SGP–TR–57

EFFECTS OF WATER INJECTION INTO FRACTURED GEOTHERMAL RESERVOIRS:
A SUMMARY OF EXPERIENCE WORLDWIDE

BY

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JUNE 1982

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THE GEOTHERMAL AND HYDROPOWER TECHNOLOGIES DIVISION
OF THE DEPARTMENT OF ENERGY
STANFORD–DOE CONTRACT DE-AT03-80SF11459

EFFECTS OF WATER INJECTION INTO FRACTURED GEOTHERMAL RESERVOIRS
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ABSTRACT

Reinjection of water into fractured geothermal reservoirs holds potential both for improvement and degradation of total energy recovery. The replacement of reservoir fluid can mean support of reservoir pressures and also more efficient thermal energy recovery, but at the same time the premature invasion of reinjected water back into production wells through high permeability fractures can reduce discharge enthalpy and hence deliverability and useful energy output. Increases in reservoir pressure and maintenance of field output have been observed in operating fields, but unfortunately so too have premature thermal breakthroughs. The design of reinjection schemes, therefore, requires careful investigation into the likely effects, using field experimentation. This paper summarizes field experience with reinjection around the world, with the intention of elucidating characteristics of possible problems. The results summarized in this paper fall into three categories of interest: permeability changes due to injection (both increases and decreases have been observed); the path followed by injected water (as indicated by tracer tests); and the thermal and hydraulic influences of injection on the reinjection well itself and on surrounding producers.

INTRODUCTION

Reinjection of water into geothermal reservoirs during utilization is intended to serve the dual purposes of waste water disposal and improved resource recovery. In order to correctly apportion importance between these two purposes, it should be noted that reservoir maintenance by reinjection is a controversial subject and in actual field cases to date, water has been reinjected solely for disposal purposes. Reinjection is a method of water disposal at the present time, and consideration of reservoir maintenance by reinjection is largely restricted to the avoidance of detrimental effects.

Commercial scale reinjection in geothermal power plants has been practiced at The Geysers, East Mesa and Brawley, California; Ahuachapan, El Salvador; Mak Ban, Philippines; Larderello, Italy; and in the five Japanese fields: Otake, Onuma, Onikobe, Hatchobaru, and Kakkonda. Except for Lardarello and The Geysers, all of these fields are liquid dominated, with producing steam/water ratios between 1:2 and 1:6. The liquid-dominated geothermal utilization represents the most difficult configuration for reinjection, since the quantity of hot water to be disposed of is greater than those of steam-dominated geothermal or conventional thermal generation systems. Since almost all of the future planned geothermal utilizations will be of the liquid-dominated type, it is of major importance to evaluate current experience in reinjection in this type of system. For example, power stations under construction or planning with definite commitments to reinject waste water include Heber in California; Tongonan in the Philippines; Broadlands in New Zealand; and Nigorikawa in Japan. In addition, reinjection has been suggested for existing power stations at Cerro Prieto, in Mexico, Tiwi, in the Philippines, and Wairakei, in New Zealand.

In terms of its principal role as a means of waste disposal, reinjection is clearly a greater problem when the quantity of water to be reinjected (relative to the useful steam produced) is larger. However, there are additional constraints on the physical characteristics of the injected water. Due to dissolved solid deposition effects, the temperature of the injected water is a critical parameter. Thus, the evaluation of a reinjection scheme needs to consider the quality, temperature, and chemical nature of the water to be injected.

The supposed benefits of reinjection to the reservoir itself are usually attributed to the maintenance of reservoir pressure and mass of fluid in place. In theory, maintaining high reservoir pressures and mass in place should reduce the effects of loss of deliverability, and also those of subsidence or formation collapse. In practice, it has not proved difficult to keep the reservoir pressures and total discharge high; however, it is now evident that it is important not to reduce discharge enthalpy by reinjection, since if this happens, steam discharge rates will decline. In fact, recent experience reported here suggests the maintenance of discharge enthalpy is at least as important as maintaining reservoir pressure. Aside from the loss in steam production, long-tern experience at Wairakei indicates total production also reduces with decreasing discharge enthalpy due to the increasing hydrostatic pressure of the fluid in the well, even though the reservoir pressure at Wairakei is now almost constant (Thain, 1981).

This paper examines recent experience of reinjection throughout the world. The purpose is to collect all relevant information to attempt to determine which fields have experienced increases in production due to reinjection and which have experienced production declines. In making such a summary, it is suggested that the nature and extent of reservoir fracturing most significantly affects the outcome of a reinjection scheme. Furthermore. there appears to be a direct correlation between rate of tracer return during tracer injection tests and subsequent performance of reinjection schemes. Accordingly, experience with tracer testing in the same geothermal fields is also summarized.

Geothermal fields examined in this paper include several liquid dominated fields around the world. These include five fields in Japan (Otake. Onuma, Onikobe, Hatchobaru, and Kakkonda), Ahuachapan in El Salvador, Tongonan in the Philippines and, Wairakei and Broadlands in New Zealand.

Large scale reinjection has also taken place into the vapor-dominated fields at the Geysers in California and Larderello in Italy. However, since the results proved somewhat different from those in the liquid-dominated fields they have been held over for a separate paper.

This paper will seek the answers to three most important questions in reinjection design:

(a) Can injectivity be maintained?
(b) Where does the injected water go?
(c) What are the effects on the injection well itself and on surrounding producing wells?

NEW ZEALAND

Injection of water into newly drilled geothermal wells is standard procedure during completion testing in New Zealand. However since 1914, long and medium term injection tests have been carried out at Broadlands as part of the development design for reinjection for the planned Ohaki power station. In addition, several wells at Wairakei have experienced a downflow of colder water from shallower to deeper feed depths within the wellbore and have thus constituted an "accidental" injection test.

Injection has taken place into wells BR7, 13, 23, 28, 30, 33 and 34 at Broadlands and the downflowing wells in Wairakei were WK80, 101, and 107. In all cases at Broadlands except BR34, injectivity increased with time - probably due to thermal contraction of the fissured rock. In BR7 and 28 static formation pressure also fell with injection, probably due to injection of cooler water into the two-phase reservoir. Tracer returns have shown the injected fluid in both Broadlands and Wairakei to migrate over long distances due to the fractured nature of the reservoirs. The tracer movement also seems to be slightly downward; however, since only small percentages of the tracers were ever recovered in any of the tests, it is not clear exactly where the injected water is going.

Broadlands

Broadlands (Ohaki) geothermal field was drilled extensively in the late sixties, discharged for three years until 1971 and then shut in. Since that time, political and technical decisions concerning its developnent have been more or less continuously discussed. Reinjection is one of the prominent technical questions at Broadlands since the field is bisected by the Waikato River which has a mean water level only a few meters below its banks (see Figure 1). Consequently any subsidence would cause the river to flood or perhaps even change its course. The question as to where to reinject has not as yet been resolved and several different methods have been tried, including injection into the field itself and injection outside the field into cold ground.

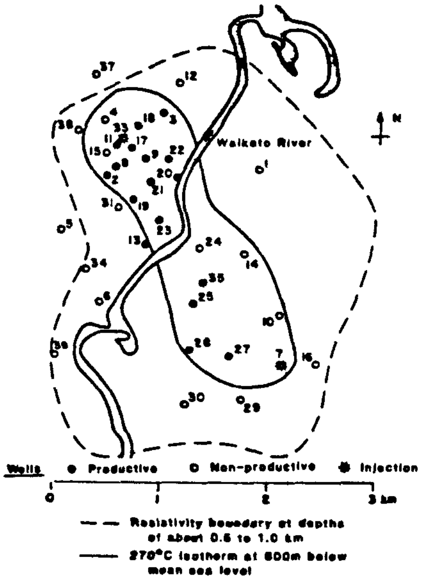

Figure 1. Map of Broadlands (Ohaki) Geothermal Area

Each has its difficulties; injection into cold ground brings problems with silica deposition in surface equipment, wellbore and formation and injection of cooler water into the two-phase reservoir carries the risk of reducing pressures due to steam collapse. Broadlands is two-phase largely because of its high non-condensible gas content (Grant, 1977) and the results of reinjection experiments here will be of interest to other two-phase reservoirs in the world.

Reinjection experiments have been carried out at BR7, 13, 23, 28, 30, 33 and 34 as well as brief tests at other wells. Both hot and cold water have been injected. Many of these wells are producers and lie within the hot (<260°C) part of the field. However, BR30 is non-productive and has temperatures around 220°C and BR34 was a well intentionally drilled outside the field. In its original injection configuration BR34 had a depth of 400m and was effectively cold (interestingly this well has since been deepened to 2600 meters and reached 300°C). BR33 was also drilled as a shallow (365m) reinjection well but lies in the center of the hottest part of the field (see Fig. 1). Injection performance of each of these wells will be discussed individually.

