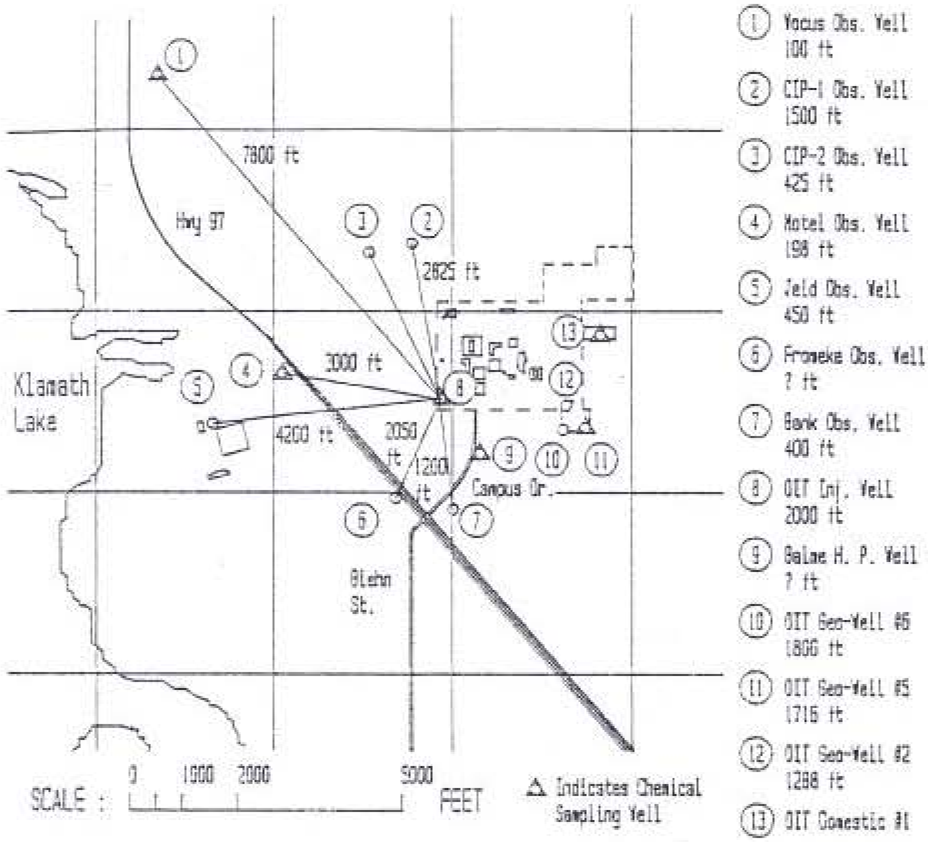

Figure 9. OIT injection well monitoring network.

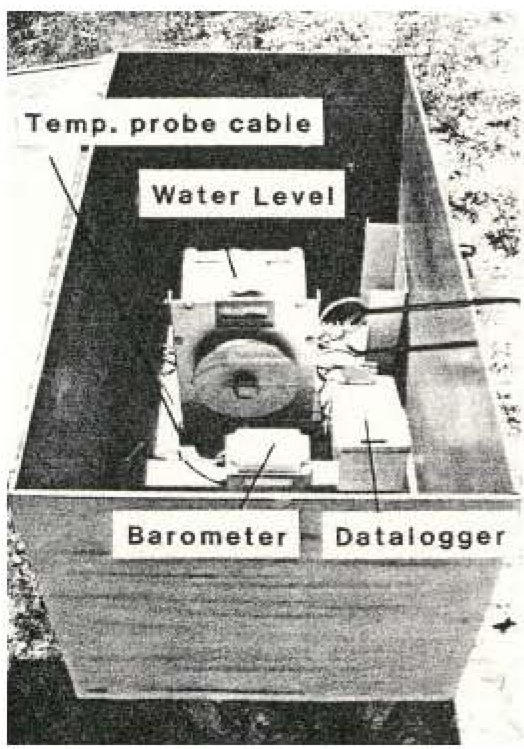

Figure 10. Observation well instrumentation.

Based on the above tests, it was recommended that an injection monitoring plan be submitted, and step and constant rate injection tests run. Plans were submitted and approved, and the tests run. Analysis this time predicted the well would accept a maximum of 375 gpm at 50 psi, the requested maximum injection pressure. There was some uncertainty in the analysis since there were unexplained 70 psi spikes near the end of the test. A response to injection was perceived only in the Bank, Motel and Jeld-Wen wells. It was small, in the range of only a few hundredths of a foot (Nork, 1990).

