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ABSTRACT

In all active liquid-dominated geothermal systems there is continuous circulation of mass and transfer of heat, otherwise they would slowly cool and fade away. In the natural state these systems are in dynamic equilibrium with the surrounding colder groundwater aquifers. The ascending geothermal fluids cool conductively, boil, or mix with groundwaters, and ultimately may discharge at the surface as fumaroles or hot springs.

With the start of fluid production and the lowering of reservoir pressure, the natural equilibrium is disrupted and cooler groundwater tends to enter the reservoir. Improperly constructed or damaged wells, and wells located near the margins of the geothermal system, exhibit temperature reductions (and possibly scaling from mixing of chemically distinct fluids) as the cooler-water moves into the reservoir. These negative effects, especially in peripheral wells are, however, compensated by the maintenance of reservoir pressure and a reduction in reservoir boiling that might result in mineral precipitation in the formation pores and fractures.

The positive effect of cold groundwater entry on the behavior of liquid-dominated systems is illustrated by using simple reservoir models. The simulation results show that even though groundwater influx into the reservoir causes cooling of fluids produced from wells located near the cold-water recharge area, it also reduces pressure drawdown and boiling in the exploited zone, and sweeps the heat stored in the reservoir rocks toward production wells, thus increasing the productive life of the wells and field.

INTRODUCTION

In many liquid-dominated geothermal systems the reservoir is in good hydraulic communication with adjacent groundwater aquifers, either laterally along the margins of the system, or vertically by way of permeable faults or fracture zones. In contrast, vapor-dominated systems have little or no interaction between geothermal fluids and groundwaters because of the low permeability of the confining rock formations.

Under natural state conditions there is a dynamic equilibrium between the "bubble" of hot fluids that constitutes the liquid-dominated geothermal anomaly and the surrounding colder groundwaters. At or near the surface, the upflowing geothermal fluids tend to mix with groundwaters, boil, cool conductively, and/or discharge into surface waters or to the atmosphere. In response to exploitation, this natural equilibrium is disturbed and surrounding groundwaters tend to enter the geothermal reservoir.

In some high-temperature fields (those developed for electrical power production) this natural recharge of cooler fluid is not sufficient to compensate for the general pressure decrease observed over the entire reservoir, and an extensive boiling zone develops (i.e. Wairakei; Grant *et al.*, 1984). In others, groundwater recharge is large enough to avoid the formation of a generalized boiling zone, and only near-well boiling occurs (i.e., the shallower α reservoir at Cerro Prieto; Grant *et al.*, 1984; Truesdell and Lippmann, 1990). During exploitation of lower temperature fields boiling seldom occurs, but colder groundwater encroachment into the reservoir is also observed.

When groundwater entry is discussed in the geothermal literature, the negative cooling aspect of the recharge is usually emphasized (e.g., Bixley, 1990). This is understandable if we consider the severe impact on produced fluid enthalpy and wellbore scaling when, because of improperly cemented or completed wells, cooler waters descend into the reservoir through the casing or wellbore annulus.

Natural recharge is beneficial, however, when as the result of fluid production cooler groundwaters move into the reservoir at some distance from the wells, not directly through or around the wellbore. Reservoir pressures are supported, heat is swept toward the wells, and reservoir boiling and mineral precipitation in the rock pores and fractures are reduced, resulting in an increase in well and field productivity and commercial lifetime. The experience at Cerro Prieto, Mexico, has demonstrated the benefits of groundwater entry into an intensively exploited liquid-dominated system (Truesdell and Lippmann, 1990).

In this theoretical study simplified models are used to simulate the effects of cold-water recharge on the response of high-temperature, porous medium, liquid-dominated systems and illustrate the beneficial effects on heat and mass flow rates and total heat extracted from the reservoir. The end results tend to be similar to those of a well-designed reinjection operation, a reservoir management practice that has been studied theoretically since at least the mid 1970's (e.g., Gringarten and Sauty, 1975; Kasameyer and Schroeder, 1976, Lippmann *et al.*, 1977, O'Sullivan and Pruess, 1980) and implemented in many liquid-dominated geothermal fields throughout the world.

NUMERICAL SIMULATIONS

Two simple models were developed to simulate the entry and effects of cold water on the productivity of porous geothermal systems. The modeling of fractured reservoirs would have been much more cumbersome and computer intensive, requiring very detailed computational meshes to accurately model the mass and heat transfer between rock matrix blocks and an arbitrary (and simplified) network of fractures. The main purpose here is to illustrate the reservoir pressure maintenance and heat-sweeping effects of natural colder-water recharge and its impact on productivity. The thermal degradation of wells related to groundwater entry into fractured reservoirs could be more severe than shown by our models since fractures tend to channel flow between fluid sources and the producing wells (e.g., Pruess and Bodvarsson, 1984).