BR7

This 1000m deep well injected for nearly two years in 1976 and 1977 (Bixley, 1978). Injection temperatures were 150°C for five months, then 120 C for five months, then 110°C for ten months. Injection rate was about 30 tonnes/hour throughout the test, except for several shut-in periods of up to a week for transient testing. The injected water was piped from BR27 and was supersaturated with silica. Figure 2 shows the variation of flow, wellhead pressure and downhole pressure at 823 m depth during 1977. The breaks in the curves are where the shut-ins occurred. It is seen that both wellhead and downhole pressures dropped steadily throughout this period even though injection rate was maintained - ease of injection was therefore markedly improved during the test. The suggested explanation for this is that the reservoir fluid in the vicinity was originally two-phase, and cooling of the reservoir condensed some steam and lowered the pressure.

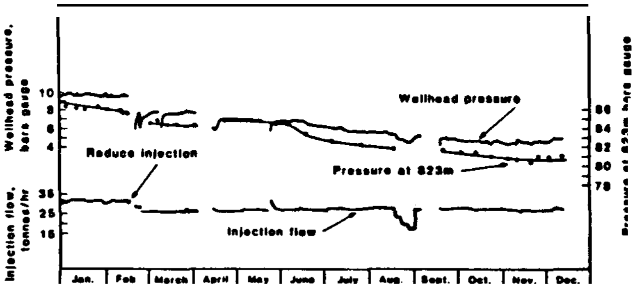

Figure 2: Injection performance of BR7 during 1977, from Bixley (1978)

It is not known where the water injected into BR7 went. In June of 1981 Iodine-131 tracer was injected into BR7 (McCabe, Barry and Manning, 1981) in a forty day injection using water from BR27, but none was recovered in BR10, 16, 27, 29 or 36. There was a thermal effect on BR7 in the 1976-77 test, which was demonstrated by the reduction in enthalpy when the well was subsequently discharged after warm-up. It is not known whether this enthalpy would have increased with time, since BR7 ceased production while its discharge enthalpy was still low.

BR13

Water at 98°C was pumped into BR13 at rates around 205 tonnes/hour from July to August 1979. The well is around 1000m deep and has loss zones into the Rangitaiki Ignimbrite at about that depth. The injection pump was stopped and restarted eleven times during the test, and pressure falloffs and buildups were recorded. Analysis of these falloff tests (Grant, 1979a) showed that the permeability-thickness product increased with injection, and Figure 3 shows this variation as a function of cumulative water injected. This increase in injectivity is in spite of the fact that the water was supersaturated with silica. On the other hand, no reduction of downhole pressure was observed, indicating a different response to reinjection than BR7 - although the duration of the test was very much shorter. The increase in injectivity (permeability) is probably due to the opening of fissures by thermal contraction - this idea is suggested more strongly from the BR23 experience and will be discussed later.

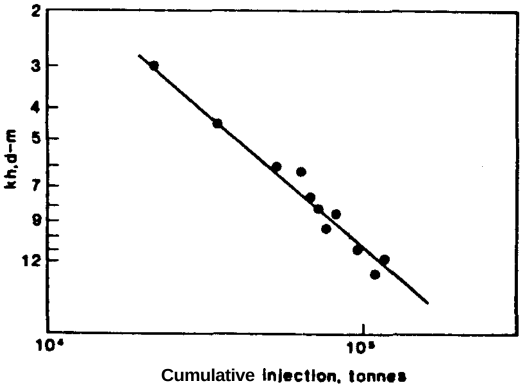

Figure 3: Permeability-thickness as a function of cumulative injection for BR13, from Grant (1979a)

The course of the injected water was determined to some extent by tracer testing. In a second injection of 150 tonnes/hour of 160°C water in 1980, Iodine-131 was injected into BR13 and wells BR19, 20 and 23 were monitored. Tracer was recovered in BR23 but not in 19 or 20, despite the fact that 13, 19, 20 and 23 are known to be in good pressure communication (McCabe, Barry and Manning, 1981). BR19 was on full discharge during the test (150 tonnes/hour) supplying the water to BR13 but still did not induce a flow underground from BR13. BR20 and 23 were originally only on bleed flows (around 1 tonne/hour) but BR23 was opened to 47 tonnes/hour on the seventh day of injection when the bleed rate began to fall off. Tracer had already been retrieved at BR23 on the fifth day, peak arrival times indicate a transit speed of around 0.4 m/hour. Eventually 6% of the tracer was recovered at BR23 although this figure may have been different had the flow rate not been changed. BR23 feeds in the same Rangitaiki Ignimbrite as BR13, BR20 feeds in the next higher formation (the Rautawiri Breccia) and BR19 feeds in both the Rautawiri Breccia and the much higher Waiora formation.

In March 1981 sixty-six tonnes (i.e., two wellbore volumes) of cold river water were injected into BR13 with a tracer slug, but no tracer was returned to either BR19, 20 or 23 in the thirty days of monitoring. It seems evident then that the flow between 13 and 23 in the 1980 test was a result of the reinjection and not a natural flow within the reservoir.

After injection the well was allowed to warm-up before discharge. As in BR7, the enthalpy of BR13 was still depressed even after the warm-up, indicating a thermal drawdown of the reservoir in the vicinity of the well due to the reinjection. There were no effects observed on the surrounding producers - the decline in production of BR23 mentioned above appears not to be attributable to a cooling of its inflow.

BR23

BR23 is a deep two-phase production well of around 1000m depth and is similar to BR13. Spinner surveys during injection show that all injected water is lost below 1000m, close to the bottom of the hole, into the Rangitaiki Ignimbrite. In June 1979, 98°C water was injected into BR23 for one week at around 150 tonnes/hour. Four pressure transients were carried out after 1, 4, 6 and 7 days (Grant 1979b). The injectivity determined from these tests is plotted in Figure 4, and is seen to increase with increasing injection. It seems that this increase in injectivity is as a result of the opening of fractures due to the injection. The well was left to warm-up after injection and then produced; productivity was higher than before but fell during production. Injection then resumed; injectivity was below its previous high, but above its earliest value, and again increased. This is shown in Figure A1.18 of Grant, Donaldson and Bixley (1982).

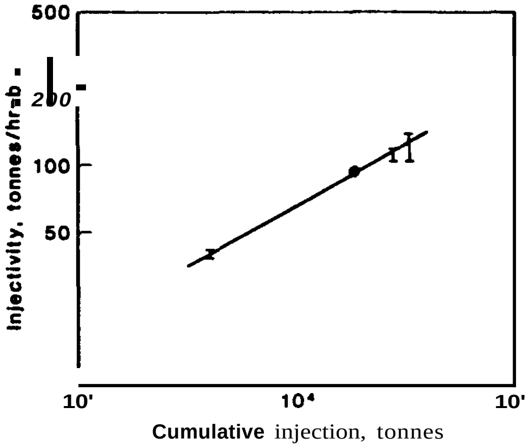

Figure 4: Injectivity as a function of cumulative injection for BR23, from Grant (1979b)

There were never any tracer tests performed at BR23 and therefore it is not known where the injected water went. Considering the observations of tracer return to BR23 from injection into BR13, it would be very interesting to see if the reverse flow occurred. BR23 was able to discharge again after a two month period of warm-up, although at a reduced enthalpy - 1110kJ/kg compared to its original enthalpy of 1320 kJ/kg. The enthalpy rose to 1190 kJ/kg after two weeks of discharge (Grant 1980a). After a second injection the enthalpy was reduced to 1030 kJ/kg in subsequent discharge.

BR28

BR28 is about 1100m deep and is a two-phase producer. 155 tonnes/hour of 155°C water were injected between January and March of 1980. The stable downhole pressure fell during injection (see Fig. 5) and continued to fall with injection shut down (Grant 1980b). As in BR7 this seems due to the injection of cooler water into two-phase conditions, collapsing steam and hence lowering the pressure.

Iodine-131 tracer was injected into BR28 with 150 tonnes/hour of 160°C water from BR35 in November 1980. A small return was received at BR25 on the sixth day indicating a speed of movement 0.8 m/hour. No returns were measured in BR35 or in any other monitored well.

BR28 is the only well in New Zealand which has been discharged immediately after injection. The discharge enthalpy was initially that of the injected water, and slowly increased.

