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UNITED STATES DEPARTMENT OF ENERGY

RESEARCH CONTRACT

TRACER DYE TRANSPORT FROM A WELL FITTED WITH
A DOWNHOLE HEAT EXCHANGER

KLAMATH FALLS OREGON

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Date: February 1990

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1.0 SUMMARY

During the summer of 1989 a research programme was set up by the Geo Heat Center, Oregon, to investigate the interaction of a well fitted with a downhole heat exchanger and the Klamath Falls geothermal reservoir. Funding for the project was provided by the United States Department of Energy. Computer modelling was attempted for the area of interest, followed by a tracer dye and temperature logging programme. The test wells were located in the Old Fort Road area of Klamath Falls, Oregon.

Computer flow modelling studies used an established ground water flow package to which a random walk dye dispersion routine was added. Because the package was designed to simulate flow in a uniform porous media it was not well suited to modelling the 'dual-permeability' of the Klamath Falls reservoir. Assumptions made in the model and unknown reservoir parameters limited the results of this work to helping with design of the dye tests. Estimation of the required dye injection quantity was based on the computer model and several tracer dye transport equations.

The results of the first dye test showed that a nearby pumped city district heating well has considerable influence on the flow. A rapid break-through of dye occurred in this test indicating that reservoir volumes are quite low. The dye concentration was however quite low, considering the break-through time, indicating that mixing volumes are high. Large flow rate variations occurred in the city heating system pumped wells during the remainder of the test period and this interfered considerably with subsequent tests. Better results may be obtained if testing is carried out in winter since natural flow in the reservoir is higher, due to draw off in downstream wells, and the pumped wells operate in a more stable condition.

The downhole heat exchanger supplied 500 kW of steady heat load during a twelve day test. More heat was obtained during the first hour of the test, as heat stored in the well bore was extracted. Temperatures in the well declined quickly during this period but levelled off to steady values for the remainder of the test. At the completion of the test the well quickly regained the temperatures it had before testing began. The heat load of 500 kW was achieved with a lower inlet temperature than is usual, since once through cooling was used. If fluid was recirculated after supplying the heat load, as in a closed loop heating system, it would probably have a steady output of around 300-350 kW.

During the test period the monitor well showed a steady drop in temperature. This occurred before, during and after periods of downhole heat exchanger use. Similar temperature drops have been recorded in other Klamath Falls wells during summer months and are not attributable to heat loading of nearby wells.

2.0 INTRODUCTION

Low or medium temperature geothermal resources are often used for space and domestic hot water heating. If the resource is located at reasonably shallow depths and adjacent to a major population centre large amounts of relatively cheap, clean heat can be provided.

Geothermal fluid is often brought to the surface, either under natural artesian pressure or by pumping, to be used in surface heat exchangers (SHEs). This method generally requires a second well for disposal of the cooled fluid and a substantial capital outlay for pumps and heat exchangers. Large amounts of heat can be extracted from just one or two wells using surface heat exchangers and the method can prove very cost effective in areas with a high density of energy intensive users. For smaller heat loads surface heat exchangers can become expensive and in many instances a downhole heat exchanger (DHE) installed directly in the well bore is capable of supplying cheap heat to a smaller number of users.

A DHE system extracts heat from the geothermal reservoir by circulating a coolant fluid through a heat exchanger coil installed within the well. Heat is supplied to this coil by the hot fluid within the well. If the DHE is to meet a sustained heat load the well must be capable of replenishing heat at the same rate, or a cooling off of the well will occur. This heat is supplied by fresh hot fluid flowing into the well or by conduction from rock surrounding the well. Fresh inflow of hot water is the key to providing large amounts of heat over an extended period. Where permeability and flow of hot water are very low conductive heating becomes the primary mechanism for well heating but once the initial storage of heat is used, conductive systems are generally capable of sustaining only low heat loads.

Field testing of a DHE and surrounding wells was carried out in an attempt to gain further information on the interaction between the DHE well and the reservoir. Past research has concentrated on how DHE configuration and well completion are related to performance. This has been valuable for improving performance and cost effectiveness of these devices in specific aquifers. Unfortunately this type of information has been of limited use in assessing the application of DHEs to new resources. Characteristics of reservoirs vary widely at different locations with parameters such as downhole temperature, hydraulic gradient, depth to production zones, transmissivity, porosity and permeability all playing an important part in DHE performance. As a consequence of these variables a DHE may perform well in one area and poorly in another. Even if two systems are of identical construction, performance can vary by an order of magnitude or more.

The mechanism by which fresh hot fluid enters the well is not clearly understood. Any method of well completion which encourages this flow, or places a greater surface area of the DHE coil in contact with the flow, has the potential to increase DHE output. In the simplest case natural cross flow is the only means by which the heat exchanger receives fresh fluid. At Rotorua, New Zealand, a DHE was tested in an old 4in (100mm) production well. The well was drilled to 123m (404ft) and lined to 112m (367ft) with a 4in (100mm) casing since it was originally intended to produce a steam / water mixture to surface heat exchangers for space heating purposes. A simple U-tube DHE constructed from 1in (25mm) pipe was installed to full depth to test the practicality of adapting such a bore to DHE use. No attempt was made to promote natural circulation within the well casing and it is believed that most of the heat transfer to the DHE occurred in the bottom section (below the casing shoe) (Dunstall and Freeston, 1988). Hot fluid flowing through the reservoir supplies heat to those sections of the DHE coil which extend below the casing. This flow may in some way be stimulated by cooled fluid descending in the reservoir but no large scale convection is thought to occur in the well bore itself.

At Klamath Falls, Oregon, a typical system has a much larger well diameter and is fitted with an undersized casing which is slotted at the bottom of the well and just below the static water level. The DHE is placed inside the casing and cooled well fluid (being of higher density) descends in the casing. Hot fluid flows up the annulus to replace it and the resulting convection cell supplies heat to most of the submerged length of the coil, greatly enhancing heat output (Lund, 19742). Some of the circulating fluid mixes with fresh fluid flowing in at the bottom of the well, providing the heat input necessary to maintain the convection cell (see figure 2.1). Fresh fluid input varies widely in different wells and is highly dependent on the permeability of the aquifer (Allis, 1981). The rate at which this fresh fluid flows into the well controls the long term heat output capability of the DHE.

Interference between nearby wells is a constant concern to closely spaced geothermal users. Pumped wells may cause water level declines in surrounding wells and injection wells may drive a flow of cold water into nearby, previously hot, wells. Similar concerns are held with Downhole Heat Exchangers. The cold fluid leaving a DHE well may flow under the influence of the natural hydraulic gradient toward downstream wells, cooling them.

A tracer dye test was carried out in the Old Fort Road area of Klamath Falls. The aim was to see if any fluid connection could be detected between two wells, one loaded with a DHE, under the influence of the natural hydraulic gradient alone. We were also interested in possible temperature effects on adjacent wells, which could be related to downhole heat exchanger use. Since the tracer dyes were injected into a DHE well it was hoped that the same series of tests may provide some useful data on the mixing process occurring at the bottom of the well.

Tests were carried out with the well in both its natural state and when thermally loaded by the DHE. With the DHE running the well water cools considerably and the convection cell changes direction (Culver and Reistad, 1978). One concept for fluid flow in a loaded DHE well, fitted with a slotted under size casing, presents the following idea: The descending plume of dense cold water, falling from the coil in the casing, sinks down into the aquifer and hot, more buoyant fluid flows in from the sides of the well to replace it. It was thought that increased water viscosity (due to cooling) and the convection cell reversal may have an effect on the dye concentration curves or arrival times. It was hoped that if a different dye breakthrough response was detected with the DHE running a comparison between the two conditions may help us to better understand the fluid dynamics involved in the DHE / well interaction.

This report first describes the methods used to carry out the series of dye tests, from well selection to injection of the dye samples. It then discusses the results of these tests in terms of how much dye was recovered, where it was recovered from and how long it took to arrive. The results of the concurrent temperature monitoring work and DHE heat output performance are also presented. Some recommendations are made for any future testing.

Figure 2.1

Typical DHE installation at Klamath Falls, Oregon (Culver and Reistad, 1978).

3.0 WELL SELECTION AND INITIAL WELL TESTING

3.1 Well Selection

At the establishment of the project it was decided that the interaction of the reservoir with the well bore was of primary concern in the investigation. It was thought that the best hope to understand behaviour at the bottom of the well bore was to monitor the 'reservoir' in the near vicinity, with the test well loaded and unloaded.

Two wells (#514, #203) in the Old Fort Road area were targeted for testing. The well we intended to load with a DHE (#203) had been completed with an undersized casing for DHE use and was known to be a good producer of heat (Culver and Reistad, 1978). The undersize casing promotes a convection cell and is a typical feature of many Klamath Falls DHE wells. The other well was cased to a shallow depth, above the static water level and was not thought to have significant natural circulation of well fluid. This type of well was considered to be a reasonable 'window' on the aquifer. It was positioned 84ft (25.6m) from the intended test well and thought to be almost directly 'downstream', under the natural hydraulic gradient (see section 3.2.2).

