

A Review of Worldwide Experience of Reinjection in Geothermal Fields

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A REVIEW OF WORLDWIDE EXPERIENCE OF REINJECTION IN GEOTHERMAL FIELDS

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SUMMARY – Worldwide experiences of reinjection in 92 electric-power producing geothermal fields are reviewed. The study shows that: a reinjection plan should be developed as early as possible and it should be flexible i.e. it is likely to change with time. The optimum reinjection strategy for liquid dominated systems (hot water, low enthalpy two-phase, medium enthalpy two-phase) is likely to involve a mix of infield and outfield injection with the exact details dependent on the type of system and the geological structure. The infield reinjection provides pressure support and thus reduces drawdown and the potential for subsidence, whereas outfield reinjection reduces the risk of cold water returning to the production area. Deep reinjection reduces the risk of groundwater contamination and ground surface inflation. The proportion of infield to outfield reinjection their location (deep or shallow) is case specific and typically the infield reinjection rate will vary with time as part of the steam field management strategy.

1- INTRODUCTION

1.1 Classification of geothermal systems

The effect of injection on production depends on the structure of the individual system but there are some generic differences depending on the thermodynamic state of the geothermal system. In this review the following five categories are considered:

1. Hot water systems
2. Two-phase, low-enthalpy systems
3. Two-phase, medium-enthalpy systems
4. Two-phase, high-enthalpy systems
5. Two-phase, vapour-dominated systems

The criteria used for defining these categories are shown in Table 1.1. They are not rigid criteria. For example some wells in medium enthalpy systems may have discharge enthalpies greater than 1500kJ/kg. Similarly within a single geothermal system there may be distinct zones of different types. For example at Wairakei (New Zealand) there is a shallow vapour-dominated zone in a predominantly low enthalpy system.

1.2 Location of injection wells

The location of injection wells relative to production wells is probably the most important issue in the design of a reinjection system. In this review *infield reinjection* refers to reinjection wells located close to the production wells and within the hot part of system – say within the resistivity boundary. *Outfield reinjection* refers to the reinjection wells further away from the production wells and outside the hot part of system. Unfortunately these definitions are not precise and distances cannot be given definitively.

Some authors (SKM, 2004) have attempted to define *infield reinjection* and *outfield reinjection* in terms of how well the injection wells and

production wells are connected, measured by pressure communication. However this classification requires information that is not usually available, particularly before the injection wells are drilled, and is therefore not practically useful.

Table 1.1 Categories of geothermal systems

Category	Temperature (T)	Production Enthalpy (h)
Hot water	$T < 220^{\circ}\text{C}$	$h < 943 \text{ kJ/kg}$
Two-phase, low-enthalpy	$220^{\circ}\text{C} < T < 250^{\circ}\text{C}$	$943 \text{ kJ/kg} < h < 1100 \text{ kJ/kg}$
Two-phase, medium-enthalpy	$250^{\circ}\text{C} < T < 300^{\circ}\text{C}$	$1100 \text{ kJ/kg} < h < 1500 \text{ kJ/kg}$
Two-phase, high enthalpy	$250^{\circ}\text{C} < T < 330^{\circ}\text{C}$	$1500 \text{ kJ/kg} < h < 2600 \text{ kJ/kg}$
Two-phase, vapour-dominated	$250^{\circ}\text{C} < T < 330^{\circ}\text{C}$	$2600 \text{ kJ/kg} < h < 2800 \text{ kJ/kg}$

1.3 Hotwater Systems

In these systems no boiling occurs before or after production commences. Thus large pressure gradients must be set up to move fluid towards the production wells. Without any injection the pressure will continue to decline until the induced recharge from above, from below and laterally matches the overall production rate. In many cases, without injection, the pressure will drop too low to allow the production wells to continue operation. Injection assists by providing an extra mass flow and by boosting pressures. From this perspective, it is desirable to have infield injection with injection wells close to production wells in such systems. However, there is a fundamental tension between this beneficial pressure maintenance effect and thermal breakthrough (when the cool injected water reaches the production wells). In some fields, particularly

those with a few large faults, thermal breakthrough has occurred rapidly and injection has been moved further out, e.g. Brady, USA (Krieger and Sponsler, 2002).