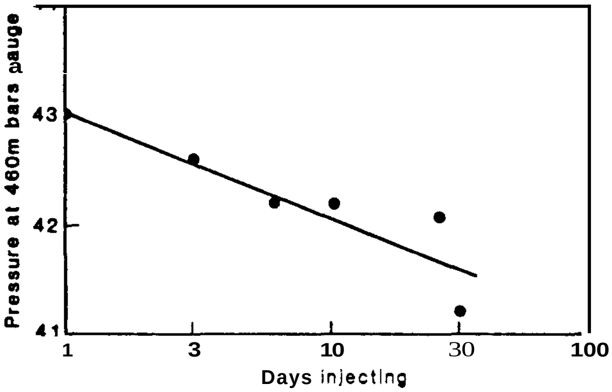

Figure 5: Reservoir pressure as a function of days of injection for BR28, from Grant (1980b)

BR30

BR30 was drilled in December 1975 and is generally listed as non-productive, although it can discharge at low enthalpy (930-980 kJ/kg). In August of 1980 a stimulation experiment was carried out by Ministry of Works and Development in which 300 tonnes/hour of cold water were pumped for about two weeks. Permeability (injectivity) was found to increase exponentially with increasing pressure (Grant, 1981a). At small flows the permeability-thickness product was about 0.1-0.3 d-m but at 400 tonnes/hour it increased to over 10 d-m. The increase was found to be reversible, that is, it went away with reduction in pumping pressure. This injectivity increase, therefore, seems different from those of BR13 and 23 which are thermally rather than hydraulically produced.

A second test was carried out starting in February of 1981 in which hot water from BR35 was injected at 130-180°C. Injection lasted a period of months although rates were changed between 100 and 200 tonnes/hour. The injectivity/pressure dependence observed in the cold water tests was essentially reproduced (Grant, 1981b).

Iodine-131 tracer was injected into BR30 in March 1981, and wells BR25, 27, 28 and 35 were monitored for five weeks. No tracer was detected at any of them.

BR33

BR33 was drilled to 365m as an experimental shallow injection well in the center of the field. A reinjection scheme was run for six months in 1977 in which 300 tonnes/hour of water from BR11 was discharged to a pond and subsequently pumped into BR33 at 80°C.

In May of 1977, Iodine-131 tracer was injected into BR33 and wells BR11 and BR8 were monitored. Tracer was detected in both wells. Travel time betweeen BR33 and BR11 was two days to the first appearance and eight days to the peak, giving a mean transit speed of 0.4 m/hour. Twelve percent of the tracer was recovered at BR11 (McCabe, Barry and Manning 1981). Five percent of the tracer was recovered at BR8, although the peak arrival was not until around 35 days. These recovery rates are unusually large compared to most of the other tests in New Zealand (although not as large as some observed in Japan - Horne, 1982), and could indicate a tendency for cold reinjected water to sink - BR11 is cased to 500m and is only 75m laterally separated from BR33. At the same time, an earlier test in 1974 in which tracer was injected into BR11 and detected in BR8 without either well flowing indicated very similar transit times. The tracer response during the BR33 test could therefore be affected by a natural flow within the reservoir.

The 12% tracer recovery at BR11 also indicates that 12% of the 300 tonnes/hour produced from BR11 originated at BR33 (this water was, of course, originally from BR11 and was thus recycled). The injected water was at 80°C and had little gas and higher chloride than the 245°C water produced originally from BR11. Surprisingly, there were no changes observed in the enthalpy or chemistry of the BR11 discharge (Grant, 1982a). The water is presumably reheated as it passes through the reservoir, but the lack of chemical variation is unexplained.

BR34

BR34 was drilled in 1978 as an experimental shallow, cold, peripheral reinjection well and at the time of the injection tests was 400m deep. Water from BR2 was separated at atmospheric pressure, but not exposed to the air, and piped through an uninsulated pipeline nearly one (1) km long to BR34. Two 400m deep slim-hole monitor wells were drilled close to BR34; BRM2 is 45m to the north and BRM4 is 70m to the southeast. Water was injected at roughly 50°C at a rate of 160 tonnes/hour into BR34 for several months.

Quite different to the other reinjection tests, injectivity at BR34 declined spectacularly, and permeability of BRM2 and BRM4 also declined. Clearly silica was deposited within the BR34 wellbore and also far out into the formation. That this occurred at BR34 and not at the other sites despite the injected water also being supersaturated with silica in most of the other tests is probably due to the fact that injected water was reheated in time to prevent precipitation in the other tests (all of which were **into** high temperature formations).

Tracer injection into BR34 in December 1978 traveled at 0.6 m/hr to BRM 2 and 1.2 m/hr to BRM4. Although only about 4% of the tracer was recovered, it is estimated that 75% of the water airlifted from BRM2 and *508* of that from BRM4 originated from BR34 (McCabe, Barry and Manning, 1981).

There were no thermal effects observed in the BR34 test since the injected water and formation were both cold.

Wairakei

In 1982, the first reinjection tests have been performed at Wairakei, with water from WK218 being injected into WK220. However, some unintentional injection at Wairakei has been taking place for some time. In 1969, production in WK101 (**Fig.** 6 shows well locations) ceased after a downflow from a shallow feed zone at 360m (just below the casing shoe) to a deeper feed zone at 600m depth. WK107 ceased production in 1916 and a downflow of 160°C water was measured by spinner at a rate of 300 tonnesfhour. WK80 still produces steam from around 300m depth but has a downflow of 175°C water from 350m depth to 600m depth. Other wells in the northwest corner have failed similarly over the years and have been grouted up.

Extensive tracer testing in WK101, 107 and 80 was carried out in 1978 and 1979 (McCabe, Barry and Manning, 1980, 1981). In the three WK107 tests, the two deeper wells WK24 and WK48 rapidly returned 3.7% and 1.3% of the tracer respectively, with transit speeds of 22 m/hr and 7 m/hr respectively. The other wells monitored (67, 70, 68, 30, 83, 81, *55* and 108) showed returns between 0.1 and 0.3% with transit speeds **around** 1 m/hr. These results are summarized in Figure 6 from McCabe, **Barry** and Manning (1981), together with the WK101 **and** WK80 results. The results were reproduced over all three WK107 tracer injections (for those wells tested each time) including the third test which used Bromine-82 isotope instead of the Iodine-131 used in all others. Figure 7 from McCabe, Barry and Manning (1981) shows the WK24 results for **two** of the tests.

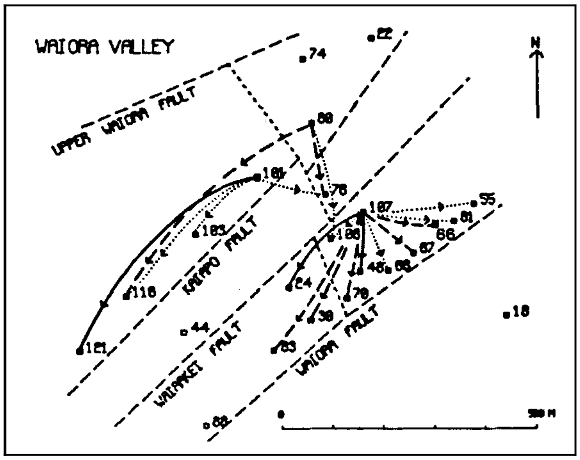

Figure 6: Tracer returns in the Waiora Valley section of Wairakei, from McCabe, Barry and Manning (1980)

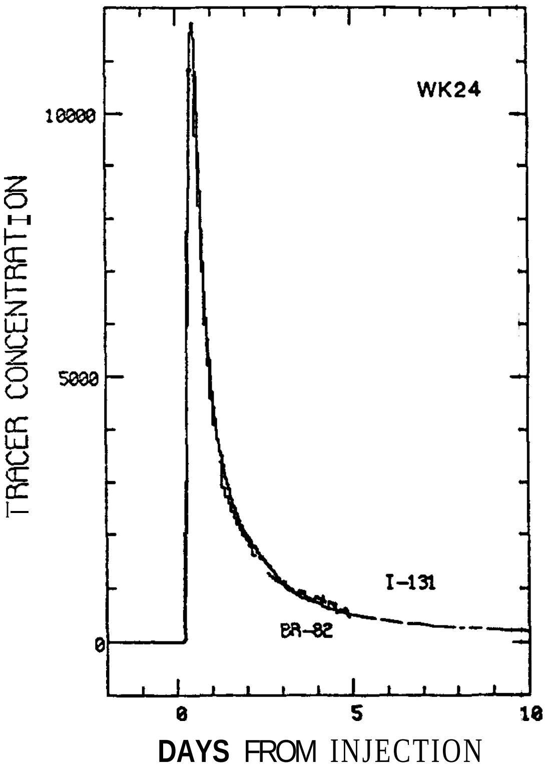

Figure 7: Tracer concentrations at WK24 due to injection into WK107. Two separate tests are with 1-131 and the other with Br-82, from McCabe, Barry and Manning (1981)

In 1980 WK107 was worked over and the offending upper feed zone was successfully sealed off. Surprisingly, after four years of accepting 300 tonnes/hour of 160°C water, the well again produced at its earlier temperature. There is some evidence (Grant 1982b) that WK48 experienced an enthalpy drop of around 40 kJ/kg and a wellhead pressure drop of 1 bar (100 kPa) in 1976. Other wells in the vicinity do also appear to be negatively affected to a small extent by the WK107 accident; however, the changes are only of similar magnitude to normal operating fluctuations and are thus difficult to recognize. For the same reason, there have been no clearly defined improvements since WK107 was repaired and placed back on production.