The Klamath Falls system is thought to have a predominantly lateral flow, charged by hot water rising up a fault which defines the north-eastern boundary of the field (USGS, 1984). Our intended test wells were positioned quite near the boundary of the exploitable resource, just downstream of the fault thought to be the source of up-flowing hot water (see figure 3.1). A sub-divided area between the fault and the wells was not developed so there were no loaded wells upstream which could affect the test wells. The wells were also a reasonable distance from the most heavily exploited downstream areas so dye testing was not going to cause problems. The only disadvantage with the location was the close proximity of the city's number one district heating well (see figure 3.2). This was producing at a very low rate however, due to a low summer demand for heat.

Neither bore was currently being used and both lay in vacant lots with easy access, presenting the ideal test site. Provision of cooling water and waste disposal were the only drawbacks, requiring quite long runs of piping. Permission was obtained to use the bores, since they were both privately owned and work began on preparing the wells for use.

3.2 Well Description

3.2.1 DHE Test Well #203

The DHE test well (#203) was completed to a depth of 215ft (65.5m) in August 1976. It has a drilled diameter of 10in (255mm) from 24ft (7.3m) to the bottom and is fitted with an 8in (200mm) perforated casing. The casing is grouted from the surface to a depth of 24ft (7.3m) in a 12in (305mm) diameter section of the hole. Slots in the bottom of the casing and just below the static water level allow for natural convection. The top perforations consist of sixteen 6x1/2in flame cut slots between 55ft (16.8m) and 72ft (22.0m). Forty similar slots form the feed zone perforations between 186ft (56.7m) and 215ft (65.5m). The drillers log shows that water was found flowing into the well from 195ft (59.4m) to 210ft (64.0m) through a layer of cemented gravel and rock, and a layer of pumice gravel. (see figure 3.3a, 3.3b). It was noted that the well started getting hot at around 85ft (25.9m).

3.2.2 Monitor Well #514

The observation well is located 84ft (25.6m) from the DHE well (#203) in an approximately south-westerly direction. It was drilled in August 1987 to a depth of 207ft (63.1m). A line through the two wells is almost perpendicular to the up-flow fault trace, with temperature and water level profiles of the area suggesting it lies almost directly downstream of the test well (see figure 3.4a, 3.4b).

Casing in this well serves only to exclude surface water and stabilize the upper formation. A 10in (255mm) casing is cemented into a 14in (355mm) hole for the first 40ft (12.2m). The well is an uncased 8in (200mm) hole from this depth to the well bottom and has a static water level of 55ft (16.8m) (see figure 3.5a, 3.5b).

During drilling it was noted that water was produced from two distinct horizons. A flow of around 10gpm (0.63l/s) was obtained from black rock at a depth of 121ft (36.9m) to 126ft (38.4m) and a flow of around 500gpm (31.5l/s) from layers of black rock, fractured blue shale and fractured grey rock at a depth of 172ft (52.4m) to 207ft (63.1m). The two producing zones both had a static water level of 55ft (16.8m), indicating that they are hydraulically connected. The rock through which fluid is produced is at a similar depth, but of a different type to that in the feed zone of the DHE test well (#203). Because this well lacks an undersize casing to promote convection it was considered to be a reasonable 'window' on the aquifer.

3.3 Well Temperature Profiles

3.3.1 DHE Well (#203) Temperatures

Downhole temperature profiling of the DHE test well showed an almost isothermal temperature gradient before the DHE was installed, due to the convective circulation occurring in the well (Culver and Reistad, 1978; McGuinness, 1988) (see figure 3.6a). Heat loss due to boiling at the surface and conduction to cooler surrounding rock maintains this circulation cell. With the well in an unloaded condition hot water flows up the well casing and descends in the annulus (see figure 3.7). This flow pattern was confirmed by spinner measurements and dye studies in earlier tests on the well (Culver and Reistad, 1978).

A closer examination of the temperature profile, on an expanded scale (see figure 3.6b), shows variation in temperature within the casing. The lowest temperature measured was at the level of the upper perforations, where boiling occurs. This temperature corresponds to the saturation temperature for a water/steam mixture at this elevation (95.2°C @ 1220m) (203.4°F @ 4000ft). Below this depth the temperature increased slightly, almost linearly to the depth of the bottom perforations. Fluid flowing up inside the casing is warmest at the bottom. It then loses heat by conduction, through the casing wall, to cooler water descending in the annulus. Water in the annulus is cooler due to loss of latent heat during boiling and conduction losses to the cooler surrounding rock in the upper levels of the well.

The temperatures recorded at the bottom of the well were slightly lower than those found above the bottom perforations. This is an area of much mixing as fresh hot fluid flows into the well from the aquifer and mixes with colder fluid descending in the annulus. It is therefore unlikely that the temperature is uniform throughout this region. The probe may have been in a position to be influenced by colder water flowing in from the annulus when these measurements were taken.

3.3.2 Monitor Well (#514) Temperatures

The monitor well has a profile typical of a well not fitted with any kind of convection promoter (McGuinness 1988) (see figure 3.8). Highest temperatures are measured near the bottom of the well in the region of high fluid flow. The upper region of the well appears to be heated by conduction from below, hence the near linear rise in temperature with depth. A slight reversal in the temperature profile can be seen at the very bottom of the well. This is typical for wells drilled through the producing horizon in an aquifer with lateral hot water flow. (USGS,1984). It is therefore likely that the bottom few feet of the well is not supplied with a steady flow of fresh fluid.

3.4 Water Levels and Hydraulic Gradient

The difference in elevation between the well casing tops was surveyed so that water level measurements could be used to determine the hydraulic gradient between the wells. Because the two wells are completed differently they have different temperature profiles (see section 3.3) resulting in a difference in the average density of the water column. Since communication between the wells is governed by flow through the aquifer (at a depth of 200ft) it is important to determine the pressure at this depth. If the wells were similar in temperature profile the head difference would be indicative of the downhole pressure difference. Pressure at the bottom of the monitor well can however be maintained by a lower head of water, since that water is colder and hence has higher density than that in the DHE well.

In order to correct for temperature difference the density of water in the monitor well was integrated over the length of the well, to obtain the true bottom hole pressure. An equivalent head was then calculated which would provide the same pressure if the water was at 205°F (96°C) over the entire well length, as in the DHE well. This calculation indicated that the monitor well water level would be 1.3ft (0.40m) higher if the fluid were at the same temperature as that in the DHE well. Since monitor well water level changes were very small in comparison to well depth and the temperature profile remained constant, the equivalent head difference found could be used in all subsequent calculations with very little error.

Hydraulic gradient is a measure of the pressure difference between two points relative to their separation (ie. Pressure / Distance). If the pressure is expressed as a hydraulic head, such as feet of water, then the gradient can be expressed as a percentage. The measured hydraulic gradient between the two wells was around 3.4% from the DHE well to the monitor well. Without temperature correction the indicated gradient is 4.9%. During the test period the gradient was frequently measured and was generally in the range 1-3% , which is typical for the Klamath Falls area (Lund et al, 1979). Because the wells were so closely spaced (84ft) (25.6m), a relatively small change in water level results in quite a large difference in the measured gradient. Measuring the water level at the DHE well was particularly difficult because the well was constantly boiling. The level appeared to fluctuate several centimetres as the fluid circulated in the well and it was difficult to get close to the casing top to take measurements because of the steam. Steam condensing on the test probe could also cause false readings. These difficulties led to some uncertainty in water level measurements for the DHE well and hence the hydraulic gradient.

Figure 3.1

Principal Geothermal Features in the Klamath Falls area
(USGS, 1984).

Figure 3.2 Location of the DHE test well, Monitor well and City heating system well.

DHE TEST WELL #203

Figure 3.3b

Well lithology for DHE test well (# 203).

Figure 3.4a

Well water levels (feet above sea level). Contours define regions in which most wells lie within the indicated range (USGS, 1984).

Figure 3.4b Maximum well temperatures. Isotherms define regions in which most wells have temperatures within the indicated range (USGS, 1984).

STATE OF OREGON CHF 1-48 feet below
WATER WELL REPORT CHF #203
(as required by ORS 637.765)

#514
 82' apt.

Obs. Well
 #514

(1) OWNER: _____ Well Number: _____
 Name Leslie Daniel
 Address 124 N. 1st St.
Clatsop County, OR 97101 State OR Zip 97101

(2) TYPE OF WORK:
☒ New Well ☐ Deepen ☐ Recondition ☐ Abandon

(3) DRILL METHOD
☒ Rotary Air ☐ Rotary Mud ☐ Cable
☐ Other _____

(4) PROPOSED USE:
☐ Domestic ☐ Community ☐ Industrial ☐ Irrigation
☒ Thermal ☐ Injection ☐ Other _____

(5) BORE HOLE CONSTRUCTION:
 Special Construction approval Yes ☐ No ☒ Depth of Completed Well 207 ft.
 Explosives used ☐ Yes ☒ No ☐ Type _____ Amount _____

HOLE		SEAL		Amount	
Diameter	From To	Material	From To	From To	acks or pounds
14"	0	50' Cement-Sand	0	40'	500 lbs.
12"	40'	207'			

How was seal placed: Method ☐ A ☐ B ☒ C ☐ D ☐ E

☐ Other _____

Backfill placed from _____ ft. to _____ ft. Material _____

Gravel placed from _____ ft. to _____ ft. Size of gravel _____

(6) CASING/LINER:

Diameter	From	To	Gauge	Steel	Plastic	Welded	Threaded
10"	+1	41	.250	☒	☐	☒	☐
				☐	☐	☐	☐
				☐	☐	☐	☐
				☐	☐	☐	☐
				☐	☐	☐	☐
				☐	☐	☐	☐

Liner: _____

Final location of shoe(s) _____

(7) PERFORATIONS/SCREENS: none

☐ Perforations Method _____
☐ Screens Type _____ Material _____

From	To	Slot size	Number	Diameter	Tele/pipe size	Casing	Liner
						☐	☐
						☐	☐
						☐	☐
						☐	☐
						☐	☐

(8) WELL TESTS: Minimum testing time is 1 hour

☐ Pump ☐ Sailer ☒ Air ☐ Flowing Artesian

Yield gal/min	Drawdown	Drill stem at	Time
200		200	1 hr.