On the basis of the above test, OWRD is permitting continued injection with water level and chemical monitoring of the wells listed in Table 1, and water level monitoring in CIP-1. Water levels are recorded at 6-hour intervals by data loggers and chart recorders, and pressure and flow at the injection well monitored on continuous chart recorders. Typical observation well instrumentation is shown in Figure 10 and typical results in Figures 11 and 12. Water chemistry for the constituents in Table 1 were required

TABLE 1
CHEMICAL ANALYSIS

Well a:	1	2	3	4	5	6
Temperature, °F	98	192	78	89	54	57
pH	6.90	8.45	7.65	7.50	6.60	7.15
Specific Conductance	340	993	270	320	190	230
Total Dissolved Solids	--	737	175	228	164	183
Total Coliform	<2.2	<2.2				
Chloride, mg/l	41.0	46.4	3.0	7.8	7.8	5.2
Sulfate, mg/l	7.6	389	25.1	43.6	4.7	13.1
Sodium, mg/l	39.0	186	25.4	34.0	17.5	20.9
Silica, mg/l	38.9	85.2	29.5	30.4	53.1	48.8
Bicarbonate, mg/l	104	25.6				
Fluoride, mg/l	7.9	1.3				
Potassium, mg/l	1.5	3.9				
Calcium, mg/l	30.5	22.7				
Arsenic, ug/l	14	47				
Boron, ug/l	70	916				
Iron, ug/l	454	<40				
Magnesium, ug/l	734	<50				
Manganese, ug/l	212	1				

a. Well
1. OIT Injection Well
2. OIT Geo-Well No. 5
3. OIT Domestic Well No. 1
4. Balme Heat Pump Well
5. Wocus Irrigation Well
6. Motel Domestic Well

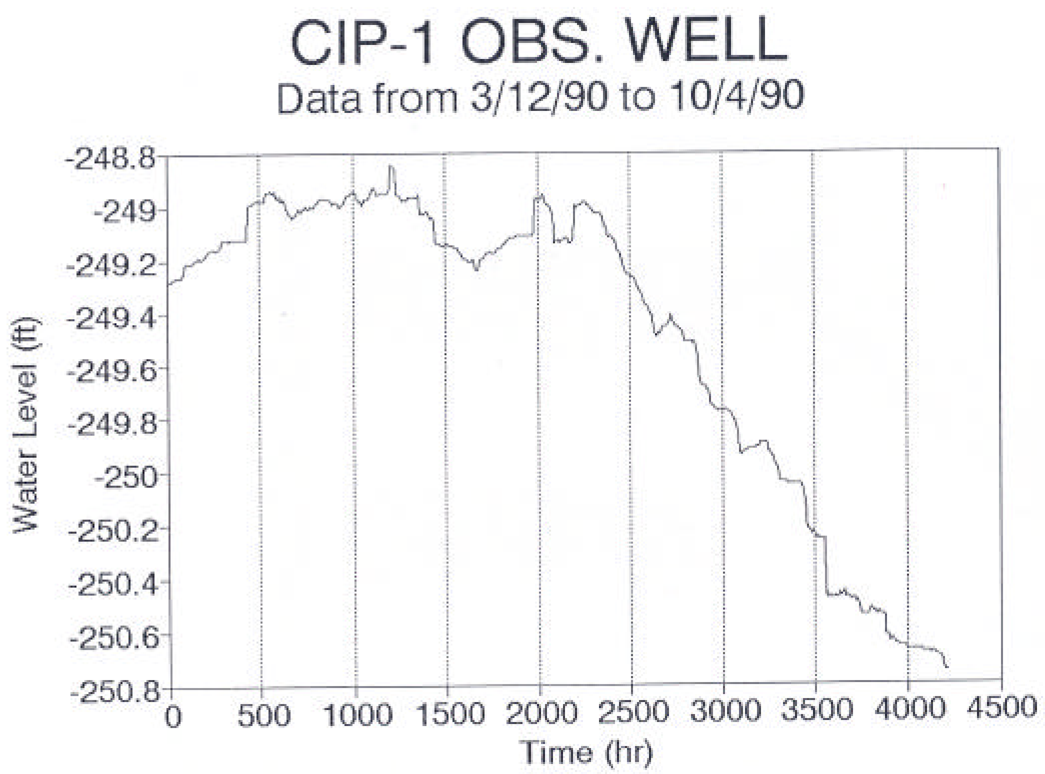

Figure 11.