In the WK101 and Wk80 tests the rather startling return patterns show that injected water moves in complex paths (see Fig. 6). Tracer injected into WK101 arrived first at WK121 (the most distant) moving at 8 m/hr, second at Wk103 (the closest) moving at 1.3 m/hr and last at Wk116 (in a line between the other two) moving at 2 m/hr. Wk121 is a very deep well - the deepest at Wairakei - with 2250 m total depth, although it produces mainly from perforations at 975 m depth (still deeper than the usual 600 m depth in that area). WK121 received 6% of the tracer injected at WK101 despite being 500 m distant. It is not known whether WK121 has been affected by the WK101 downflow since it was not drilled until after 1969, but there is an unusual 215°C temperature inversion in the well. WK121 could perhaps be made productive if WK101 were repaired. During the WK80 injection, WK121 was not monitored as the separator installed to discharge it specially for the WK101 test had been removed. However, returns from WK80 to WK116 and WK76 were an order of magnitude larger than those from WK101 which leads to speculation as to what WK121 may have shown had it been monitored.

The flow of reinjected water at Wairakei is clearly within the faults although not necessarily by direct paths. The water from WK107 apparently moves down and to the southwest through the Wairakei fault, being recovered first at WK24 which intersects the fault at around 760 m. The Waiora fault meets the Wairakei fault at about 1000 m depth and the returns to WK48 (which intersects the Waiora fault at 760 m depth) and the other shallower and later-responding wells seem to be up the Waiora fault. This explains the roughly simultaneous arrival at all these wells (except for the deeper WK48).

summary

Reinjected water at Broadlands seems to move through the reservoir at speeds around 0.5 m/hour indicating that reservoir short-circuiting may not be a severe problem (tracer return speeds are similar to those observed at Otake in Japan - Horne, 1982). No thermal effects have been observed at neighboring wells, although it is clear that in some cases quite large percentages (up to 12%) of the reinjected water do break through. Reservoir enthalpy is reduced in the vicinity of the injection well as expected, but the extent of the depression is limited.

With the exception of BR34, injectivity increases as a result of temperature effects (BR13 and 23) pressure effects (BR30), or reduction in reservoir pressure (BR7 and 28). The loss of reservoir pressure caused by injection into two-phase conditions should be avoided as the resulting pressure sink will reduce production in the vicinity.

The speeds of underground fluid movement at Wairakei are as much as 20 times greater than those in Broadlands, indicating a greater potential for reservoir short circuiting during reinjection. The rapid pressure response across the field is a characteristic of Wairakei compared to Broadlands, although this difference is also attributable to the large gas content at Broadlands (and corresponding high compressibility).

JAPAN

Japan has a wide range of geothermal power systems, including vapor-dominated (Matsukawa), two-phase (Onikobe), and compressed liquids (Onuma, Kakkonda, Otake, and Hatchobaru (see Fig. 8).

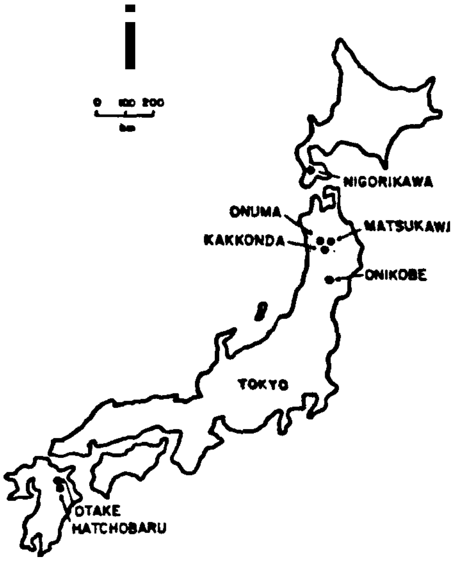

Figure 8. Geothermal Production Sites in Japan

TABLE 1: SUMMARY OF PRODUCTION AND REINJECTION IN JAPAN, SEPTEMBER 1980

	Station	Onikobe	Kakkonda	Onuma	Hatchobaru	Otake
	Capacity	25 Mw	50 Mw	10 Mw	55 Mw	12 Mw
	1980 Production	7.5 Mw	-40 Mw	7 Mw	55 Mw	12 Mw
Production	No. of wells	12	11	5	8	4
	Av. depth	300 m	1000 m	1600 m	1000 m	500 m
	Total steam	75 t/hr	380 t/hr	91 t/hr	400 t/hr	120 tfhr
	w.h.p.	200 kPa	686 kPa	300 kPa	481 kPa	304 kPa
Reinjection	no. of wells	1	15	4	14	8
	Av. depth	1000 m	700 m	800 m	1000 m	500 m
	Total flow	115 t/hr	2700 t/hr	360 t/hr	400 t/hr	680 tfhr
	Temperature	95°C	-160°C	95°C	60/95°C	95°C
	Pressure	0	540 kPa	0	0	0
	Configuration	side/below	mixed/above	side/above	side/equal	side/equal
	Tracer flow rate	--	n.a.	up to 4 m/hr	up to 80 m/hr	-0.3 m/hr
	Comments	Gas Interference	-	-	Silica Scaling	Accepts water from Hatchobaru 175 t/hr

All the liquid-dominated systems have single flash steam generation schemes, with the exception of Hatchobaru, which has a double-flash system. All except Matsukawa have total waste water reinjection schemes, necessitated primarily by environmental requirements. Several different reinjection configurations are in use, allowing an array of schemes to be evaluated. Each of the fields will be discussed separately in detail, but summary data for all five fields undergoing reinjection are listed in Table 1 for comparison purposes. Specific items of interest to this discussion are the quantity and temperature of the reinjected water, the reinjection strategy used, and the observed effects on production.

Onikobe

Onikobe geothermal station in the Tohoku district of the island of Honshu is operated by the Electric Power Development Company, Ltd. (EPDC), and has an installed capacity of 25 MW. Licensed capacity is 12.5 MW, and actual production in 1980 was at 7.5 MW. Onikobe is a very unusual field in that, at the targeted production depth of 1000 m, highly acidic water (pH 2.8) was intercepted. For this reason, a shallower, less acidic (pH 5) production horizon was tapped at 300 m. The lower productivity of this upper horizon (around 10 tonnes/hour steam flowrate per well compared to 20 to 30 tonnes/hour at 1000 m) is the reason for the reduced output from the station.

Production at Onikobe is from 12 wells at an average depth of 300 m, although one new well directionally drilled in 1980 produces pH 5 water from a 1000 m deep formation (presumably different to that with pH 2.8 water). At the turbine inlet pressure of 200 kPa (29 psig) the combined steam output from the wells is 75 tonnes/hour (20.8 kg/sec). Water produced, added to the waste water from the station, makes up a tottal of 115 tonnes/hour (31.9 kg/sec) that is reinjected into a single well at atmospheric pressure. This single reinjection well is located at one end of the field (see Fig. 9), and has its fluid exit points in the 1000 m deep, acidic portion of the reservoir. This represents the most desirable configuration proposed by Grant and Horne (1980) namely, a peripheral well, deeper than the production depth.

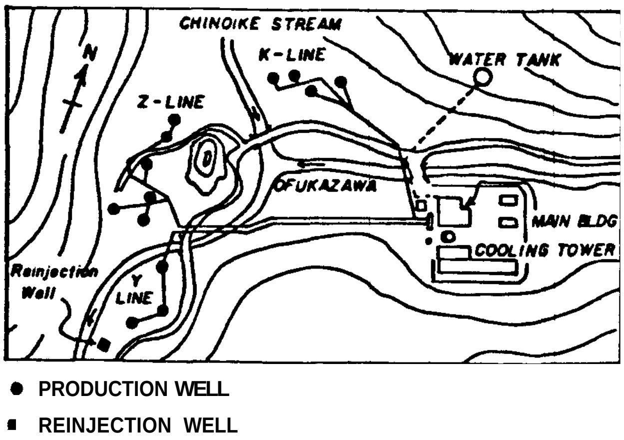

Figure 9. Sketch Map of Well Locations at Onikobe

The performance history of the Onikobe field shows a decrease in the steam output from the wells, but an increase in water output from about 60 tonnes/hour in 1975 to 120 tonnes/hour in 1980 (see Fig. 10). This effect may be due to the influx of colder water from the surface. It could also be due to the effects of reinjection. However, there has been no noticeable additional alteration in the thermal or pressure behavior of the field since reinjection commenced in 1978, and, in fact, the greatest increase in water production has been from "K" area, which is most distant from the re-injection site. On the other hand, there was a distinct rise in the nitrogen content of the non-condensable gas production in the months following the start of reinjection. This rise in nitrogen content (which was accompanied by a fall in CO_2) was attributed to the entrainment of air into the reinjection well (Amagai and Kawamura, personal communication, 1980). The reinjection wellhead consisted of a funnel arrangement into which three hot water pipelines exhausted. This arrangement was "boxed in" during 1980 to prevent air entrainment, and the nitrogen content of the producing wells has since declined. Similar transport of nitrogen has been observed at Hatchobaru (Hirowatari, personal communication, 1981).