Temperature of water 61 Depth Artesian Flow Found _____

Water analysis done? ☐ Yes ☒ No By whom _____

Did any strata contain water not suitable for intended use? ☐ Too little

☐ Salty ☐ Muddy ☐ Odor ☐ Colored ☐ Other _____

Depth of strata: _____

(9) LOCATION OF WELL by legal description:

County Clatsop Latitude _____ Longitude _____
 Township 30 North Range 7 East E or W. W.M. _____
 Section 20 1/4 1/4 1/4 1/4
 Tax Lot _____ Lot 4 Block 10 Subdivision _____
 Street Address of Well (or nearest address) Corner of Gibbs and Old Port Rd. in city of Klaskan Falls, OR.

(10) STATIC WATER LEVEL:

5 ft. below land surface. Date 3, 13, 87

Artesian pressure _____ lb. per square inch. Date _____

(11) WATER BEARING ZONES:

Depth at which water was first found 121'

From	To	Estimated Flow Rate	SWL
121	128	10	55
172	207	500	55

(12) WELL LOG: Ground elevation 4100

Material	From	To	SWL
Top soil	0	2	
Brown clay	2	34	
Blue claystone	34	36	
Blue clay	36	49	
Brown claystone	49	71	
Blue shale	71	121	
Black rock	121	128	55'
Blue claystone	128	172	
Black rock	172	184	55'
Fractured blue shale	184	192	55'
Fractured gray rock	192	207	55'

Date started 8, 13, 87 Completed 8, 13, 87

(unbonded) Water Well Constructor Certification:

I certify that the work I performed on the construction, alteration, or abandonment of this well is in compliance with Oregon well construction standards. Materials used and information reported above are true to my best knowledge and belief.

WWC Number _____
 Signed _____ Date _____

(bonded) Water Well Constructor Certification:

I accept responsibility for the construction, alteration, or abandonment work performed on this well during the construction dates reported above. All work performed during this time is in compliance with Oregon well construction standards. This report is true to the best of my knowledge and belief.

WWC Number 463
 Signed 7/1/87 Date 7, 24, 87

WHITE COPIES - WATER RESOURCES DEPARTMENT

YELLOW COPY - CONSTRUCTOR

PINK COPY - CUSTOMER

5000C 10/86

Figure 3.5a

Drillers log for monitor well (# 514).

Figure 3.5b

Well lithology for monitor well (# 514).

Figure 3.6a DHE test well profile (DHE off).

Figure 3.6b DHE test well profile (DHE off). (expanded scale).

Figure 3.7

Circulation of fluid in the test well with the DHE off.

Figure 3.8 Monitor well temperature profile.

4.0 MONITORING EQUIPMENT AND WELL PREPARATION

4.1 Casing repair

The casing head of well #203 (DHE test well) was in a sound but neglected state of repair at the start of the project. The well was drilled in 1976 and was completed with a slotted undersize casing, for DHE use. It was fitted with a 2in (50mm) U-tube DHE and used to heat several houses for a period of time. The original DHE was removed from the well some time after the lot became vacant and it sat unused for several years. Because it is fitted with an undersized casing the well circulates by natural convection and is constantly boiling. The resulting plume of steam constantly rising up from the well seems to have excluded oxygen, protecting the casing from corrosion. The casing and its surrounds had however, subsided to below the level of the current ground surface and repairs were needed to allow easy access to the well and to ensure surface water could not enter the well. A six foot long extension was welded to the existing casing to bring it above the current ground surface. Cement was then poured around this section of casing to protect it from ground water and to seal it to the original casing grout. The hole was back-filled and finished off with a large concrete pad to provide a clean working environment (see figure 4.1).

4.2 DHE Installation

With the pad complete, a U-tube DHE was installed in the test well. This was made from 2in (50mm) black steel water pipe and was fitted with a short mud leg at the bottom. The DHE ran the full length of the well and was suspended from the top of the casing by a simple flat bar clamp. Permission was obtained to use the city water supply to test the DHE and a total volume flow meter was fitted to a water main to monitor the amount used. The flow rate of water supplied to the DHE could be calculated by noting the time taken to pass a known volume through the meter. The meter was connected to the DHE by 135ft (41.2m) of 3in (75mm) aluminium irrigation pipeline. Similar piping carried the hot water from the DHE return leg 165ft (50.3m) to a city sewer.

4.3 Monitor Well Water Sampler

Sampling of fluid in the monitor well was carried out by using a small airlift pump. The pump consisted of a 1/2in (13mm) black steel water pipe suspended from the surface to a depth of 190ft (57.9m) (thought to be the centre of the well feed zone). A 1/4in (6mm) OD copper air supply tube was fitted to a depth of 100ft (30.5m) and compressed air was supplied at 40-60 psi (275-410 kPa) to lift the water in the pipe the sixty feet (18.3m) to the surface (see figure 4.2). Around five minutes of continuous pumping was required to be sure of a fresh sample (from the bottom of the well), since the piping held around three gallons (11.5l) of water. A small electric compressor, stored in the city well pump house, was used to charge a portable air tank which held enough air to sample the well once.

4.4 Temperature Monitoring

As well as sampling the monitor well for dye the temperature was recorded at feed zone depth. Temperatures were also measured at three points in the DHE test well and at the inlet and outlet of the DHE. Thermistors were used for all temperature monitoring, since they were relatively inexpensive and had been used successfully in the past.

The resistance of a thermistor changes with temperature, dropping as the temperature increases. Three hundred kilo-ohm (at 25°C) thermistors were selected and were placed in a series circuit with an accurate metal film 'reference' resistor. A constant voltage source was used to form a voltage divider circuit. The voltage drop across the reference resistor can be measured and used to calculate the thermistor resistance and hence temperature.

A portable *Unidata* data logger supplied a regulated 5 volts to the divider circuit and recorded the divided voltage. This was stored in digital form through an eight bit analogue to digital (A/D) converter. The eight bit converter limits resolution to 255 discrete steps so individual reference resistors were supplied for each channel to make the best of the available resolution. Reference resistors were selected so that the expected temperature gave a thermistor resistance close to the reference resistance. This meant that reasonable resolution could be achieved for all channels (see section 4.5).

The thermistors were attached to suitable lengths of waterproof cable then surrounded by a shrink-fit tube and encased in epoxy resin. All but one of the thermistors performed as required during the short test run, with no short circuits occurring due to leakage. The one failed thermistor gave an open circuit reading when it was hot, probably due to expansion of the epoxy and a poorly soldered joint. Another thermistor produced incorrect results later in the test period, the cause of which is unknown.

A small circuit board was made up for the reference resistors with connections to the data logger and a termination block for the thermistor cabling. Provision was also made to plug in a portable digital multi-meter to measure the resistance of the thermistors independently, as a check (see figure 4.3).

The monitored temperatures were;

- Channel 1: Feed zone depth in the monitor well
- Channel 2: Not used (DHE annulus)
- Channel 3: Top perforations DHE well (66ft)
- Channel 4: Midway DHE well (135ft)
- Channel 5: Bottom perforations DHE well, feed zone depth (200ft)
- Channel 6: DHE outlet temperature
- Channel 7: DHE inlet temperature

NB: Channel 2 was left unused. It was originally intended to monitor the temperature of the water rising up the annulus at various depths. No provision had been made to leave access to the annulus when the well was drilled and it was eventually decided that drilling the 24ft (7.3m) cement seal in the hope of targeting the annulus was too difficult.

The main difficulty in measuring temperature in the DHE well (with the DHE running) was that we could not be sure of the position of the thermistors in relation to the DHE pipes. A thermistor resting against the cold inlet leg would, for example, give a lower reading than that of the well water at that point. The converse would be true for a thermistor resting on the hot return leg or the well casing, which is in contact with hot water flowing up the annulus. When the DHE is not running this is not such a problem since the DHE pipes are at equilibrium with water inside the casing. A thermistor touching the casing could still be influenced however, due to the cooler water flowing down the annulus in this mode.