The numerical code MULKOM developed at LBL (Pruess, 1988) was used to compute heat and mass transfer under natural and exploitation conditions. In the model well production rates were allowed to vary with time in response to changes in reservoir pressure and fluid mobilities. Constant well productivity indices and downhole pressures were assumed.

In both models all materials had linear relative permeability curves with residual saturations of 0.4 and 0.05 for liquid and steam, respectively. The geothermal and recharge fluids were assumed to be pure water; they only differ in temperature.

Radial Model

The geothermal system and surrounding aquifers of lower temperature are represented by a radial, 100 m-thick, horizontal permeable layer extending to a distance of 250 km. A well with a one-meter effective radius is located at the center. The system behaves like an infinite one, since for the assumed conditions and time of simulation, the radius of influence is smaller than 250 km. The productivity index for the well was assumed to be 5×10^{-12} m^3, and the bottomhole pressure, 55 bars; neither parameter changed with time.

In this model thermal conduction was neglected. The layer was assumed to have a permeability of 50 md and a porosity of 15 percent. Initially the system showed uniform pressure (100 bars) and gradual decrease of temperature away from its center (i.e., 300°C for $0<r<100$ m; 290°C for $100<r<200$ m; ... ; 200°C for $r>1000$ m). The 1000 m-radius, hotter inner volume was considered as the "core" of the geothermal reservoir.

Two cases were studied. The first one presented a uniform permeability, and the entry of cooler water into the core of the reservoir was "open". In the second case, the outer system (i.e., $r>1000$ m) showed lower permeability (5 md) than the central part, and the recharge was "restricted" due to the lower permeability of the outer zone.

Open-Radial System

At time zero the well is allowed to flow. After a sharp decrease at very early time (an artifact because of the assumed constant downhole pressure conditions) the mass flow rate and bottomhole temperature are stable for about three years (Figs. 1 and 2). During this initial period, the fluid recharge toward the well is not sufficient and boiling occurs (Fig. 3). Progressively an adequate pressure gradient (and fluid recharge) builds up in the reservoir and the near-well boiling decreases, stopping at about 3 years. When the two-phase zone disappears there is an increase in reservoir fluid mobility, and the mass flow rate jumps upward (Fig. 1). From there on, the flow rate slowly decreases as cooler, more viscous water from adjacent reservoir zones begins to affect the area around the well (Fig. 2). During the first three years, boiling occurred and the bottomhole temperature did not change because the reservoir pressure was almost constant (after the very early drop).

In Fig. 4 the heat flow rate (i.e., the product of enthalpy of the produced fluids multiplied by the mass flow rate) is shown. The shape is similar to that of the mass flow rate since the enthalpy of the produced fluid did not change significantly (i.e., steam saturation was always low, never exceeding 15 percent; Fig. 3). Integrating the area under the heat flow rate curve, we obtained that during the assumed 20-year production period, 5.0×10^{16} Joules (about 1,590 MW-years) of thermal energy had been extracted from the system.

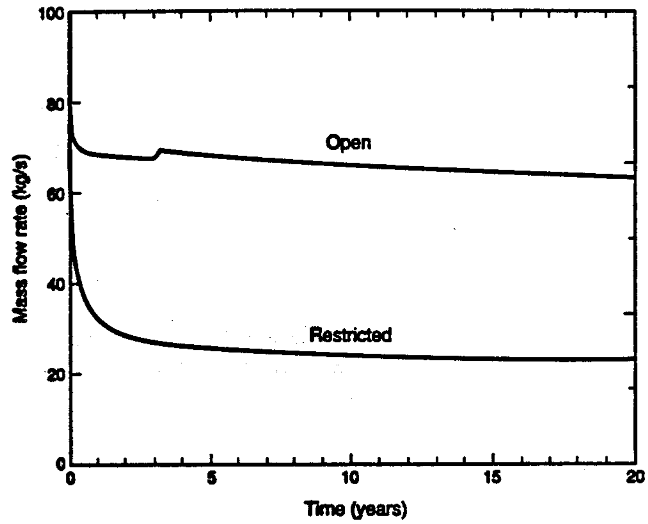

Figure 1. Radial Model - Mass production rate versus time for the Open and Restricted Cases.