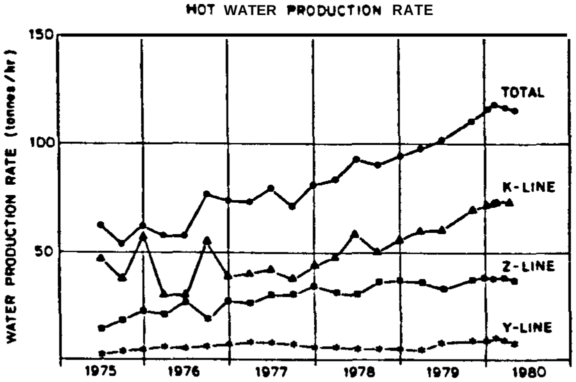

Figure 10. Changes in Hot Water Production Rate at Onikobe

It seems then at least the noncondensable gases are mobile between the two reservoir levels at 300 m and 1000 m at Onikobe. This indicates permeable connection between them in spite of the water in the two reservoirs being chemically very different. The fact that no thermal interference due to reinjection has been observed beyond the steady enthalpy decline already observed while a hydraulic connection clearly exists may be due either to the relatively short duration of injection, or to the fact that water is heated before reaching the production depth. In either case, there was no obvious "short-circuiting" in the Onikobe reservoir as of August 1980. Although further observation is necessary (EPDC is investigating the possibility of a tracer test), it currently appears that the "side and below" reinjection configuration at Onikobe is working successfully.

Kakkonda (Takinoue)

The newest geothermal power station in Japan, Kakkonda, is a 50 MW station operated by Japan Metals and Chemicals Co., Ltd. (JMC), and Tdhoku Electric Power Company. It has been producing since May of 1978.

The reinjection program at Kakkonda is unusual in Japan in that the hot water is reinjected at separator pressure rather than at atmospheric pressure, as is the case everywhere else in Japan. Kakkonda is also unusual in the very large quantities of water that are injected, the field enthalpy being rather low. The reinjection wells are "intermixed" with the production wells, but are somewhat shallower depth (around 700 m, compared to 1000 m for the production wells). Figure 11 shows the traces of the directiondlly drilled wells (JMC, 1978). Although the reinjection scheme could be broadly characterized to be "intermixed/above," there is in fact some degree of overlap between production and reinjection levels.

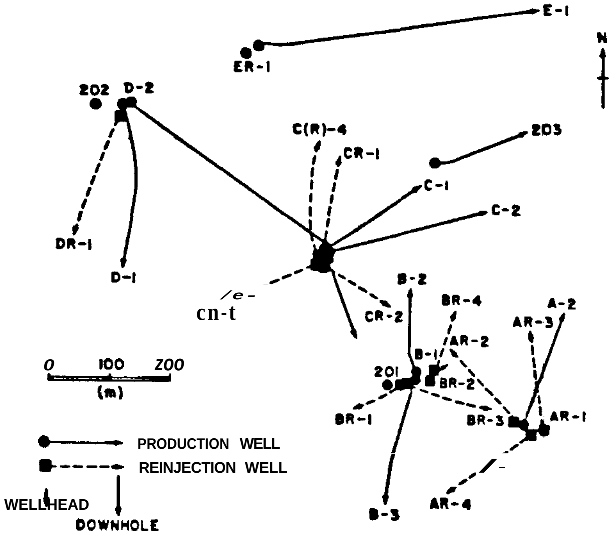

Figure 11. Sketch Map of Well Locations at Kakkonda

The very large quantity of water injected at Kakkonda (3000 tonnes/hour for 500 tonnes/hour of steam produced) represents a "worst case" for reservoir short-circuiting. Such short-circuiting has been clearly identified by tracer tests (Nakamura, 1981). Although station output remained essentially constant from startup (May 1978) until July 1979, after that time it declined rapidly from 50 MW in July 1979 to 37 MW in April 1981. Most producing wells maintained production or decreased only modestly during that period (see Fig. 12) but wells which had rapid tracer arrival times from four particular injection wells declined significantly in output even from the start of operations. Cessation of in-

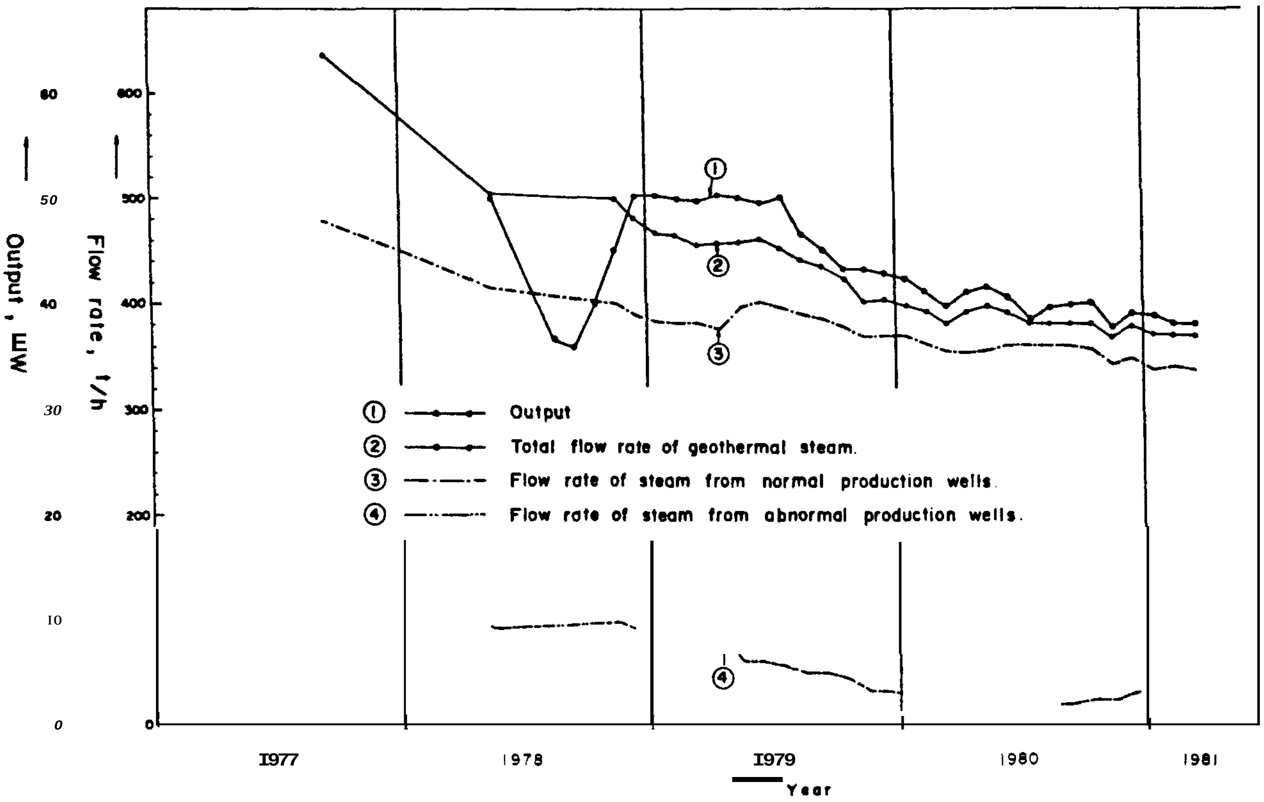

Figure 12. Changes in Total Output and Steam Production Rate at Kakkonda (from Nakamura, by permission of Geothermal Resources Council)

jection into those four particular wells resulted in a recovery of production to 41 MW by October 1981 (Nakamura, 1981).

Other than possible reservoir problems, injection at separator pressure and temperature seems to have avoided many of the deposition problems causing injectivity decline in several of the atmospheric reinjection schemes. This is in line with the high temperature reinjection experience in El Salvador (Einarsson, Vides, and Cuellar, 1975) where SiO_2 deposition was also successfully avoided. It has been suggested that pressurized reinjection might induce an earthquake in Japan; however, extensive monitoring at Kakkonda has shown no evidence of this (Di Pippo, 1980).