4.5 Temperature Logging

As previously mentioned, a *Unidata* 16 kilo-byte, eight channel data logger was used to record all temperature readings. This unit had a regulated 5 volt outlet which was used as the supply voltage to the thermistor voltage divider circuit. The unit was self contained and battery powered, enabling it to be left unattended in the field. Sixteen kilo-bytes of memory provided plenty of storage space for the tests we performed and the stored voltages could be converted to temperatures by a software package on an IBM PC, which was used to down-load the raw data. This same PC was used to programme the log interval, channels logged and sensor type into the unit before it was placed in the field. Plugging the unit into the interface board (containing reference resistors and thermistor cable connections) started the logging process. Logging stopped when the unit was unplugged or the memory was full.

Once the logging instructions and temperature conversion software had been prepared the logger was relatively straight forward to use. The greatest draw back of this particular unit was its resolution. Input to each channel was a voltage between 0 and 2.55 volts, stored digitally after passing through an 8 bit A/D converter. An 8 bit converter gives 2^8 increments between 0 and 2.55 volts, ie. 256 increments of 0.01 volts each. The maximum possible accuracy is therefore 0.5% of full scale if the full linear range is used. This limitation required careful selection of reference resistors so that the divided voltage would provide a broad spread of values within the 0-2.55 volt range. The logarithmic variation of voltage with temperature in the thermistors compounded the problem, decreasing the range of useful resolution even further. At the low end of temperature range resolution was good whereas voltage changed slowly with temperature at the high end of the range (see figure 4.4).

Measured temperatures ranged from 60°F to 230°F (15°C to 110°C), with corresponding thermistor resistances of 495 k-ohm to 14.5 k-ohm. A high reference resistance allowed lower temperatures to be measured but gave less resolution at higher temperatures. The reference resistor size corresponded roughly to the highest resistance measurable at the thermistor and therefore set the low temperature limit for that channel. A 30 k-ohm reference would for example allow measurement to 31.2 k-ohm at the thermistor before going off scale. This would represent the lowest temperature measurable with a 30 k-ohm reference ie. 173.1°F (78.4°C) for the thermistor used. Resolution would be 0.2-0.4°F (0.1-0.2°C), decreasing as the temperature increased. If a 510 k-ohm resistor was used a resistance of up to 530 k-ohm could be measured (ie. a temperature of 56.7°F (13.7°C)). Resolution would once again be around 0.2-0.4°F (0.1-0.2°C) at the bottom of the temperature range, but for the same configuration to measure 173.1°F (78.4°C) (as above) the resolution would be down to 1.8°F (1.0°C). It can be seen that matching the reference resistance to the expected temperature is important if good resolution is to be had in the operating range. One must of course be careful to allow enough range beneath the expected temperature to allow for unexpected lows. Interchangeability of thermistors was considered desirable so all thermistors were of the 300 k-ohm at 25°C type. Having a high thermistor resistance meant that line resistance would not cause false temperature indications, even though cables were up to 250 feet (76m) long.

Figure 4.1 The completed well pad and casing extension.

Figure 4.2 The monitor well (airlift pump installed).

Figure 4.3 Data logging equipment at the test site.

Figure 4.4 Data logger resolution of temperature (at different reference resistances).

5.0 DYE SELECTION AND COMPUTER MODEL

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5.1 Objectives

The intention of the tracer tests was to investigate communication between wells under the influence of the natural hydraulic gradient. Differences in the level of any communication, with and without the DHE running were of particular interest.

Tracer dyes are often used in production / injection systems to try and predict the likely time for thermal breakthrough to occur, since a dye front can travel many times faster than a thermal front. In a production / injection system the wells often interact with the reservoir in a relatively predictable way, and pumping gradients are often several times higher than the natural gradient. Consequently, this type of testing is fairly well understood.

The well / reservoir interaction is not well understood for DHEs. It appears to involve a complex convective mixing process which is thought to behave differently at different heat loads (Culver and Reistad, 1978). When a geothermal system is exploited by the use of many closely spaced DHEs the thermal interference of one unit on another is of great concern to system operators. This is of particular importance when DHEs are operated at near full load capacity. It was hoped that a natural communication between two wells could be detected and that changes in the communication process could be observed with varied DHE loading. This type of information could lead to prediction of DHE interaction and long term performance in a more reliable way.

5.2 Dye Selection

Rhodamine W.T. dye has been used for at least two previous tracer tests in Klamath Falls, both of which were successful. Investigation of the dye for these earlier tests had shown that it did not pose a health risk, was environmentally benign and breaks down after a period of time. The dye was easy to detect at low concentrations and a machine was available to do this. Because the dye had a successful history and the intended test quantities were quite small no problems were expected, so once again it was selected. Approval for the use of the dye was obtained from the Department of Environmental Quality and a quantity of the dye was supplied by the Idaho National Engineering Laboratory.

Rhodamine W.T. has been used as a (cold) ground water tracing dye in many instances (Smart and Laidlaw, 1977) and has been tried (without return) in the Rotorua Geothermal field in New Zealand. A bulletin published by the University of Utah Research Institute makes the point that dyes used for ground water studies (such as Rhodamine W.T.) often decay very quickly in geothermal fluid, due to the high temperature (UURI, Aug-Oct 1989). Temperatures as low as 260° F (125° C) can cause decay, possibly affecting the Rotorua tests (280-350° F) (140-180° C). The Klamath Falls experience has however been that the dye is useful, perhaps due to the lower temperatures found there (generally less than 190-210° F (90-100° C)). The same bulletin also states that decay of organic dyes can be caused by the presence of molecular oxygen. This is not normally a problem with geothermal fluids, which contain very little oxygen, but care is needed when tests are performed with re-injected fluids (UURI, Aug-Oct 1989).

5.3 Dye Analysis

The property of Rhodamine W.T. which allows it to be detected in water is its fluorescence. When the dye is exposed to certain wavelengths of ultra-violet (UV) light it absorbs that light then re-emits it, at a slightly different wave length.

A Turner fluorometer was used to detect this behaviour. The machine produces a UV light, which is passed through a filter to provide a wavelength which will cause the dye to fluoresce. This light is passed into the sample and a second filter, perpendicular to the first, allows the re-emitted light (of shifted wave length) into a photo sensor. This sensor compares the intensity of re-emitted light to that which was passed to the first filter and gives a direct read-out on the unit. The filters and lamp used were recommended by the machine manufacturer for the analysis of Rhodamine dye.

For low dye concentrations the intensity of light re-emitted is in direct proportion to the concentration of dye in the sample, providing a simple linear correlation between the instrument read out and dye concentration.

A minimum of two standard solutions can therefore be used to calibrate the machine.

Fresh standard solutions were prepared to calibrate the instrument during analysis of the dye injection tests. Standard solutions had been previously prepared to find the detection limit of the machine, but these were not used since the dye breaks down over time when exposed to UV light. The dye was supplied as a 20% active solution and this was diluted until it could no longer be reliably detected by the instrument, establishing a detection limit of about 0.1-0.2 ppb (parts per billion). The dye has no perceptible colour until it reaches concentrations of around 10 ppb.

5.4 How Much

The quantity of dye to inject was assessed by computer simulation and using simple tracer formulas. Since the detection limit was known we aimed for a maximum concentration at the monitor well of around 100 times the detection limit (ie. 10 ppb), to provide a good resolution of the dye pulse on the fluorometer. No other wells in the area were likely to be adversely affected by the presence of the dye if it showed up at even higher concentrations since the nearest wells were used only for space heating. Wells used for drinking or laundry water supply were far enough away that dye was unlikely to be detectable in them.

5.5 Computer Simulation

A random walk computer simulation was carried out to try and predict the concentration of dye at the monitor well. This involved superimposing a random-walk method over an analytical two dimensional reservoir streamline analysis package. Unfortunately the package treats flow in the reservoir as flow through a uniform porous medium. From previous work on the Klamath Falls reservoir it would appear that this is an unreasonable assumption. The reservoir is thought to consist of a 'dual-permeability' network. (Porous media containing fractures and cracks which allow preferential flow in certain directions) (Lund, 1974¹). Other limitations on a successful simulation were that neither the transmissivity nor the hydraulic gradient (magnitude or direction) could be accurately determined for the area of interest. The model also relied on experimental data from core samples to establish parameters such as the dispersivity of the dye. Dispersivity is the combination of microscopic diffusion between streamlines (driven by concentration gradient) and macroscopic mixing (which is influenced by the size of the pores, cracks or faults and their alignment). This parameter governs the spreading of the dye plume as it moves away from the source well.

In spite of these limitations a model was attempted, using best guesses for reservoir parameters which were unknown. The model could then at least provide a first estimate for the quantity of dye required and the possible flow diverting potential of a nearby pumped well, which supplies the city district heating scheme.

5.6 Computer Results Analysis

A computer model was set up for the area of interest, including the test well, monitor well and pumped well. One thousand 'particles' of dye were then 'released'. Using probability functions each particle moves with the flow in a sequence of steps, the magnitude and direction of the movement being controlled by the random functions. If enough particles are followed, using short enough discrete steps, the overall distribution of particles becomes representative of an average flow pattern.

Dye particle positions were presented on the computer monitor as a distribution of dots, with a high density of dots indicating a high concentration of dye in that area. The visual impression obtained is that of a plume of dye streaming out from the source well, spreading as it travels downstream. This type of information is of course purely qualitative.

