

GEOHERMAL RESOURCES - UTILISATION STRATEGIES TO PROMOTE BENEFICIAL ENVIRONMENTAL EFFECTS AND TO OPTIMIZE SUSTAINABILITY

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Practical strategies to manage geothermal fields in order to optimize sustainability and to promote beneficial environmental effects are discussed. Collaboration between IEA countries participating in the Geothermal Implementing Agreement allows comparisons of strategies. This paper covers aspects of sustainable geothermal resource use related to cyclic utilization, timescales of depletion and recovery, and rates of mass and heat recharge. Practical environmental strategies include: enhancement of surface thermal features by targeted fluid injection or production, reinjection of gases, and enhancements of thermal habitats. Examples from Matsukawa (Japan), Wairakei and Kawerau (New Zealand), The Geysers (USA), Larderello (Italy), Cerro Prieto (Mexico) and Laugarnes (Iceland) illustrate the various strategies.

Keywords: geothermal, sustainability, environmental, development strategies

INTRODUCTION

Geothermal Resources

The global geothermal resource base is extremely large and ubiquitous. Terrestrial heat flow is currently about 40 million MW_t. At this rate it would take over 10⁹ years to exhaust the earth's heat [1]. Optimizing maximum sustainable production from a geothermal resource is a desirable management objective [2]. Sustainable geothermal energy production can be achieved by properly managing fluid production and injection rates and locations. Total energy yields achieved using low extraction rates over long duration cycles are similar to those achieved with high extraction rates for short duration cycles [1]. Balanced fluid/heat production that does not exceed the recharge (natural and induced) can be considered indefinitely sustainable. If extraction rates exceed the rate of recharge, reservoir depletion will occur, but following termination of production, geothermal resources will undergo asymptotic recovery towards their pre-production pressure and temperature states. Practical replenishment (~95% recovery) will occur on time scales of the same order as the lifetime of the geothermal production cycle (typically ~50-300 years). The optimum level of long-term sustainable production depends on the utilization technology as well as on the geothermal resource characteristics [2].

Sustainable Developments

Examples of successful sustainable geothermal developments, where reservoir performance has stabilized during production, include both higher enthalpy systems (eg. Matsukawa [3], Wairakei [4], Kawerau [5], and Larderello [6]) and lower enthalpy systems (Laugarnes [7], and the Paris Basin [8]). In these cases,

the recovery factors that determine the long term response of the systems to energy extraction are dynamic. Recovery is influenced by an enhanced recharge driven by the strong pressure and temperature gradients initially created by the fluid and heat extraction. Because of this dynamic recovery process, in many cases cyclic utilization of geothermal resources may be a viable long-term strategy, and may also be an economic and sustainable alternative to the strategy of simply limiting extraction to maintain continuous steady-state reservoir conditions. The cycle durations can be tailored to meet demand cycles (daily or seasonal), or can be extended out to periods of the order of 100 years, with resource utilization possibly alternating between neighbouring geothermal systems. A hypothetical example is given in Figure 1.

Environmental Effects

In high-enthalpy liquid-dominated systems (eg. Wairakei and Cerro Prieto), a consequence of deliberately enhancing hot deep recharge by drawing down reservoir pressure is that reservoir liquids may boil and two-phase conditions may develop in production sectors. In reinjection sectors, re-saturation of two-phase conditions may occur. This can affect the relative upflows of hot liquid and steam to the surface. Changes may include a decline in mineralised hot springs and an increase in steam-heated thermal features above production sectors, while the converse may occur above injection sectors. For geothermal reservoirs that are naturally steam-dominated (eg. The Geysers and Larderello), a decline in reservoir pressure will probably reduce the natural upflow of steam to surface features. Such pressure changes can have both adverse and beneficial effects on established users of the surface thermal features (such as hot spring spas), as well as the associated natural environment (eg. thermal ecosystems), and surrounding structures.