JMC is investigating the possibility of reinjection at a remote heat exchanger site, in combination with direct uses of the recovered heat.

Onuma

The Onuma geothermal field is the site of the third geothermal power station completed in Japan, and began production in 1973. The plant has a rated capacity of 10 MW, and was built and operated by the Mitsubishi Metal Corporation. Its output in 1980 was about 7 MW, down slightly from 7.7 MW in 1977. Water is reinjected on one side of the field only, at somewhat shallower depth than production (see Fig. 13). An earlier report on reinjection experience at Onuma by fto, Iubota, and Kurosawa (1977) indicated that pressure interference had occurred, in that reservoir pressures had been maintained. Water flowrates actually increased while steam flowrates remained the same indicating a net loss in producing enthalpy. Tracer injected into reinjection wells O-7(T) and O-7(R) was returned into wells O-6(R) and O-3(R)a at such a level that Ito et al. (1977) calculated an intervening permeability of 10 darcies, which is clearly a high permeability connection compared to the rest of the reservoir. In more recent times, the same two wells [O-6(R) and O-3(R)a] have shown a greater enthalpy loss than other production wells and steam production rate has declined (Koto, 1980). Examination of the subsurface locations of these two wells (many of the wells at Onuma are directionally drilled) shows than to be closer to reinjection wells O-7(T) and O-7(R) than the other producers.

Thus there is also evidence of "short-circuiting" during reinjection at Onuma, although to a lesser degree than Kakkonda. In spite of higher conductivity zones in the reservoir tracer return rates are an order of magnitude slower than at Kakkonda and it appears that reinjection and production coexist fairly successfully, provided wells are not too closely sited. Mitsubishi Metal Corporation is currently drilling exploratory wells 1-2 km north of the power station in search of a more distant reinjection site.

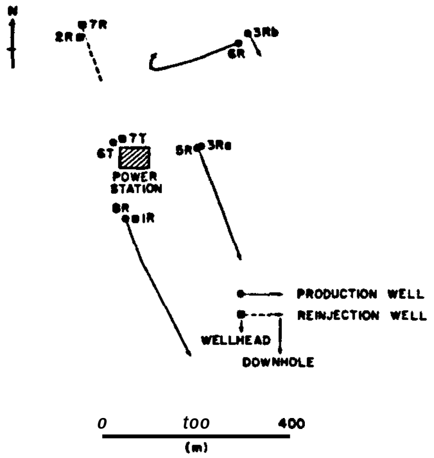

Figure 13. Sketch Map of Well Locations at Onuma

Hatchobaru

Hatchobaru geothermal field in the southern island of Kyushu has an installed capacity of 55 MW, and is owned and operated by the Kyushu Electric Power Co., Inc. The plant was opened at approximately half capacity in 1977, and reached full capacity only during 1980; obtaining a sufficient number of production and reinjection wells was partly responsible for the delay. The station is unique in Japan in that it uses a double stage flash system that, in itself, precludes the reinjection of waste water at a pressure as high as that at Kakkonda. The reinjection and production wells are arranged roughly in a "side-by-side" configuration (Fig. 14) with reinjection in the northwest and production in the southeast. Reinjection and production depths are more or less equivalent. This rather unusual arrangement was necessary simply because no other permeable level was located (Hayashi, Mimura, and Yamasaki, 1978).

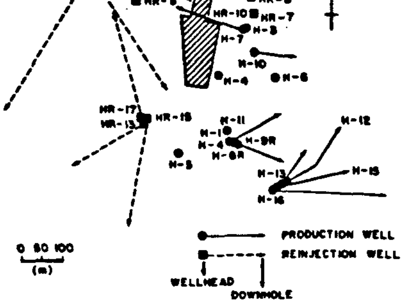

Figure 14. Sketch Map of Well Locations at Hatchobaru

TABLE 2: TRACER RETURNS IN HATCHOBARU TESTS OCTOBER - DECEMBER 1979
(Kyushu Electric Power Co., unpublished data)

Injected Well	Producing Well	Producing Rate (Tonnes/hr)	Speed of Tracer Movement (meters/hr)
HR-17	H-7	127	78
	H-4	140	76
	11-13	40	58
	H-3	n.a.	16
	11-14	126	
	H-10	75	
H-6	11-14	126	IS
	H-7	127	29
	H-4	140	8
	11-13	40	1
H-9R	11-13	40	62
	H-7	127	
	H-4	140	
H-3**	H-6	n.a.	33.8
	R-1	n.a.	9.0
	P-4	n.a.	6.1

(Injection rates: HR-17, 350 tonnes/hr; H-6, 40 tonnes/hr; H-9R, 70 tonnes/hr)

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*Secondary return only

**Earlier test reported by Hayashi, Mimura, and Yamasaki (1978)

Extensive tracer tests at Hatchobaru by Kyushu Electric Power Co. have indicated strong connectivity between some wells with actual speed of tracer movement in the reservoir as high as 80 m/hour, with strong returns over distances as far as 600 m. Table 2 shows the rates of return for the three tracer injection tests. Production wells H-4 and H-7, which both showed tracer returns in all three of the tests, have since shown a decline in two-phase flowrate, particularly H-4 which has now ceased production altogether.

Another problem with reinjection at Hatchobaru has been loss of injectivity, possibly due to silica deposition since the hot water is injected at atmospheric pressure and air is entrained in some of the older wellhead separator configurations. In order to achieve sufficient injection capacity to maintain 55 MW of Electrical generation and to avoid thermal interference by reinjected water, 175 tonnes/hour of the 645 tonnes/hour of waste water are exported to Otake and injected there. Kyushu Electric Power Co. has successfully identified possible reservoir short-circuiting problems using the tracer tests and has avoided the problems by injection at a remote site (Yoshida, 1980). Interestingly, tracer tests at Hatchobaru are conducted extremely economically using fluorescein dye. Although the more expensive Potassium Iodide tracer has been used there it was determined that fluorescein could easily provide data on first arrival times which are considered the most important parameters.

Otake

Otake power station was the first liquid-dominated geothermal field under production in Japan, and the second such in the world. Owned and operated by the Kyushu Electric Power Co., Inc., it has a capacity of 12.5 MW, and has been operating since 1967. Originally, the waste water was rejected to a pond; however, reinjection was started in 1972 to avoid chemical pollution due to the arsenic content of the water. Initially, an improvement of recovery was observed (Kubota and Aosaki, 1975) indicating the support of reservoir pressures, but by 1975 this improvement ceased, and well 0-7 (see Fig. 15) ceased production due to a loss in enthalpy (Onodera and Fukuda, 1976) indicating thermal interference. Since that time, reservoir output has been declining at about the same rate (6% per year) as prior to reinjection (Fig. 16). In 1979 and 1980, production was raised to the installed capacity by the drilling of new production wells 0-14 and 0-15, and reinjection increased to a total of 663 tonnes/hour including 175 tonnes/hour of waste water piped from Hatchobaru.

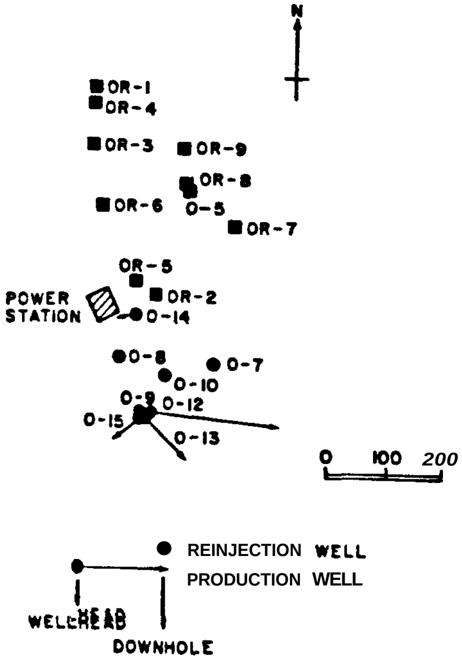

Figure 15. Sketch Map of Well Locations at Otake

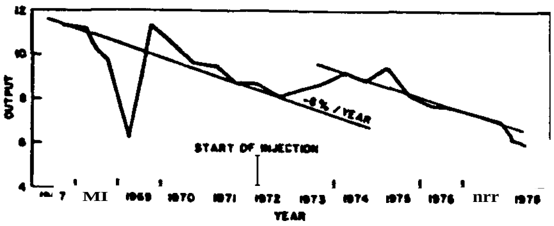

Figure 16. Changes in Total Electrical Output at Otake

Despite the demise of well 0-7, reinjection appears to be very successful from a reservoir standpoint. Tracer tests performed at Otake by Kyushu Electric Power Company in 1976 showed tracer permeation speeds on the order of 0.3 m/hour (Hayashi, Mimura, and Yamasaki, 1978) which is two to three <u>orders of magnitude</u> smaller than observed in Hatchobaru. Tracer was injected into reinjection well OR-2 (see Fig. 15), and was detected in wells 0-8, 0-9, and 0-10 within about 600 hours. Tracer returns in the Hatchobaru tests were detected as early as two hours after injection. It appears that inter-well connectivity at Otake is not high, and in fact, wells 0-9 and 0-10 continue to produce after seven years of reinjection into well OR-2, which is 203 meters distant from 0-9, and 140 meters distant from well 0-10.