1.4 Two-phase, Low-Enthalpy Systems.

These systems are quite similar to the medium-enthalpy systems discussed below, except for their permeability. Low-enthalpy systems are typically much more generally fractured with larger permeability. Thus when production begins, the pressure does not drop as much and less boiling occurs. Hence production enthalpies are lower - typically at or not much above the enthalpy of hot water at the reservoir temperature.

There is not necessarily a permeability boundary around the whole edge of the hot reservoir, and cold recharge from the sides of the reservoir can easily flow into it from some directions. Typically, vertical permeabilities are also high. As a result, cold recharge may flow down into the reservoir from above or extra hot recharge may flow into the reservoir from below. The balance between hot and cold recharge varies from one system to the next. The common experience of infield injection in this type of geothermal field is that it has caused degradation of the resource by thermal breakthrough and injection has been moved outfield, e.g. Miravalles (Gonzalez-Vargas et al., 2005), Ahuachapán (Steingrímsson et al., 1991.).

1.5 Two-phase Medium-Enthalpy Systems.

In their pre-exploitation or natural state these systems contain all, or mostly, very hot water (i.e. the boiling zones are non-existent or small). However, when production wells are drilled, at least some of them discharge at medium enthalpies (usually in the range 1100 – 1500 kJ/kg). This is because boiling occurs at the feed zones of the wells, caused by large pressure drops. This situation is in turn caused by low reservoir permeability, often resulting from a few large fractures within a “tight” rock matrix.

The permeability in the rock surrounding the hot reservoir in such systems may be similar to that inside the reservoir, i.e. there is not necessarily any permeability contrast between the inside (the hot part) and outside (the cold part) of the reservoir.

The distinguishing feature between this type of system and the low-enthalpy liquid-dominated systems discussed in the previous section is the level of fracturing. The medium enthalpy version (e.g. Mokai) typically has a few major fractures whereas the low enthalpy versions (e.g. Wairakei) have more general fracturing and more widely spread permeability.

In two-phase medium enthalpy systems, the boiling zones that develop as a result of production are typically localised and have a high steam fraction. The steam fraction may increase during production, and in some cases a localised vapour-dominated zone may develop. In low enthalpy liquid-dominated systems, by comparison, the boiling zones are large in extent and are “wet”, i.e. they have a low steam fraction.

The large pressure drop at production wells and the boiling induced in the reservoir are not undesirable effects from a reservoir engineering point of view. A medium enthalpy mixture of water and steam is desirable because the conversion of thermal energy to electricity is more efficient and less separated water has to be dealt with. The drop in reservoir pressure may result in some subsidence (Bodvarsson and Stefánsson, 1989), a reduction in surface flows in liquid features and an increased surface heat flow, mainly from steam, through the surface at some locations.

The pressure drop in the reservoir near the production wells is in practice buffered by the boiling process. The pressure declines rapidly until boiling occurs, and then the pressure declines more slowly. It tracks down the boiling curve following the temperature decline resulting from two processes:

- The heat extracted from the rock matrix boils off the water, turning it into steam.
- The cool recharge (mainly water rather than steam) is attracted to the low-pressure zone both from the top and the sides of the reservoir.

In some cases, hot deep recharge offsets the cool recharge or even exceeds the cool recharge, depending on the balance between lateral and vertical permeabilities.