In order to obtain a figure for the concentration at a particular location a code sequence which analysed the dot distribution was written. The dot representation is for a two dimensional aquifer with dispersion in the horizontal plane only. The dye release is therefore considered to form a line of uniform concentration through the depth of the permeable zone. No vertical spreading or absorption of the dye to country rock was allowed. Because the dispersion of dye was limited to two directions it was considered that a particle would contribute to the concentration at a given point in an inverse square ratio. A particle at twice the distance to the chosen point would then have only one quarter the influence on concentration at that point. This method created numerical problems if the distance from a particle to a given point of interest became very small. In such a case the concentration contribution of just one particle could substantially influence the overall result. To alleviate this situation a particle was considered to be at the point of interest if it lay within 1 foot (0.316m) of the point. All particles within this radius were assigned the same concentration contribution factor (see figure 5.1a,b).

The sum of the individual concentration factors was divided by the number of dye particles to give a final result, with a possible maximum of 10. If all the dye particles released lie within a one foot radius the total concentration factor would be 10 at that point, which corresponds to the physical situation of all the dye lying in a 1ft (0.32m) radius column, in the 30ft (10m) thick permeable zone. This is probably a fair approximation at the time of dye injection and corresponds to a concentration of 13 ppm (parts per million) with a 40g injected sample. For a 40g injection the concentration at a given point is then easily found by multiplying the concentration factor by one tenth of 13 ppm.

By analysing a grid network of points, a concentration distribution could be obtained for the aquifer model. If a sufficient number of grid points are analysed, a smooth curved surface can be obtained representing the concentration distribution. The actual concentrations predicted by the model were quite high, indicating that between 1 and 5 grams of dye would be sufficient to obtain suitable samples at the monitor well.

When the city well was included in the calculation, pumping at its low summer rate, the dye plume was diverted slightly from the original streamlines. The magnitude of the deflection was of the order of a few metres over the distance between the wells and was considerably less than the uncertainty in the actual undisturbed flow direction. This information was therefore not useful from the standpoint of determining an absolute concentration required or for predicting the path of the dye. It

did however give the impression that the pump was unlikely to draw large amounts of the dye away from the undisturbed flow streamline at its present pumping rate.

5.7 Radial/Doublet/Solid block approximations

5.7.1 Adapting the standard formulas

When the Klamath Union High School doublet system was dye tested in 1983, radial and doublet flow models were considered as possibilities for dye dispersion. These models predicted break through times and were chosen as most likely to represent two possible extremes. Once a break through time had been found the dye concentration at break through was determined from the known injection rate (Gudmundsson et al, 1983). Even though such formulas are based on many assumptions, some of which were known to be violated in the Klamath Falls reservoir, they provided a starting point for designing the test.

These standard tracer formulas (see equations 5.1, 5.2 below) are intended for use where injection and pumping are occurring at about the same rate in two wells. Despite this, they were used to help calculate the quantity of dye needed for our tests. Both formulas include a term for the injection rate of fluid into one well and consider the injection and production processes to be the only driving force for dye transport. Natural flow in the reservoir is therefore not considered. In our situation there is no injection or production at the release well or monitor well and natural flow is the only mechanism for dye transport, so an artificial injection rate was used in the formulas to find break through times. The quantity of dye required can be found without considering the injection rate since the reservoir volume involved is the same at all rates (see equation 5.3, 5.4).

$$t_r = \frac{\pi r^2 \phi h}{Q}$$

Equation 5.1

$$t_d = \frac{\pi r^2 \phi h}{3Q}$$

Equation 5.2

But $V = Qt$ so

$$V_r = \pi r^2 \phi h$$

Equation 5.3

and

$$V_d = \frac{\pi r^2 \phi h}{3}$$

Equation 5.4

Where

- t = break-through time
- r = well separation
- ϕ = reservoir porosity
- h = reservoir thickness
- Q = injection flow-rate
- V = injected volume

If $r = 25\text{m}$, $\phi = 0.1$ and $h = 10\text{m}$ then $V_r = 1965\text{m}^3$ and $V_d = 655\text{m}^3$ (from equations 5.3, 5.4). To achieve a dye concentration of 10 ppb these volumes require the addition of 19.65g and 6.55g respectively.

5.7.2 Determining the injection rate

A permeability-thickness value had been found for the test well in a previous study (USGS, 1984) and this was used to calculate a pseudo injection rate for the release well. Flux across the reservoir was calculated from the permeability-thickness product, water viscosity, reservoir thickness (from drillers logs) and the hydraulic gradient measured between the wells. The cross sectional area of well which intersects the live water zone was then multiplied by this flux to determine the injection rate, which was used in the tracer formulas (see calculation 5.1).

$$\begin{aligned} kh &= 1.34 \times 10^6 \text{ mdft @ } 20^\circ\text{C (USGS, 1884)} \\ &= 0.4084 \times 10^3 \text{ dm} \end{aligned}$$

If we assume 10m reservoir thickness;

$$\Rightarrow k = 40.84 \text{ darcy}$$

Using a conversion factor from USGS (1984) to express permeability as hydraulic conductivity ($k \Rightarrow K$);

$$K = 34.1 \text{ m/day @ } 20^\circ\text{C}$$

$$\text{Now } k = \frac{K v}{g} \quad \text{and} \quad \frac{v}{g} = \frac{\mu}{\rho g}$$

$$\text{so } K = \frac{k \rho g}{\mu}$$

but the reservoir temperature is 100°C , so viscosity is much lower than at 20°C .

$$\begin{array}{lll} \mu = 279 \times 10^{-6} \text{ Ns/m}^2, & \rho = 959 \text{ kg/m}^3 & @ 100^\circ\text{C} \\ \mu = 959 \times 10^{-6} \text{ Ns/m}^2, & \rho = 998 \text{ kg/m}^3 & @ 20^\circ\text{C} \end{array}$$

So

$$K_{100} = K_{20} \frac{\left(\frac{\rho}{\mu}\right)_{100}}{\left(\frac{\rho}{\mu}\right)_{20}}$$

substitution gives

$$\begin{aligned} K_{100} &= 3.3 \times K_{20} \\ &= 112.5 \text{ m/day} \end{aligned}$$

@ 3.4% hydraulic gradient

$$\Rightarrow 3.83 \text{ m/day}$$

Well cross sectional area

$$\begin{aligned} &= 10 \text{ m} \times 0.255 \text{ m} \\ &= 2.55 \text{ m}^2 \\ &\Rightarrow 0.11 \text{ kg/s inflow} \end{aligned}$$

Using $r = 25 \text{ m}$, $\phi = 0.1$, $h = 10 \text{ m}$ and $Q = 0.11 \text{ kg/s}$ in equations 5.1, 5.2 gives;

$$\begin{array}{ll} t_r = 17.4 & \times 10^6 \text{ seconds (201 days)} \\ t_d = 5.8 & \times 10^6 \text{ seconds (67 days)} \end{array}$$

Calculation 5.1

The flux calculation was also used independently to find an arrival time due to natural flow alone. (see calculation 5.2).

Dye arrival time is given by;

$$t = \frac{r\phi}{v}$$

Equation 5.5

Where

t	=	break-through time
r	=	well separation
ϕ	=	reservoir porosity
v	=	reservoir flow-rate

Assume a reservoir flow of 3.83m/day (from calculation 1), $r = 25\text{m}$ and $\phi = 0.1$.

$$\begin{aligned} t &= \frac{25 \times 0.1}{3.83} \\ &= 0.65 \text{ days (16 hours)} \end{aligned}$$

Calculation 5.2

A heat balance, performed with the DHE operating in the well, was also used to calculate an injection rate. During DHE operation, the bulk temperature of the reservoir is considered to stay the same as the undisturbed temperature and the minimum temperature at the inlet to the DHE is used as a base temperature. Using these two temperature extremes puts a lower bound on the mass of fresh fluid which must be flowing into the well to sustain the heat output. This mass is used as the injection rate in the tracer equations. The cross sectional area of the bore is then used to calculate a reservoir flow speed which will provide this quantity of fluid, to independently calculate an arrival time for the dye front (see calculation 5.3).

From DHE testing by Culver and Reistad (1978) the implied fresh fluid inflow (from a heat balance) is 1-2 kg/s.

$$\begin{aligned} \text{Well cross sectional area} &= 10\text{m} \times 0.255\text{m} \\ &= 2.55\text{m}^2 \end{aligned}$$

$$\begin{aligned} \text{Using } v &= \frac{Q}{A} \text{ gives} & v &= \frac{1.0 \times 10^{-3}}{10 \times 0.255} \\ & & &= 0.39 \times 10^{-3} \text{ m/s} \\ & & &= 33.9 \text{ m/day} \end{aligned}$$

Dye arrival time is given by equation 5.5;

$$\begin{aligned} t &= \frac{r\phi}{v} \\ t &= \frac{25 \times 0.1}{33.9} \\ &= 0.074 \text{ days (1.8 hours)} \end{aligned}$$

Calculation 5.3

This method is considered less reliable than the previous one since the actual process of fluid passing into the bore is so poorly understood. Nevertheless, this result was another possibility, providing more information on which we could base a final decision. In all cases best guesses were used for unknown reservoir parameters.