Otake does have a loss of injectivity problem similar to that at Hatchobaru, probably attributable to the supersaturated silica conditions at atmospheric pressure. Kyushu Electric Power Company is conducting extensive waste water treatment studies in attempts both to remove silica to avoid injectivity problems and to remove arsenic in order to be able to avoid reinjection altogether.

Summary

In cases where inter-well flows do occur in Japan, the resulting thermal interference can be greatly detrimental to the performance of the producing well. Specific instances of wells thermally influenced (mentioned in this paper) include well 0-7 at Otake, wells H-4 and H-7 in Hatchobaru, wells O-6(R) and O-3(R)a at Onuma and several unnamed wells at Kakkonda. On the other hand, the hydraulic interference may be beneficial in providing pressure support. The problem is one of removing the reinjection well to such a distance that the cooler reinjected water is reheated before arriving at the producing well, Previous estimates of the "safe distance" have varied. Hayashi, Mimura, and Yamasaki, (1978) suggested 150 m, which is apparently "safe" for Otake, but not for Hatchobaru.

Maintenance of reservoir performance by reinjection may indeed be beneficial; however, in Japan, only a single example of performance improvement has been observed (at Otake). On the other hand, three examples of reduction in performance by thermal interference have been observed (Hatchobaru, Kakkonda, and Onuma). If priorities are to be allocated, in highly fractured systems it appears to be expedient to avoid thermal interaction even at the cost of losing hydraulic support. One attractive method of achieving this is to inject at a neighboring but separate site.

Tracer testing has been used to great advantage in Japan and has helped identify ana overcome some of the reinjection breakthrough problems - particularly at Kakkonda. Both the results and the tracer tests themselves contrast with those described earlier in New Zealand. Radioactive tracers were used exclusively in New Zealand whereas chemical tracers were used in Japan. In addition, the percentages of tracer recovered in Japan were much higher - up to 35% (Sunshine Project, 1980), and speeds of underground movement were much faster - as high as 80 m/hr (see Table 2).

Loss of injectivity has proved a difficulty in Make and Hatchobaru. It is not clear why the silica supersaturation prwoes problematic in Kyushu but not in other fields (New Zealand for example), but smaller flowrate seems to be a distinguishing difference. Kakkonda has few injectivity problems with its pressurized higher temperature reinjection.

EL SALVADOR - Ahuachapan

El Salvador generates a substantial percentage of its electricity requirements fran geothermal energy at the 95 MW_e power station at Ahuachapan (Cuellar, Choussy and Escobar, 1981). Well depths are between 600 and 1000 meters depth and usually have an enthalpy of between 1000 and 1200 kJ/kg. Wells Ah-6 and Ah-26 appear to have greater fractions of steam in their feeds, and have enthalpies around 1500 kJ/kg. A well map is shown in Figure 17.

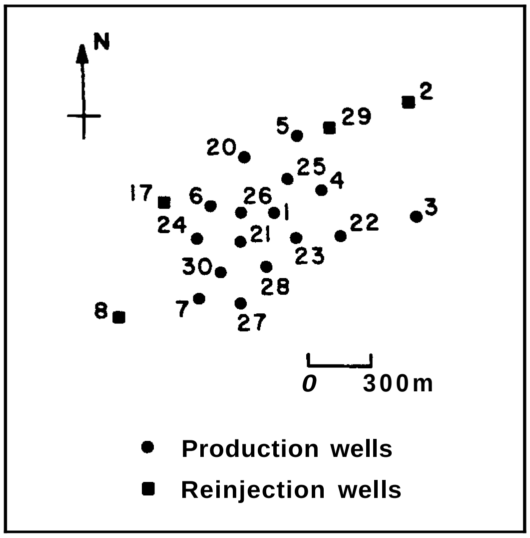

Figure 17. Sketch Map of Well Locations at Ahuachapan

A reinjection program commenced in 1976 and presently 40% of the produced fluid is reinjected into wells Ah-2, 8, 17 and 29. Wells Ah-2 and Ah-8 are drilled away from the production zone, but Ah-29 and more particularly Ah-17 are close to the production wells. The water is injected at separator pressure (around 540 kPa gauge) at a temperature around 160°C. Keeping the temperature high has apparently avoided problems of silica deposition and there is some indication that the injectivity of Ah-17 increase$. At a pressure of 590 kPa in October 1976 Ah-17 accepted 167.1 tonnes/hour of water, but by December 1977 accepted 473.2 tonnes/hour at a pressure of 610 kPa (Cuellar, Choussy and Escobar, 1981). There was also evidence of improvement of injectivity in early reinjection tests into Ah-5 in 1971 (Einarsson, Vides and Cuellar, 1975).

The paths of the injected water have been determined by repetitive chloride analyses of the production wells. The water injected into Ah-29 seems to mwe both to the east and also towards the center of the field. On the other hand water injected into Ah-17 mwes towards the center of the field. In 1971 a tritium tracer injection into well Ah-5 (which is a production well but was used experimentally for reinjection) indicated returns to wells Ah-1, Ah-6 and Ah-7. Well Ah-1 responded within two days, indicating a speed of tracer flow around 8 m/hour, but wells Ah-6 and Ah-7 did not respond for several weeks and after three months had still not reached a peak of tritium concentration. There is, therefore, clear evidence of channeling in the reservoir, but not uniformly.

The effects of reinjection have been a general support of reservoir pressures (Cuellar, Choussy and Escobar, 1981) although the decrease in pressure decline may also be due to transition to two-phase conditions in the reservoir (Grant, 1980c). Temperature effects have been more difficult to recognize; Ah-5 was thermally reduced by the reinjection in 1971, but regained its earlier discharge enthalpy after roughly the same time as the duration of the injection tests. Since full scale reinjection has been undertaken, there are some indications of thermal influence at wells Ah-6 and Ah-24 due to reinjection into Ah-17, although this effect could also be attributed to boiling in that vicinity since the temperature in Ah-6 also decreased prior to reinjection. There is some suggestion also of a temperature effect on Ah-30 due to reinjection into Ah-8 (Aumento, Liguori, Choussy, Santana, Campos and Escobar, 1982).

summary

Loss of injectivity has not been a problem in El Salvador, and reinjection seems generally to have supported field performance. Channeling has been seen to occur in the field, and there are indications that more recently thermal breakthrough has occurred. Tracer tests and repeated chemical sampling shows the reinjected water to be moving into the production area fran wells Ah-17 and Ah-29.

THE PHILIPPINES

The Republic of the Philippines has undertaken a very aggressive geothermal development policy since the early 1970's and has rapidly risen to be the largest producer of electrical power from liquid-dominated geothermal resources in the world.

There are volcanoes and geothermal fields distributed throughout the many islands of the Philippines and developnent is continuing at a rapid pace. Of the fields in production or under construction, Mak-Ban in Luzon and Tongonan in Leyte have undergone reinjection. At 220 MW_e, Mak-Ban is the largest geothermal station in the world undergoing reinjection of wastewater. Reinjection is into 14 wells, most of them in the periphery of the producing area (Raasch, 1980). By December of 1980 over 15 million tonnes of wastewater had been injected without any observable negative effects (Raasch, 1980). No other published results of this reinjection scheme could be located, so Mak-Ban has not been included in this comparative summary,

Tongonan

The Tongonan geothermal field is situated in the Bao river valley on the island of Leyte. Exploration drilling began in 1973 and the first deep well (401) was completed in January 1977 to a depth of 1942 m in the Mahiao sector of the reservoir. The maximum downhole temperature was 324°C and the well was connected to a 3 MW_e back-pressure turbine in July 1977 to generate electricity for the project and for the city of Ormoc 20 km away. Since that time, around 45 wells have been drilled at Tongonan, and a 112 MW_e power station will enter service in 1982. Discharge enthalpies vary from 1200 to 2500 kJ/kg and most wells are substantial producers (around 72 tonnes/hour of separated steam).

Reinjection of the wastewater from the station seems the most viable alternative for disposal as the exhaust rate will be around 1150 tonnes/hour of 160°C water (Dobbie and Menzies, 1979a, b). The reservoir fluid contains approximately 12,000 ppm dissolved solids and after flashing and separation the reinjected water will have higher concentrations. Reinjection testing has been carried out since February 1978, with well 4R1 accepting wastewater from the 3 MW plant (Dobbie and Menzies, 1979a), and an injection experiment into well 2R2 was carried out for five months in 1981 (Sarit, 1981). A third test was also carried out in which water was injected into well 105 (PNOC, 1981). The results of these three injections will be discussed here. A map of well locations is shown in Figure 18.