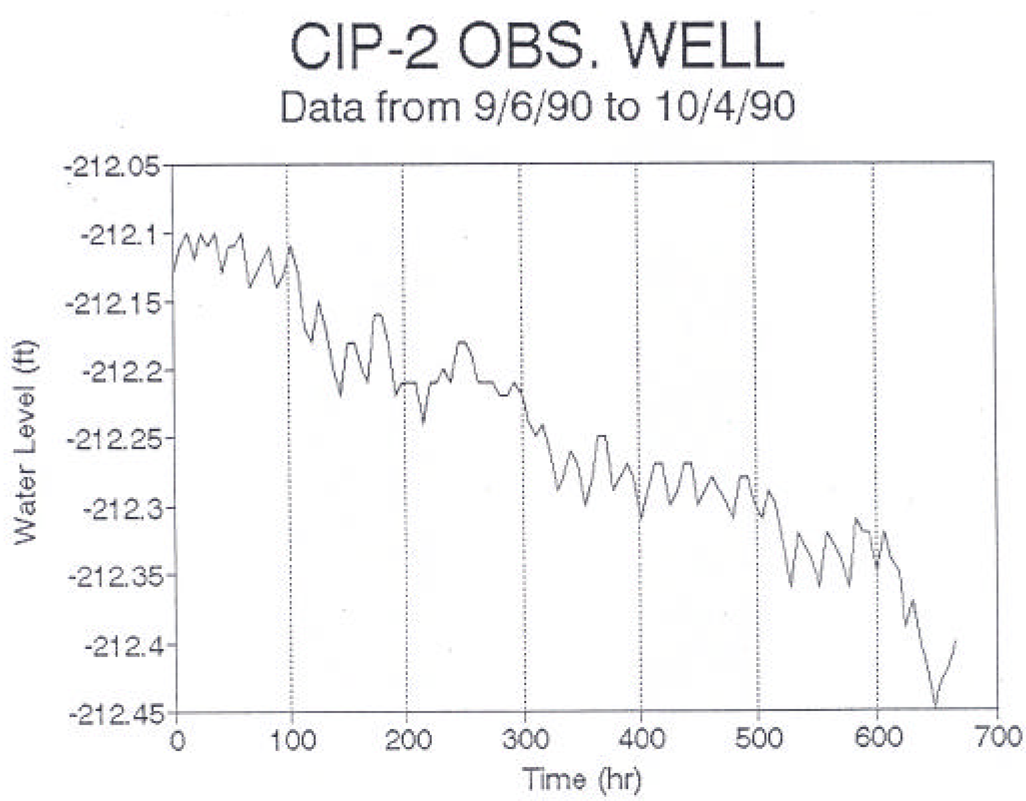

Figure 12.