5.7.3 The solid block model

Another method, where the block of permeable resource between the two wells was considered to be uniformly filled with the dye was also used. Dispersion of the dye plume was allowed for as it travelled down stream. A normal distribution was assumed, with a standard deviation of 15ft (5m) from the centre streamline. The fluid volume contained within this block was calculated assuming a porosity of 10%. The quantity of dye needed to provide the desired sample concentration could then be calculated (see calculation 5.4).

Dye spreads 5m each side of the centre stream-line.

$$\Rightarrow \text{Volume in block} = 10 \times 10 \times 25 \\ = 2500\text{m}^3$$

If $\phi = 0.1$ the volume of water in the block is 250m^3 .

For a normal distribution (standard deviation 5m) 68% of the dye lies within the block.

To achieve a dye concentration of 10 ppb in 250m^3 requires the addition of 3.8g (2.5g/0.68) of dye.

Calculation 5.4

5.8 Final determination of injection quantity

The only consideration in setting an upper bound on the injected dye mass was that we did not want to interfere with certain wells downstream, since they were used for drinking water and a laundry. Calculations of the required dye quantity varied by a considerable degree depending on the method used and ranged from 1-2g to 19g. Results of the 1983 doublet test had shown break through times much earlier than expected and quite low dye concentrations, considering the small volumes injected up to break through. It was concluded from that series of tests that large scale mixing occurred as the dye travelled quickly along faults and cracks (Gudmundsson et al, 1983). In consideration of these results we decided to inject 40g slugs of dye. We were confident this would not cause adverse effects down stream yet would be returned in measurable quantities. The dye was supplied in the form of a 20% active solution so 200g samples were injected.

Figure 5.1a The concentration factor curve showing the problem area.

Figure 5.1b The modified concentration factor curve (as used to analyse data).

6.0 DYE INJECTION TESTS (KF1, KF2, KF3, KF4)

6.1 KF1: CW1 pumped / DHE off (31/8/89-11/9/89)

With the DHE installed, temperature monitoring equipment in place and an airlift pump fitted to the monitor well the first dye test was run.

A two hundred gram slug of Rhodamine W.T. (20% active solution) was injected to feed zone depth in the DHE well through a 200ft (61m) length of garden hose (fitted with a weight). Around 5 gallons (20l) of water (warm geothermal) was used to flush out the hose. Compressed air was supplied to the airlift pump tube to obtain samples from the monitor well, initially every quarter of an hour and later at half hourly intervals. Samples of water produced from the city well were also taken, bled from a pressure gauge fitting at the well head. All samples were stored in clean polythene bottles until they could be analysed in the laboratory the next day.

Since dye was added to the test well with the DHE not running the well was boiling throughout the test. A sample of steam condensed on a pipe wrench positioned above the well was collected and analysed for dye. When it was found that the dye could be detected in the steam it was decided to collect the condensate more regularly on the next test to observe its concentration change as the dye left the well. The collection of this first sample served only to confirm the presence of dye in the steam phase.

Dye was detected at the city well around 6 hours after injection, reaching peak concentration after approximately 11 hours. The pumped well was around the same distance from the injection (DHE) well as the intended destination, the monitor well. This arrival time was much faster than predicted by the flow modelling which had been done with the adapted tracer formulas. Estimates of arrival time based solely on natural flow speeds were closer, although these had not considered the pumping influence (see section 5.7). The pumping rate was quite low during this test (around 100gpm) (6.3 l/s), because of the low summer heat load.

The concentration verses time plot for the first test is shown in figure 6.1. It has a sharp rise and a long tail, similar to that found during the doublet tests at Klamath Union High School in 1983. Both tests were also characterized by early dye arrivals, a matter of only a few hours in each case. The peak concentration observed was relatively low, considering the early arrival time and it appears that the dye has mixed with a large volume of fluid in its short time underground, rather than travelling directly toward the city well. It should be noted that the peak may in fact be higher than the 8 ppb suggested by figure 6.1. Water samples were being collected manually and analysed in the laboratory the next day. Not until after the samples were analysed was it realized that the peak had occurred at some time between midnight and 8:30am. No samples had been taken over this period. During later tests the fluorometer was brought to the test site so that a quick check could be made as the test progressed, to pick up any trends. Samples were always re-tested after a cooling period since it was discovered that a lower fluorescence was measured if the sample was hot. Recorded results, as presented here, are for samples at room temperature.

The rapid break through to the pump seems to indicate a relatively small volume of fluid is being drawn on by the pump, or that the DHE well and pumped well lie on some type of well connected zone, through which the pump gains a proportion of its water. This second possibility seems more consistent with the low dye concentration found at the pump. There is no reason to doubt that the pump draws from all directions and this will have a diluting effect on dye drawn from the direction of the DHE well. Such a low concentration suggests that the dye has mixed with a very large volume of water, unless only a small fraction of the injected sample was drawn toward the pump. For dilution to the concentrations found the dye would be required to mix with 5000 cubic metres of water, yet the pump only extracted 190 cubic metres

from the time of injection until break through. Strong mixing of reservoir fluids is thought to explain the long term thermal behaviour and dye test results of the Klamath Union High School doublet, tested in 1983 by Gene Culver and others.

Armed with this new information (arrival time) the simple tracer formulas can be put to use to estimate the size of fractures or matrix porosity. These formulas for radial and doublet flow give a 'ball-park' figure for fracture size and porosity. The city well pump rate is used as the volume flow rate in the formulas (see calculation 6.1). Application of these formulas indicates that a planar fracture, or combination of fractures, with an equivalent width of 1-3 in (25-75 mm) can provide a suitable flow path for the arrival time achieved in our test. A similar arrival time would be achieved in a uniformly porous 30ft (10m) thick aquifer of 0.5-1.5% porosity.

$$\text{Radial flow (equation 5.1)} \quad t_r = \frac{\pi r^2 \phi h}{Q}$$

$$\text{Doublet flow (equation 5.2)} \quad t_d = \frac{\pi r^2 \phi h}{3Q}$$

Rearranging and substituting, using a pump rate (Q) of 100gpm (6.3 l/s), a radius of 128 ft (39m) and an arrival time of 6 hours (21600 s);

$$\text{gives } \phi h = 0.025 \text{ or } \phi h = 0.075$$

ie. a 1-3 in (25-75 mm) planar fracture would give similar arrival times to those measured as would a 30ft (10m) thick aquifer with porosity of 0.5-1.5%.

Calculation 6.1

No measurable quantities of dye were found at the monitor well during the test. The airlift tube produced rusty water on occasion and this gave a slight indication on the fluorometer due to some scatter of the incident light in the turbid solution.

It was the intention of the test programme to obtain dye samples from the monitor well, carried by the natural flow, rather than from the pumped city well. Several possible reasons for the absence of dye were considered: A poor underground connection might exist between the wells; the city well may be drawing the dye away from the normal flow direction; the normal flow may be in a direction we did not suspect; our sampling method may be unsuitable; low summer draw-off may have slowed the flow (not waiting long enough) or the dye may be diluted to below the measurable limit. Of these possibilities most were out of our control and we could offer no remedy even if we could pin-point the problem. Total dye recovery achieved in the DHE well test was around 8 grams to Friday the 8th of September, with more than 50% of the dye recovered being captured in the 48 hours following breakthrough. This represents 20% of the 40g of active Rhodamine injected, so the pumped well was having a significant effect on the test, unless the natural fluid path was toward the pump anyway. Since it was likely that the pump was influencing the flow to some (probably large) degree it was decided to shut it off and run the city heating system from the city back-up well (CW2). This well is located further away and 'upstream' of the DHE test well and monitor well (approx. 2300ft north) (see figure 6.2). City well 1 was shut off on the 1.1th of September once the dye trace was down to near the detection limit and city well 2 started.

6.2 KF2: CW2 pumped / DHE off (12/9/89-14/9/89)

The second test was started twelve days after the first injection, once again with a 200g sample of dye, followed by 5 gallons (20l) of city water. This test was in effect a repeat of the first test, but with the nearby city well influence removed. The second city well was running but is a lot further away from the test area. Using cold city water to flush dye from the injection hose was the only difference in test procedure. It was thought that water in the well would heat the water in the hose before it reached the well bottom so that the density difference would be negligible. It is estimated that using cold tap water instead of warm geothermal water to flush the hose places an additional load of 10-15 kW on the well for around 5 minutes. Density changes occurring due to this heat load are, in the authors opinion, unlikely to affect the placement of dye in the feed zone.

Samples of the steam emitted at the well-head were collected regularly at the start of the test as well as sampling for dye at the monitor well and back-up city production well (CW2). The release of dye from the injection (DHE) well into the aquifer can be seen as a drop in the dye concentration in the steam condensate (see figure 6.3). Most of the dye seems to have left the DHE well after a period of a few hours.