4R1

Wastewater at 170°C was injected under pressure from the 3 MW_e plant into 4R1 from February 1978 until June 1980, then from September 1981 until the present. Well 401 supplied steam to the plant until January 1979, after which well 404 was used. In March of 1981 the station steam supply was again switched back to well 401. Injectivity of well 4R1 was found to increase with cumulative volume injected, in a manner similar to that found in Broadlands wells in New Zealand. This is shown in Figure 1 of Dobbie and Menzies (1979a). In addition, there was a drop in downhole pressure during the 401 injection, although this could be due to the reduction in water injection rate as 401 discharge enthalpy increased during production.

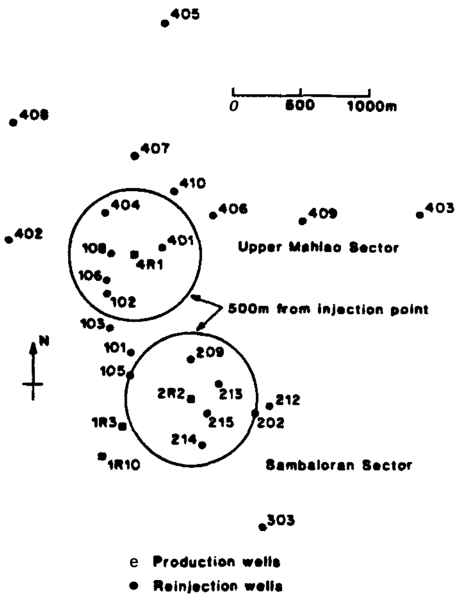

Figure 18. Tongonan Geothermal Field

In June 1981 Iodine-131 tracer was injected into well 4R1 (PNOC, 1981), and was recovered at wells 404, 401 and 108. Each return was characterized by two or more peaks, and a total of 16.29% of the tracer was recovered. A total of 11.450 was recovered in 404, with the speed of arrival of the first peak around 57 m/hour. A total of 2.849 was recovered in 401, with the speed of arrival of the first peak around 30 m/hour. Well 108 received about 2% of the tracer with a first peak arriving at around 22 m/hour (PNOC, 1981).

With such large and rapid tracer returns and the five years injection into 4R1, it is interesting to examine the effects on the reservoir performance. As mentioned earlier well 401 increased in enthalpy as it was being produaed, and strangely also while it was shut in between January 1979 and March 1981. When restarted in March 1981, well 401 had almost doubled its flowrate and, when back pressured to supply the 36 tonnes/hour of separated steam to the power plant, had a wellhead pressure of 5000 kPa. Since being reconnected to the plant both enthalpy and wellhead pressure have been slowly reducing. It is difficult to find an explanation of this behavior consistent with any known effects of reinjection, and the performance changes are attributed to feed zone interactions within the wellbore (which are a common confusing influence in fractured systems and particularly so at Tongonan).

Well 404 has exhibited a more normal response, and experienced an enthalpy decline during reinjection. This is consistent with the results of the tracer test.

2R2

In the Sambaloran sector test in the first part of 1981, more than 800,000 tonnes of 160°C water were reinjected into 2R2 from wells 202, 209, 212, 213 and 214. The five production wells were not produced simultaneously but one, two or three (and on one occasion four) at a time (Sarit, 1981). The average flowrate throughout the testing was around 200 tonnes/hour. Analysis of two-rate transient pressure tests during reinjection and fall-off tests after reinjection did not indicate any change in permeability of 2R2 (Sarit, 1981).

Sodine-131 tracer was injected into 2R2 on 28 March 1981 and again on 20 June 1981 (PNOC, 1981). In the March test wells 202, 209, 212, 213, 214, 303 and 101 were monitored, and positive returns were measured in wells 202, 209, 212 and 213. In this test the tracer was released into the upper feed zone (400 m) in 2R2. In the June test, the tracer was released into the lower feed zone (1300 m) in 2R2, and wells 213 and 214 were monitored.

net recovery at 213 was 0.34% in the June test, with peak arrival at 19 hours (around 10 m/hour), whereas, in the March test 1.68% of the tracer was recovered but the first peak did not arrive until 4.4 days (around 2 m/hour). In the March test, all of the indicated underground tracer arrival speeds were of the order 1-2 m/hour.

No published observations of the reservoir effects of this reinjection were found.

105

The 105 injection mentioned in Dobbie and Menzies (1979b) was intended to investigate the effects of a higher degree of silica supersaturation. Well 103 was produced and back pressured to reduce separator pressure and temperature. As a consequence only around 20 tonnes/hour of 120°C water was injected into 105. In order to accept water at such low pressure, well 105 was quenched with river water for almost as long as the reinjection duration, so in fact the injection test was much larger than is outwardly apparent. When well 103 water was then injected into 105, injectivity declined in 105 within one month. The well recovered on subsequent discharge, however, and after a second, short river water quench accepted water from 101 and 103 together at a larger flowrate. In this second test injectivity decline was slower, indicating an inverse dependence on flowrate.

No tracer test was carried out at 105 and no influence on the production wells observed.

Summary

Underground fluid movements in Tongonan geothermal reservoir are at rates as large as those in Kakkonda and Hatchobaru in Japan, and the potential for premature thermal breakthrough, therefore, seems high. Experience with well 404 also appears to indicate this. Interestingly tracer returns seem faster in the developed sector of the reservoir than the sector under testing, although the amount of data available is insufficient to assert this with confidence. The experience of the two tracer tests into 2R2 emphasizes the effects of fractures in reinjected water breakthrough, since tracer returns were distinctly different when injected into different fractures intersecting the same well.

Injectivity at Tongonan does not seem to be a problem when reinjection is at separator pressure, but deposition occurs at lower pressures. Increasing flowrate seems beneficial in reducing silica deposition. This experience is very similar to that observed at Broadlands.

CONCLUSIONS

1. Loss of injectivity due to silica deposition has been successfully avoided in New Zealand, Japan, El Salvador and the Philippines in cases where reinjection is under separator pressure and temperatures in excess of 150°C. Lowering the temperature below 100°C has produced injectivity losses in several places, but not always. Injecting at high rates into hot formations seems beneficial, presumably because the kinetics of the silica deposition are sufficiently slow to allow temperature and dilution to undersaturate the water before nucleation occurs.

2. In most places, injectivities have increased with injection, either by the opening of fractures due to thermal contraction or by pressure inflation of the fractures.

3. Injection of cooler water into two-phase reservoirs has in some cases produced a reduction in reservoir pressure. This is to be avoided in the design of a reinjection scheme.

4. Tracer testing has shown that underground fluid movement can be substantially altered by reinjection.

5. Collating all tracer experiments from both producing and nonproducing fields suggests that nonproducing fields tend to show slower rates of tracer return. The body of data is not yet large enough to confirm this, but if true the prediction of reinjection breakthroughs from pre-production tests could be a serious difficulty.

6. Chemical, short-lived radioactive and long-lived radioactive tracers have all been successfully used in fractured geothermal

reservoirs. It is worth noting that radioactive decay and chemical reaction would probably render the fluorescent dye, halide ion and short-lived radioactive tracers useless were it not for the very rapid recoveries seen in fractured systems.

7. There appears to be a correlation between tracer return rates and subsequent thermal breakthrough in the field.

8. Reinjected water tends to follow faults, but not necessarily in direct paths. There is a tendency for water to move downwards but this can be overcome by vigorous production close by.

ACKNOWLEDGEMENTS

The data in this paper have been collected from a very large number of sources and a great many people. Listing individuals' names would be very lengthy, but I would like to acknowledge the help of the following organizations:

(New Zealand) University of Auckland, Ministry of Works and Developnent, Department of Scientific and Industrial Research - Applied Mathematics Division and Institute of Nuclear Sciences, and Kingston, Reynolds, Thom and Allardice, Ltd.; (Japan) University of Tokyo, Kyushu University, Electric Power Developnent Co., Ltd., Japan Metals and Chemicals Co., Ltd., Mitsubishi Metal Corporation, Nippon Steel Corporation, Kyushu Electric Power Co., Inc., West Japan Engineering Consultants, Inc., and New Energy Development Organization; (Italy) ELC-Electroconsult; (The Philippines) Philippine National Oil Company and Philippine Geothermal, Inc.; (U.S.A.) Department of Energy and Union Oil Company. This paper was written under the auspices of the Stanford Geothermal Program which is funded by the U.S. Department of Energy Contract Number DE-AT03-80SF11459.

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