Recent strategies of geothermal environmental management emphasize achieving a balance through avoiding adverse effects and promoting beneficial effects [9]. A key objective of the strategies is to devise practical mitigation schemes. Production and reinjection schemes can be planned with built-in flexibility in order to allow reaction to induced adverse effects, such as reductions in natural spring discharges or increasing subsidence, without compromising the efficient utilization of the resource. Furthermore, net changes in gas emissions, from natural vents and power-plants, can be addressed in terms of their global and local effects. Technology may be applied for their avoidance, removal or injection if necessary.

Some examples of environmental benefits deriving from adaptive production/injection strategies include: hot stream and thermal feature creation using waste hot water (eg. Wairakei Terraces, Figure 2), increased steam-heated ground from liquid pressure drawdown, and increased hot spring discharge from shallow reinjection. Indirect environmental benefits have included wetland creation in subsidence areas, and enhanced thermal ecological habitats where thermal features have increased. The key to achieving a successful balance of effects is adaptive resource management.

TRANSIENT RESERVOIR BEHAVIOUR

Transient reservoir behaviour has caused long-term changes in surface thermal features and groundwater aquifers in some geothermal systems. Examples are Larderello, The Geysers and Wairakei. The time scale of these transient effects depends on properties of the aquifers such as rock porosity and degree of fracturing. High porosity rock (e.g. pumice) leads to greater fluid storage. High permeability rock (e.g. fractured rhyolite lava) leads to more rapid propagation of pressure changes. High permeability also allows for greater extraction rates of mass and energy. At Wairakei, there is a high permeability connection between the production aquifers and the underlying recharge zone. This means that the initial production pressure drawdown of 25 bars between 1958 and 1980 stimulated a large increase in flow-rate of hot recharge fluid, stabilizing liquid pressures, and thereby helping to sustain energy extraction rates.

The aquifers, in this case, can be thought of as reservoir "tanks" with various degrees of interconnection, usually along permeable paths. In some cases fluid interconnection is rapid. A small pressure gradient (such as between a production and injection well) can cause relatively fast subsurface flows of fluid over long distances. At Wairakei, known examples of rapid connection (based on tracer tests) exist along several faults passing through the production borefield area. In other areas, the aquifers are relatively weakly linked, and pressure changes can take a long time to propagate between them. In general, the longer the time lag, the more effective the conductive gain or loss of heat energy between the surrounding rocks and the fluid. This heat-sweep effect is achieved by fluid flowing through fractures and diffusing slowly in and out of the porous rock matrix.

Some aquifers are separated or capped by porous but impermeable aquicludes, such as hydrothermal clays, mudflow deposits, and lake-deposited siltstones and mudstones. These aquicludes deflect vertical flow

into horizontal flow. As a result, lateral outflows of hot liquid or steam sometimes produce surface discharges several kilometres from the upflow source. Along these subterranean outflow pathways, the hot water and steam thermally and chemically alter the rock matrix into clays. They may also deposit silica. Therefore, the rock properties (such as permeability and compressibility) of the subsurface formations in these outflow areas can vary depending on location, duration and type of hot fluid interaction.

Subsidence

As pressures have reduced across some systems (eg. Ohaaki, Wairakei and Tauhara), mudstone aquicludes or thermal clay deposits have, in some places, compacted and formed local subsidence anomalies. Parts of these formations have compressibility and permeability properties that are locally anomalous. Despite their high porosity (about 60%), the relatively low permeability of these mudstone or clay formations results in slow diffusion of pressure. This, in turn, can cause a substantial delay between the aquifer pressure decline, and the compaction of the aquiclude. Another explanation for the observed time delay is a process called 'creep' [10]. It is likely that much of the anomalous compaction originates from clays, such as smectite, inter-layered smectite-illite and kaolinite. These characteristically deform in an in-elastic (or plastic) manner, resulting in creep or ongoing compaction under constant load. As a result of creep, the compaction process, when the clay-rich material is subjected to pressure reduction, is delayed. It is also mostly permanent. Rising pressures will not 'reinflate' the ground surface within such subsidence features to any significant degree. With creep behaviour, subsidence rates generally peak and then gradually tail off with time, even under stable (but reduced) reservoir pressure conditions.