In two phase medium-enthalpy systems injecting cold water into the production zone will cause faster cooling of the production wells. In some cases, it may even suppress boiling and cause the production enthalpy to drop to that of hot water. This type of system does not run out of water, as is often the case for vapour-dominated systems. Also, these systems do not suffer from excessive pressure decline and do not require pressure maintenance, as can be the case for hot water systems. Therefore, from a reservoir engineering perspective there is no reason to inject infield in two phase medium-enthalpy geothermal systems. Experience at a number of fields supports this statement. Often injection in two-phase medium-enthalpy geothermal systems has resulted in adverse thermal breakthrough and a consequent move of injection outfield, e.g. Cerro Prieto (Lippmann et al., 2004), Tiwi (Sugiaman et al., 2004).

1.6 Two-phase, high-enthalpy

These systems are very similar to the medium-enthalpy category discussed above. They also consist of few major fractures in a low permeability matrix but in this case the volume and/or the permeability of the fractures are somewhat smaller and the boiling zones surrounding the production wells are dryer and thus the production enthalpies are in a higher range, say 1500 – 2600 kJ/kg. In this case natural recharge is limited by low permeability and some infield reinjection may be beneficial.

1.7 Two-phase, vapour-dominated

As the pressure decreases in this type of geothermal system during production, more and more of the immobile water boils to form steam which then flows towards the production wells. By their very nature, vapour-dominated two-phase systems have low permeability in the reservoir zone and very low permeability surrounding the reservoir. If this were not the case, cold water would flow into the low-pressure vapour-dominated reservoir from the surrounding cool rock. Thus the water in a vapour-dominated reservoir is not replenished by natural recharge and, after some years of production, parts of the reservoir may run out of immobile water and become superheated (i.e. the temperature of the steam is above the boiling point). In this case it is beneficial to inject water directly above the depleted reservoir and close to the production wells. In some cases, extra water as well as the steam condensate has been injected. This strategy has been successfully followed at, for example, The Geysers in California (Goyal, 1998), Larderello in Italy (Cappetti and Ceppatelli, 2005).

1.8 General issues

The design of an injection strategy for a geothermal system is a complex problem and several parameters need to be considered (Stefanson, 1997), for example: disposal of waste fluid, cost, reservoir temperature - thermal breakthrough, reservoir pressure - production decline, temperature of injected fluid, silica scaling, chemistry changes in reservoir fluid, subsidence and the selection of injection locations.

2. SUMMARY AND CONCLUSIONS

2.1 Information Available

Reports and articles, available in the open literature, on 92 geothermal fields have been reviewed (Kaya et al. (2007)). In each case we were seeking information about the total production MWe, total mass production, average production enthalpy, location and amount of reinjection and any problems associated with

production and reinjection. In many cases the information available is incomplete and the summary plots given below are based on fewer than 92 fields.

Figure 2.1 presents the data in pie-chart form for total energy production (Fig. 2.1a) and bar chart form for mass production per MWe (Fig. 2.1b) for each type of geothermal system. According to the Figure 2.1a currently half of the geothermal power comes from the combination of two-phase high-enthalpy systems and two-phase vapour-dominated systems. Two-phase medium enthalpy-systems also have a significant contribution compared with low-enthalpy and hot water systems. Since they contain a lower energy density than high- and medium-enthalpy systems, hot water and two-phase low-enthalpy systems require higher rates of mass per unit MWe of power (Figure 2.1b). It should be noted that because of the incompleteness of the information Figure 2.1a represents the data from only 79 fields out of the 92 total (93.7% according to energy production) and Figure 2.1b represents data from only 59 fields (84.7% according to energy production).

Figure 2.2a and Figure 2.2b presents the reinjection data in pie-chart form for total reinjection and bar chart form for reinjected mass per MWe, respectively, for each type of geothermal system. According to the available data, shown in Figure 2.2a, as expected the hot water and two-phase, low-enthalpy systems inject large amounts of water while two-phase vapour-dominated systems have the lowest percentage of total reinjection. For the contribution of vapour-dominated systems to Figure 2.2a and 2.2b only condensate reinjection has been considered. Additional surface water reinjection (for the fields Darajat, Larderello, The Geysers) has not been included in the charts.