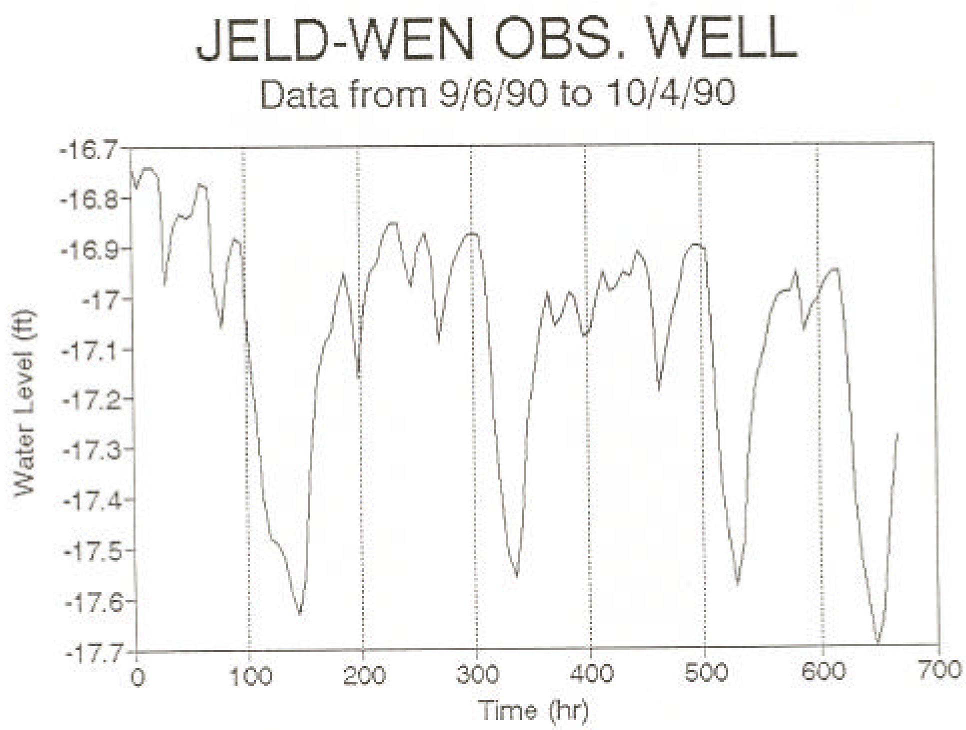

Figure 13.

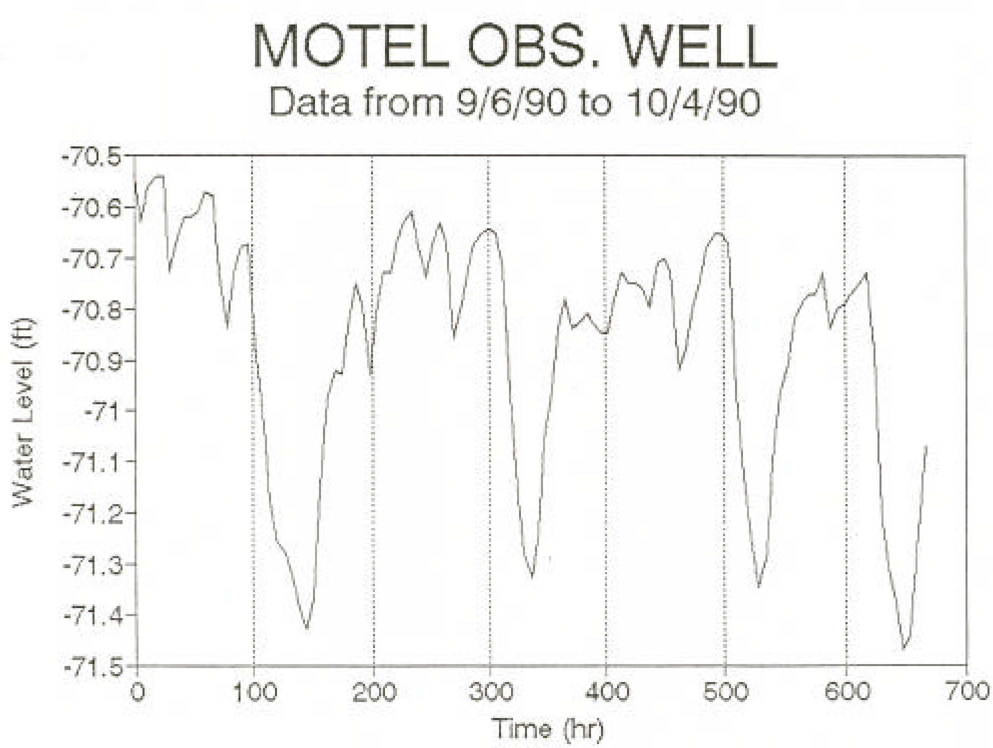

Figure 14.

monthly for the first quarter and are quarterly for one year. Water chemistry has not changed within laboratory accuracy limits. Water levels in observation wells have responded to pumping in a Jeld-Wen well (Figures 13 and 14), but in general, have declined in response to summer conditions. There has been no discernable change in observation wells directly attributable to injection.

Except for the OIT well, all the new injection wells completed so far have apparently encountered thermal fluids at about the same temperature as their production wells. Although OWRD has not approved formal pump testing procedures for the wells, the wells have been developed as part of the completion practice and developing produced hot water. We hope OWRD will not require stringent testing and long-term monitoring for them since it is an expensive procedure, and they appear to be directly connected to the hot aquifer. The OIT injection well clearly is a different situation--it is not as directly connected to the same aquifer as its production wells and long-term monitoring seems justified.

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