Induced Seismicity

As a result of induced pressure or temperature changes in the rock during fluid production from, or injection into, boreholes, some reservoirs undergo stress changes that can trigger hydraulic fracturing or micro-earthquakes. If of modest magnitude, such induced seismicity is beneficial in the sense that it relieves stress that might otherwise accumulate until a large natural earthquake eventuates. Furthermore, induced seismicity enhances the natural permeability, allowing more efficient heat extraction from hot reservoir rocks. This is the fundamental basis behind EGS (enhanced geothermal systems) and HDR (hot dry rock) geothermal projects. At some projects (eg. The Geysers), however, the induced events have reached a Richter magnitude of three or four and, although not damaging to surface structures, these are felt and have raised concerns with local residents who fear even larger damaging induced events. The results of recent research have been compiled into a 'white paper' and a draft 'protocol' by IEA GIA participants [14] to assist with public education, and to provide advice on avoiding or mitigating larger events, while at the same time promoting the beneficial smaller events.

Surface Thermal Features

Geothermal systems are naturally dynamic and this includes the variation in surface thermal features. Variations in fluid discharges at surface thermal areas

can be very large (e.g. geysers, and hydrothermal eruptions). Variation is a normal and valued characteristic. Natural variability should be taken into consideration when planning monitoring and mitigation programs. Sustaining constant surface flow should not be the principal objective of geothermal feature management. Geothermal features also have varied ecological and geological characteristics. These are governed by the previous history of changes in thermal activity. They are also dependant on other surface environmental factors (such as animal access, weathering processes and weed invasion). Nevertheless, some geothermal resource management practices can affect future discharges from thermal features (whether they are active or dormant). As such, some policy guidelines are appropriate. Attempting to balance induced increases against decreases across a region may be a reasonable approach.

Complications that arise from transient reservoir behaviour need to be considered when developing the optimum injection and production strategy. Fluid changes affect formation properties and vice versa. Consequently, field management should be approached in a flexible and adaptive manner, rather than a prescriptive manner. Such an approach has better chances of successfully minimizing or mitigating environmental effects.

STRATEGIES TO MANAGE PRODUCTIVITY

Mass and Heat Recharge

In the natural state, geothermal systems tend to approach a steady-state equilibrium whereby the deep inflows of energy and mass approximately balance the outflows. The induced pressure draw-down following initial exploitation usually increases the amount of hot recharge into the base of the production aquifer (possibly by more than 100%, as at Wairakei [4]). With time, a new pressure regime is established whereby the increased mass recharge again approximately balances the net discharge. This mass equilibrium is maintained because the deeper recharge source is relatively large. Note, however, that there are some examples of hydrologically 'closed' geothermal systems with limited natural fluid recharge, but large heat reserves (eg Beijing Urban Geothermal Field, China [2,7], and The Geysers [7,11]). In these cases, pressure maintenance by fluid injection is a key component of sustainable management strategy [12].

Over time, despite adequate fluid recharge, reservoir temperatures may decline, so energy inflows may be less than outflows. Some of the increased induced mass recharge also consists of cooler fluids from the reservoir edges and the overlying groundwater which, if in-flowing too rapidly, can prematurely cool down the production aquifer. Cooler fluids that are injected directly through wells also have the potential to cool the reservoir.

Reinjection Strategy

The relative benefits or adverse effects of 'in-field' injection depend on the temperature of the recharge fluid displaced. The injectate may be cooler than both the deep hot recharge and the inflowing groundwater recharge (which is often heated up by hotter rocks along a flow-pathway into the production aquifer). In this case,

the net effect of infield injection on the energy balance can be detrimental. Cases of detrimental cooling effects caused by reinjection fluids returning prematurely to production wells have been well documented, for example in the early development history of some Japanese fields [13].