Because of the lack of information available about the amount of reinjection in many of the fields among the 92 considered Figure 2.2 represents the data from only 40 fields (74.6% according to energy production).

Figure 2.3 presents mass production per MWe generated for the individual fields, grouped according to their enthalpy classification. The results are affected somewhat by the individual characteristics of the field but the general trends are clear. The fields that produce high enthalpy fluids require less fluid per MWe.

Figure 2.4 shows the mass reinjection for each fields per MWe produced, again grouped according to the enthalpy classification. This figure includes the additional surface water reinjected at Darajat, Larderello and The Geysers. As expected the results show that the field which

produces high enthalpy fluids reinject less amount of fluid per MWe.

Figure 2.5 shows the amount of waste water discharged to the surface from nine fields from which data are available.

2.2 Summary of ReInjection Experience

1. In *two-phase, vapour-dominated reservoirs* infield reinjection is usually used and very few adverse effects on the thermodynamic state of the reservoirs have been reported for most of the fields and injection has had an important role in maintaining steam production (Darajat, Kamojang, Larderello, Poihipi). The Geysers field has been affected thermally (temperature and wellhead enthalpy declines observed). But overall infield reinjection has assisted steam production. Recently additional make-up water has been added to the reinjection (Stark, et al. (2005) and this has significantly slowed the decline in steam production.
2. In *two-phase, high-enthalpy reservoirs* mostly infield reinjection is used. Thermal breakthrough had been observed in Olkaria I, and Bulalo but when the infield cold reinjection stopped or infield reinjection was reduced, the affected wells recovered gradually. Chemical breakthrough has been observed in Krafla and Los Azufres, but no changes have been reported on thermodynamic conditions in these fields.
2. Several of the *two-phase, medium-enthalpy reservoirs* have experienced thermal breakthrough (Hatchobaru, Matsukawa, Sumikawa, Cerro Prieto, Palinpinon, Ohaaki) or the precursor chemical breakthrough (Berlin, Tiwi, Mahanagdong) resulting from infield reinjection. Moving reinjection wells outfield has resulted in the recovery of the production wells.
3. Most *two-phase, low-enthalpy reservoirs* have experienced thermal breakthrough caused by infield reinjection (Miravalles, Ahuachapan, Mori, Onikobe). But these fields recovered when the production-reinjection scheme was changed. Some fields have not been significantly affected by thermal or chemical breakthrough (Otake and Ngawha). Reinjection returns have been recorded in Dixie Valley field but in this case pressure support from reinjection has helped to maintain production and infield reinjection has been maintained, Reed (2007).
4. Most *hot water reservoirs*, have experienced thermal breakthrough (Pauzhetsky, Kizildere, East Mesa, Beowawe, Brady, Empire, Steamboat). But infield reinjection has helped with pressure maintenance (Pauzhetsky, Kizildere). Shifting reinjection deeper to avoid temperature decline may cause an increase in pressure decline (Casa Diablo). In some cases moving reinjection wells closer to production wells has had a positive effect by reducing drawdown (Beowawe).
5. Full or partial surface discharge is still a common practice in many fields worldwide (Krafla, Nesjavellir, Svartsengi, Momotaombo, Husavik, Kawerau, Wairakei, Kizildere, Cerro Prieto, Olkaria I, Los Azufres, Pico Vermelho, Pauzhetsky, Yangbajain, Langju, Nagqu, Lihir, Bouillante). However, currently there is general agreement on the important benefits of reinjection in preventing environmental pollution from geothermal fluids (chemical and thermal), and sometimes in providing pressure support to the reservoir and preventing or reducing subsidence.
6. In most cases the adverse effects of reinjection have been reversed when the infield reinjection was abandoned or reduced (Tiwi, Ahuachapan, Miravalles, Hatchobaru, Uenotai, Bulalo, Tongonan, Palinpinon, Onikobe, Mindanao, Olkaria I, Empire). However, long term adverse effects can be seen in a few fields (Brady, Mori) and to some extent in Mahanagdong (combined with ground water inflow) where these plants are running at below design capacity after the reinjection moved outfield. For example, at Brady the temperature and flow rate of the produced fluid decreased after the start of reinjection. After 60% of reinjection was diverted outfield, the fluid production level and temperature did not recover. Similarly at Mori approximately 40% of reinjection has been moved outfield but still there are reinjection returns to the production wells and some of the reinjection returns has been replaced by cold recharge from groundwater.
7. In most cases of long-term infield reinjection thermal breakthrough to production wells has occurred within ten years of service (Ahuachapan, Brady, Bulalo, Coso, Hatchobaru, Kakkonda, Mahanagdong, Matsukawa, Mindanao, Miravalles, Palinpinon, Pauzhetsky, Sumikawa, Uenotai, The Geysers, Tiwi, Tongonan, Krafla, Mori, Ohaaki, Onikobe, Empire, East Mesa, Casa Diablo, Olkaria I, Los Humeros, Dixie Valley, Kizildere). The other cases where infield reinjection is not yet causing any thermal breakthrough may be because reinjection has not been running for long enough (Amatitlan, Rotokawa, Mokai, Ngawha, Berlin, Zunil, Salak, Ribeira-Grande, Mutnovsky, Dieng, Wayang-Windu, Los Azufres, Ngawha) or the amount of