After two days no dye had been found at the monitor well, the city back-up well, or at any other nearby unused wells. It was noted that the hydraulic gradient (from DHE to monitor well) was lower at this time, after shutting off CW1 and starting CW2, than at any other time during testing (see figure 6.4). This could be an indication that the monitor well only appears to be down gradient from the DHE well when the city well is influencing the flow. The quality of water level measurements was however considered marginal and these were eventually abandoned since it was felt that they were of limited use. Two days into the test city engineers discovered a leak in the secondary side of the heating distribution network. While repairs were carried out they offered to shut off the back-up well (CW2). This gave us the opportunity to test the aquifer in a state virtually uninfluenced by pumping. With both wells now shut off it was noted that the hydraulic gradient increased steadily from 0.5-1% during the next two days. When no dye was found after these two days (4 days after injection) we decided to inject another slug of dye before repairs to the city system were completed.

6.3 KF3: CW1 off - CW2 off / DHE off (15/9/89-29/9/89)

The third dye test was a repeat of the second, unsuccessful test, but with both city wells shut off. Cold water was once again used to flush dye from the injection hose into the well feed zone. A similar procedure was used to collect condensed steam samples at the well head, to follow the release of dye from the well into the aquifer (see figure 6.5). During this test the dye appeared to release more quickly into the aquifer than it had on the previous test (see figure 6.3). The measured hydraulic gradient from the DHE well to the monitor well was around 1% at the time of release, compared to around 0.5% when the dye was released in test KF2. This slightly higher hydraulic gradient (1%) was fairly constant over the test period and possibly contributed to the faster release rate.

Six days of sampling at the monitor well failed to show any trace of the dye. All accessible wells in the immediate area were sampled if they were large enough for a thief type water sampler, as well as any other pumped or flowing wells in the city area which had suitable bleed valves. No dye was found in any of these wells.

Repairs had been completed on the city heating system so it was decided to re-start city well 1 (CW1) and run it at the same flow rate as before, to try and duplicate the conditions of test KF1. Test KF1 had at least produced a dye response, even though it was not due to natural flow, so we thought it best to run another test similar to the first. This time a cooling load would be placed on the well and we hoped we would see a different dye response, which could be due to DHE use. The well was started and initially pumped at a higher rate (400gpm) (25l/s) while the monitor well water level was observed. No variation which was attributable to the pumping could be seen at the monitor well, perhaps due to a poor or indirect under-ground communication (see figure 6.6). It was then decided to make a check of the pumped well for residual dye. Surprisingly, a high concentration was found and large quantities of dye were produced from the well over the next few days (see figure 6.7). The highest concentration was found in the first sample taken after start-up and measured around 4.5ppb. Concentrations then tapered off over the next few days. The unusual thing was that the dye did not seem to have moved past the area immediately surrounding the pumped well, even though a long time had passed since injection, one slug being released 124 hours (5.2 days) and the other 196 hours (8.2 days) earlier. Virtually no time lag was observed between pump start-up and a high dye concentration, as had been observed in the first test, although the pump was pumping at a higher rate in this third test. The pump rate was reduced to around 150gpm (as in test KF1) and the reservoir left to settle for a few days as the residual dye was extracted in preparation for the next test (DHE running).

The indicated hydraulic gradient increased to around 2% towards the end of the test period but for most of the time it remained around 1%. As at the 22nd of September the DHE to monitor well gradient was 1.6-1.7% (toward the monitor well). From water level measurements in the city well and estimated well temperatures (no profile could be taken) the gradient from the DHE well to the city well was around 0.9% with the pump off and 1.6% with the pump on. The Adamscheck well, located to the south-west, had an indicated gradient of 1.5% toward the DHE well, totally at odds with the reservoir flow patterns we suspected (see figure 6.8). Well water level measurements were not used in later tests.

Examination of the gradient data between the different wells, which seems contradictory, and a re-examination of the temperature and water level maps show that there is some anomalous behaviour in the region of the test wells. It has been suggested that a very local cross-fault, perpendicular to the main fault, may be present here. This could cause some of the anomalies shown on the temperature and water level maps and may go some way toward explaining the strange data obtained in our tests (particularly for hydraulic gradient data) (see figures 6.9a, 6.9b).

6.4 KF4: CW1 pumped / DHE running (29/9/89-12/10/89)

Another 200g dye slug was injected into the DHE well shortly after starting the DHE at 10am on the 29th of September. The heat exchanger had been test run for several hours two days earlier but the well appeared to be in the same initial condition as for earlier tests. A few minutes after start-up the DHE had reduced the temperature in the well to below boiling. The dye hose was then placed in the well and the dye injected, with cold city water to flush out the dye.

During the course of the next few hours the well cooled off until the DHE reached a near steady heat output. Both the monitor well and the city well were regularly sampled for dye during the two days following injection. The monitor well again failed to show any trace of the dye and from the city well dye trace (see figure 6.7) it is difficult to decide if the slight bump in the tail of the curve is significant. Certainly the response at CW1 was nothing like that which had been achieved in test KF1, with the DHE shut off. The pumping rate at CW1 was thought to be slightly higher than during test KF1, at 150-170gpm (6.3-7.1 l/s). This pump rate was determined for us by city engineers, who used a hand-held tachometer on the pump shaft and then consulted the pump curve.

While taking samples from the bleed valve we noted well-head temperatures slightly lower than normal, along with a higher line pressure. When the pump blow-down valve was opened temperatures increased quite quickly and the line pressure fell. The production wells for the city heating system are at a higher elevation than the injection point so a back pressure valve is fitted at the injection well to keep the feed line and heat exchangers full, as they tend to drain. Later in the week it was found that this valve had completely closed, preventing any flow in the feed line. The high line pressure and low temperature we had observed are consistent with a closed or partially closed back pressure valve causing the pump flow rate to be reduced. The extent to which this influenced our test is unknown. We know we had some flow but it was less than the 150-170gpm (6.3-7.1 l/s) we thought we had from tachometer / pump curve measurements. If the flow was very low this could be the reason for the non-appearance of the large quantities of dye we expected at CW1.

No one was available to take water samples during the following week but the DHE was left running to gain longer term temperature data. After ten days of continuous operation the DHE was shut off. The well very quickly re-heated and resumed boiling (see section 7.0). At around this time the problem with the back-pressure valve became apparent as it closed completely and no heat could be obtained at the cities central heat exchangers. It had gone unnoticed up until this time because the very small summer heat load could be easily met by the reduced flow. The intended minimum flow rate of around 100gpm had been set in consideration of the pump mechanism rather than heating requirements. Dye concentrations found in samples taken after the flow was restored were about the same as those found on the first day of the test, but cannot be interpreted because of the unknown flow rate history for CW1.

6.5 Summary of dye tests

During the test period the city heating system was operated under a large range of conditions. Flow rates at city wells varied considerably and there are several periods when flows were not known. The first test (KF1) was influenced by pumping at the city well, indicating that pumping is an important consideration, even at the low summer flow rate. Tests KF2 and KF3 (performed with the pumps off) gave the impression that flow is almost stagnant when the city wells are not pumping, although a hydraulic gradient of 1-2% indicates a reasonable flow. Results from test four (KF4) can not be interpreted because the flow rate in city well 1 is not known for the test period.

Since pumping of the city wells has an influence on the tests it is essential that pumping rates are accurately known for any future experiments. It would be preferable to have the pump operating at a steady rate, after a long settling period, before dye is injected. This type of testing would probably be better suited to the winter season when a strong natural flow exists due to the loading of downstream wells. The pumped well could be left to stabilize for a period before testing began.

Figure 6.1 Dye concentration in city well 1 (CW1) during test KF1.

Figure 6.2

Location of wells in the city-heating system.

Figure 6.3 Dye concentration in steam condensate (test KF2).

Figure 6.4 Hydraulic gradient from DHE test well to the monitor well (from the start of testing).

Figure 6.5 Dye concentration in steam condensate (test KF3).

Figure 6.6 Monitor well water level fluctuation.
NB: No obvious change occurs after pump start-up (0 minutes).

Figure 6.7 Residual dye concentration in city well 1 (CW1) after tests KF2 and KF3. (Dye was produced at pump start-up).

Figure 6.8

Measured hydraulic gradients for DHE test well, monitor well, city heating well and Adamscheck well. (assumed flow direction also shown).

Figure 6.9a

Location of proposed cross fault on water level map.

Figure 6.9b

Location of proposed cross fault on well temperature map.

7.0 DHE / WELL THERMAL BEHAVIOUR

During the reservoir dye tests the DHE inlet and outlet temperatures and flow rate were recorded so that the heat load could be calculated. Three points in the DHE well were monitored and the monitor well bottom hole temperature was recorded. Results were collected on a *Unidata* portable logger (see sections 4.4 & 4.5). These measurements were made to assess the potential heating performance of the DHE and any interference effects resulting from its use. A short test was made on the 27th of September to test the instrumentation and to obtain cooling data for the well. The main DHE test (long test) was started on the 29th of September and continued until the 9th of October.

7.1 Monitor Well Thermal Behaviour

A temperature probe was placed at a depth of 190ft (57.9m) in the monitor well. This was the centre of the zone thought to supply hot fluid to the well and was the location of the airlift pump inlet. During the course of the DHE tests the downhole temperature showed a steady decline. It would appear however that this was not directly related to use of the DHE since the temperature fall off appears to be a continuation of a trend which started before the DHE was running (see figure 7.1). This drop in temperature is quite large (around 15°F (8°C)) over a period of about one month. Testing was however carried out at the height of summer when virtually no draw-off is occurring. Drops of up to 30°F (17°C) and water level fluctuations of up to 20ft (6.1m) have been observed in some wells in previous summers (Lund et al, 1979).