Although reinjection of discharged fluids is generally encouraged as a means of sustaining reservoir pressures, full or 100% reinjection of all discharged fluids into the production reservoir is not necessarily the most appropriate strategy. Fractured reservoirs are particularly susceptible to premature thermal breakthrough, especially if excessive quantities of reinjected fluid are allowed to channel into production sectors. Furthermore, if two-phase zones are allowed to develop, by limiting reinjection fluid returns, this also enhances the efficient recovery of stored energy in the rock. Flexibility and adaptive reinjection management are key components of successful and sustainable field developments. The best approach is to avoid prescriptive requirements, but instead to stipulate desirable outcomes for optimum geothermal system reinjection management.

An appropriate framework for addressing the potential effects of development requires high quality information about the resource to be collected and reported, and mechanisms put in place for amending field take and reinjection strategies if necessary. An adaptive management framework should allow injection, where appropriate, both within and outside the nominal boundary of the high-temperature system. The strategy should provide options for targeting suitable aquifers. A suitable sustainable reinjection strategy could be based around five key objectives or outcomes.

The first objective of the strategy should be to avoid excessive contamination of surface waterways with mineralised hot water, particularly if the environmental effects are adverse. This should not unduly inhibit efficient users of waste hot water (cascaded energy users) that may require surface disposal of limited volumes of cooled geothermal liquid, at up to pre-development (or natural) hot spring discharge rates. The second objective of the framework should be to select injection target aquifers that avoid the rapid return of injected fluid to production aquifers. This would reduce the risk of damaging the long term productivity of the geothermal aquifers by premature cooling, and promote sustainability by encouraging deep recharge through managed pressure drawdown. The third objective should be to achieve a balance between injection into infield aquifers for the purposes of minimising excessive in-field pressure drawdown, with injection into hydrologically more distant peripheral aquifers where the pressure and temperature response on the resource would be more muted. The fourth objective should be to select for injection deep peripheral aquifers that have previously been affected by diffusion or outflow of geothermal fluid or gas through the field boundary zone. The purpose would be to avoid compromising the future availability of peripheral fresh water aquifers for other purposes. The fifth objective should be to use deeper injection aquifers that are hydrologically isolated from any shallow aquifers containing high quality potable groundwater.

SUMMARY

Geothermal resources are considered to be renewable when viewed over an appropriate timeframe. With appropriate management, which includes a proper monitoring programme, the geothermal system can be utilised over a long term (~100 years). If necessary, it may then be retired. Pressure and temperature recovery will follow; the former occurring more quickly than the later. In this way, the use of the system over a long term, without prejudicing its ability to recover, constitutes a sound resource utilisation strategy.

Optimised sustainable reservoir management involves countering the adverse effects of premature temperature decline with appropriate and flexible production and injection strategies. Such strategies will, in all likelihood, need to be adjusted at times, in order to achieve the correct balance. Flexibility in locating and utilising future injection wells, both inside and outside the hydrological edges of a geothermal system, is also a key means of achieving a successful outcome.

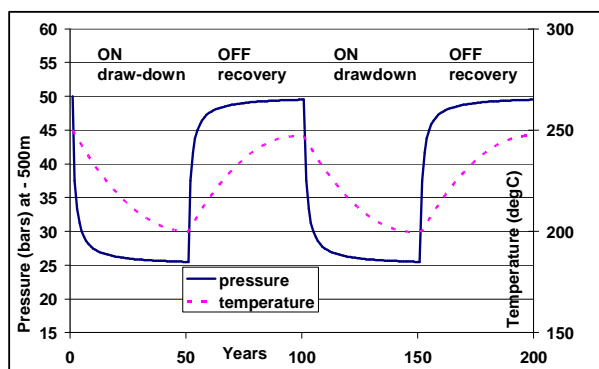


Figure 1. Hypothetical example of cyclic utilization and recovery of a geothermal resource. This provides for long-term sustainability by alternating resource use.



Figure 2. Wairakei Terraces, a recent artificial thermal feature enhancement using waste hot water.

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