reinjecting fluid is very small (Larderello, Cerro Prieto, Kamojang, Darajat, Krafla, Nesjavellir, Svartsengi, Kawerau).

8. Infield reinjection is a cheap but often temporary solution to waste fluid disposal. It is normally undertaken to reduce costs during early stages of field development (Rotokawa, Mokia, Ahuchapan, Salak, Zunil, Ngawha, Amatitlan, Brady) or as a first step in a full scale reinjection strategy in existing developments (Cerro Prieto, Matsukawa, Tiwi, Wairakei, Olkaria, Ohaaki, Kawerau, Pauzhetsky, The Geysers). In most cases existing production or investigation wells are used for reinjection at first, and these wells are usually located in the middle of the field (Rotokawa, Mokia, Ahuchapan, Salak, Zunil, Lahendong, Ngawha, Amatitlan, Cerro Prieto, Matsukawa, Tiwi, Wairakei, Olkaria, Pauzhetsky, The Geysers, Brady). Reinjection in these wells is normally abandoned or reduced when the adverse effects of infield reinjection become evident (Ahuchapan, Tiwi, Salak, Matsukawa, The Geysers, Bulalo, Tongonan, Mahanagdong, Brady, Rotokawa).
- 9 Full reinjection has been achieved in few existing reservoirs (Ahuachapan, Tiwi). Some other fields (Cerro Prieto, Wairakei, Olkaria) are in the process of a change of decreasing surface discharge by greatly increasing reinjection but may not achieve full reinjection.
10. A reinjection scheme that provides pressure support to the reservoir (infield reinjection) requires a careful monitoring program to prevent reservoir cooling. Cooling can be reversed if mitigation measures are taken promptly.
11. Shallow reinjection can result in increasing flux of fluid to the surface affecting existing natural features (e.g. Rotokawa, Mokai, Tongonan, Kawerau, Dixie Valley) and may help create new features (Rotokawa, Dixie Valley) fed directly or indirectly from the injected fluid. In some fields shallow reinjection resulted in ground inflation (Heber, Mokai, Steamboat Hills). These effects are not desirable if they take place within: residential areas, agricultural activity areas or within industrial areas. Therefore, shallow reinjection should be planned with caution.
12. Excessive reinjection pressure may make pumping uneconomical (Heber) or operationally unfeasible if it exceeds the design pressure of the surface equipments (pipes, valves etc.). Excessive reinjection

pressure can also cause hydro-fracturing or induced micro-seismic activity (The Geysers).