7.2 City Well Temperature Response

A temperature gauge mounted in the outlet pipe of city well one (CW1) was checked periodically for any variation in temperature. This data proved to be of no real use since the flow rate was so small that the uninsulated line losses obscured any possible variation due to interference. Normally the temperature at this gauge was fairly constant but with the extremely low flow (see section 6.4) the water cooled off 5-10°F (3-6°C) in the pump house alone. Water temperatures then rose sharply if the pump was discharged to a drain.

7.3 DHE Behaviour / Well Characteristics

The temperature at the DHE outlet dropped quickly in the first 30 minutes of operation in both tests while water was supplied at an approximately constant temperature (see figures 7.2a, 7.2b, 7.3a, 7.3b). After this initial cooling period the outlet temperature settled near 170°F (77°C) for the remainder of the twelve day test supplying a steady heat output of nearly 500kW. The same heat output and outlet temperature were reached in the short test.

The initial high heat output is due to heat being released from well storage to the heat exchanger coil. This energy is stored up in the well during the time it has been boiling and is stored as sensible heat in the steel casing, well water and rocks lining the well. Once this additional store of heat is used the well supplies heat by input of fresh water at the well bottom and a smaller input from rocks further afield. These more distant rocks may contribute stored heat for quite a long period after the apparent extraction of stored heat is finished (Allis, 1981) and this energy then takes a long time to replace once the heat load is removed from the well. For the purposes of home heating though, the well can probably sustain something near this early steady load for the duration of the heating season, to be replenished during the following summer. In practice the load which can be placed on this well will be considerably less than 500 kW since the inlet temperature to

the coil will normally be higher when water is recirculated. At least 300-350 KW can probably be supplied on a continuous basis to a heating system.

The re-heating curve for the outlet shows an unusual S shape after the flow is stopped (see figures 7.2b (short test), 7.3c (long test)). The drop in temperature is due to heat loss to the atmosphere from the hot water sitting in the temperature pocket. After a period of around 15 minutes (short test) the well begins boiling and the condensing steam heats the pipes up again. The cold inlet pipe also shows the effect of being heated by this steam (see figures 7.2a (short test), 7.3a (long test)). From figures 7.2b and 7.3c it can be seen that the well resumed boiling fifteen minutes after the DHE was shut off in the short test but took nearly one hour after the twelve day test. This is due to the higher draw-down of stored heat from the surrounding rock which must then be replaced at the completion of the run.

7.4 DHE Well Temperatures

The well temperatures show a steady decline in the first 30 minutes or so (as with DHE outlet temperature) as the well loses its stored heat to the coil (see figures 7.4a, 7.4b). Temperatures then stabilize as the well reaches a quasi equilibrium state. Once the DHE is shut off temperatures recover quickly at first, then more slowly (see figure 7.4c). This is shown in more detail by an independent probe installed at the well bottom to monitor recovery (see figure 7.5a). Full well recovery took about one day after the long test (see figure 7.5b). The fast recovery occurs as fresh fluid flows into the well and, without the DHE load, is able to re-heat the casing, well fluid and well bore rocks. The slower recovery noted after this phase occurs as the fluid re-heats those rocks at a larger radius from the well bore. These are the rocks which took longer to cool at start-up and are thought to be partly responsible for sustaining longer term heat loads.

The actual temperatures recorded by these probes are somewhat unusual. As expected the bottom probe at a depth of 200ft (61.0m) recorded the lowest temperature since it is exposed to fluid which has flowed past the full length of coil (effectively a shell side outlet). The top probe, which we expected to be hottest, showed a lower temperature than the middle probe. It is thought that perhaps this probe is lying next to the DHE cold leg, or that the middle probe is lying next to the casing or hot leg. Once the long test began the middle probe gave high temperature readings. The output seemed to vary by the normal amount but absolute temperatures were higher than can be expected in Klamath Falls (see figure 7.6). This probe may have suffered some damage in the well. The uncertainty in placement of the probes make the results most useful in terms of relative changes, rather than absolute temperatures. The highest relative change occurs at the bottom of the well. This is to be expected since with the DHE running it receives fluid after exposure to the whole coil whereas when the DHE is off the flow reverses and the bottom probe gets fresh hot fluid first as it flows up inside the casing. Flow reversal with the DHE running was observed in this well by Culver and Reistad in 1978.

7.5 Well Profile / DHE Running

The well profile taken with the DHE running shows the drop in temperature over the length of the coil (see figure 7.7). Highest temperatures are found at the top, where fresh fluid enters the casing. Progressively lower temperatures are found down the coil. The coldest region is at the very bottom of the well. These last few metres of the hole are not thought to produce much (if any) live water and are drilled simply to provide a place for debris to fall so that it does not block the permeable zone. Cold water appears to have sunk to this area and is not replaced by fresh fluid. This cold section at the very bottom of the well has been observed in Rotorua (Dunstall and Freeston, 1989) and in a model well (Su, 1988).

During the last dye test (KF4) dye was added to the well with the DHE running. The well was therefore circulating in the opposite direction to normal (ie. down the casing). Perhaps the cool dye slug sank into this region before it could disperse into the permeable zone. In previous tests a considerable quantity of the injected dye was probably carried up the casing by the up-welling fluid, to then flow down the well annulus past the permeable zone.

Figure 7.1 Monitor well temperature (at 190 ft) during the DHE test period.

Figure 7.2a DHE inlet temperature (short test).

Figure 7.2b DHE outlet temperature (short test).

Figure 7.3a DHE inlet temperature (long test).

Figure 7.3b DHE outlet temperature (long test).

Figure 7.3c DHE outlet temperature at shut-off (long test).

Figure 7.4a DHE well temperatures (short test).

Figure 7.4b DHE well temperatures (long test).

Figure 7.4c DHE well temperature recovery (long test).

Figure 7.5a DHE well bottom hole temperature recovery after 300 minutes (independent probe).

Figure 7.5b DHE well bottom hole temperature recovery after one day (independent probe).

Figure 7.6

Logged DHE well temperatures leading up to long test.
 NB: A response occurs at 135 ft during the short probe test but not during the twelve day test.

Figure 7.7

DHE well temperature profile (DHE running).

8.0 CONCLUSIONS AND RECOMMENDATIONS

Rhodamine dye proved to be a suitable tracer for this type of testing and the fluorometer was a simple instrument to use for its detection. The dye was found to be temperature dependent in its response to the UV light of the fluorometer so all samples were tested at the same (cold) temperature for a consistent result and maximum resolution.

Pumping of the well by air-lift to obtain a water sample was at least partially successful. The water sample was extracted from feed zone depth of 190ft (57.9m) by a reliable low technology method, over a high lift of about 60ft (18.3m). Samples were however occasionally quite cloudy due to rust inside the pipe. No dye was ever seen at this well and it may be that the sampling method is at least partly responsible for this. Other methods which may provide cleaner samples are worth consideration in any future tests. An automatic sampling system would have been of great benefit in this situation and would of meant that the peak in the first test would not have been missed.

Studies of the Klamath Falls reservoir have shown that large variations in temperature and water levels occur between seasons. Our tests may have been more successful had they been performed during the winter, when there is higher draw-off and consequently more flow in the reservoir. No upstream wells exist which would interfere with the results so winter may be the best time to test. Draw-off from the city pump would of course be higher, interfering even more in any test based on natural flow alone but dye response at the pump may give some indication of water flow paths with the DHE in various states of loading. Careful monitoring of the pump outlet temperature is just as likely to show any thermal influence from extended periods of DHE operation as any other well in the area. At the very least, a fluid connection between the DHE well and a nearby well has been found.

With the exception of one temperature probe the monitoring equipment worked well and the battery powered logger was capable of storing plenty of information in a compact package, ideal for use at remote locations. The resolution was however a little disappointing and a logger with 16 bit digital-analogue conversion (rather than 8) would have been a significant improvement, particularly when looking for very small temperature changes.

Computer modelling of the dye flow using an established ground-water flow model helped with estimates of the dye quantity for injection. Apart from this the model was based on a number of assumptions which limited the results in terms of predicting the flow. A code designed specifically to model flow in fractured rock would be needed for the Klamath Falls reservoir and even then it is unlikely that good results could be obtained for such a localized area.

The dye return seen at the city pump occurred quickly, yet had quite a low concentration. This is consistent with previous testing of the Klamath Falls area and indicates small volumes of well connected, highly mixed fluid. Natural communication between the DHE well and surrounding wells was not detected with the DHE on or off.

The DHE installation fitted to the test well supplied a heat load of nearly 500 kW during the twelve day test, with an inlet temperature of 70°F (21°C) and an outlet temperature of 170°F (77°C). If incorporated into a heating system the heat load supplied would be less, due to the higher inlet temperature, but would probably be sufficient to supply around 300-350 kW with a lower temperature difference across the coil. The long term (over the heating season) temperature draw-down is likely to be slight and will probably have no significant effect on the performance of the DHE / well system, unless it is very heavily loaded.

9.0 REFERENCES

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