13. For some cases where the cap rock is fractured or is not continuous reinjection supports the reservoir pressure and prevents cold groundwater inflow (Namafjall, Mori). Shifting reinjection to deeper parts of the reservoir to prevent returns and temperature decline may introduce pressure decline (Casa Diablo). In one case moving injection wells toward the production wells has had a positive impact by reducing drawdown (Beowawe).
14. The optimum total reinjection strategy for liquid-dominated reservoirs (hot water, low enthalpy two-phase, medium-enthalpy two-phase) is to have a mix of infield and outfield reinjection. The infield reinjection provides pressure support to the main bore field and reduces drawdown, groundwater inflow and subsidence. The outfield reinjection reduces the effect of thermal breakthrough. The proportion of infield to outfield injection flow rates is case specific and typically the infield reinjection rate needs to vary with time as a part of the steam field management strategy.
15. Experience has shown that reinjection should be planned as early as possible in the field development.

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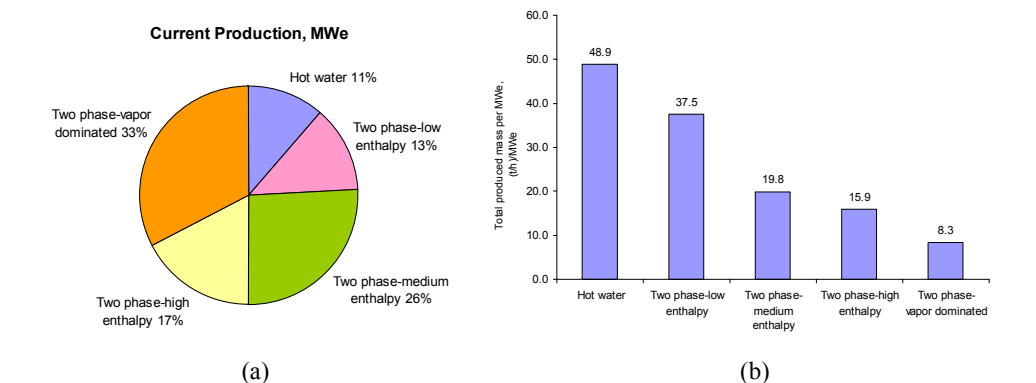


Figure 2.1 (a) Total energy production, MWe (b) total mass production (t/h) per MWe for each type of geothermal system.

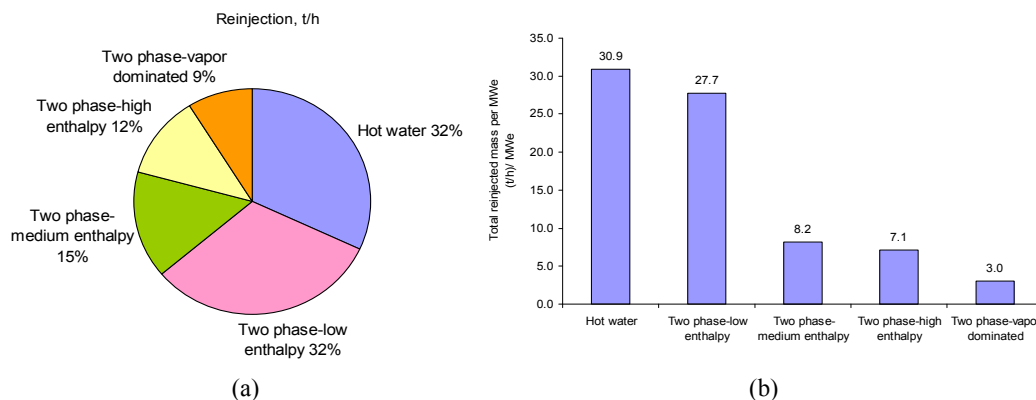


Figure 2.2 (a) Total mass reinjection (t/h) (b) total mass reinjection (t/h) per MWe for each type of geothermal system.