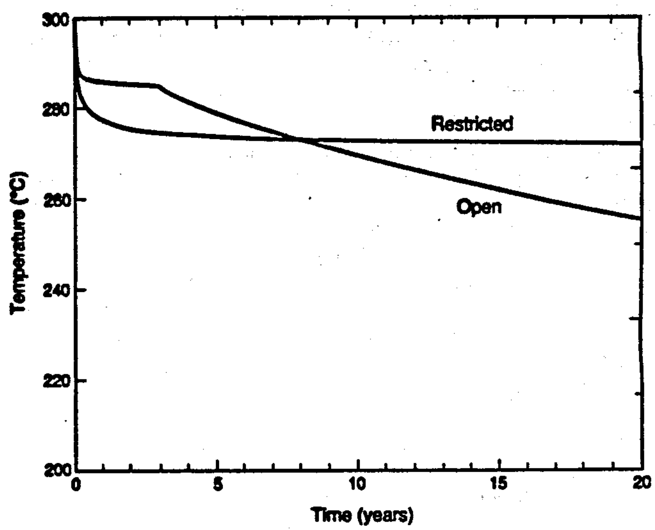

Figure 2. Radial Model - Bottomhole temperature versus time for the Open and Restricted Cases.

Restricted-Radial System

In this case because of a ten-fold reduction in the permeability of the outer regions of the system ($r>1000$ m), the entry of groundwater in response to production is less than in the open system (i.e., the cooler-water recharge to the inner core of the reservoir has been restricted). However, the rate of cold water entry is still appreciable. For example, at time equals 10 years it was 25.2 kg/s; for the open case, 68.2 kg/s.

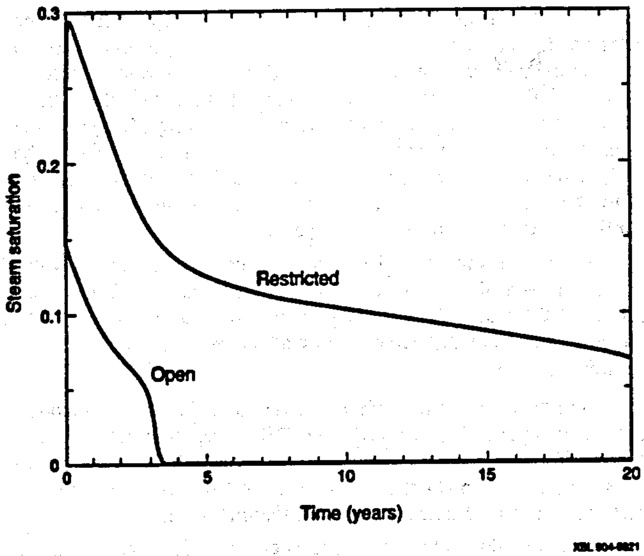

Figure 3. Radial Model - Bottomhole steam saturation versus time for the Open and Restricted Cases.

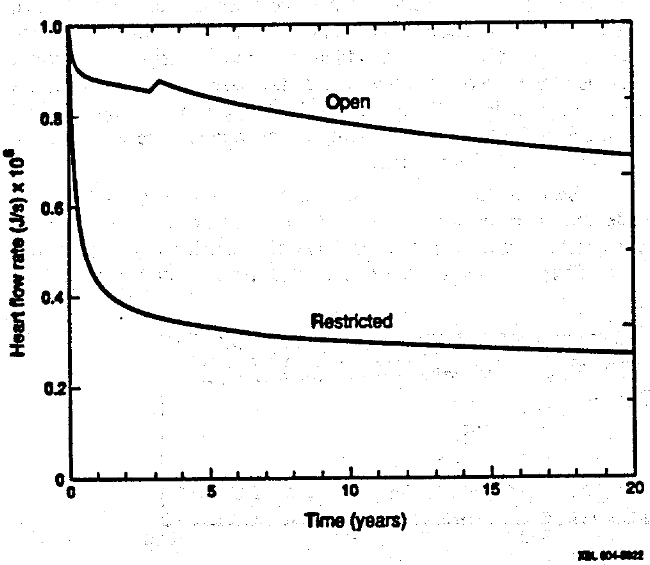

Figure 4. Radial Model - Heat production rate versus time for the Open and Restricted Cases.

Figures 1–4 show the mass flow rate, temperature, steam saturation and heat flow rate changes over 20 years of exploitation, respectively. (The curves have been smoothed by deleting some of the numerical oscillations that occur when cooler liquid water enters nodes that show boiling).

Because the amount of fluid recharge is less in the restricted case than in the open case, there is continuous boiling around the well during the entire period (Fig. 3). The steam saturation stays below 30 percent and decreases with time, as (after an initial transition period) the recharge is similar to the well production rate.

Since there is a relative balance between fluid production and recharge, the pressure in the system decreases only slightly after an initial sharp drop. This is reflected in the temperature history of the produced fluids (Fig. 2). Because there is near-well boiling throughout the 20 years of simulation and pressure and temperature are correlated, the temperature exhibits only a small decrease after about four years. As a result of this near stabilization and smaller rate of heat extraction (see below), the temperature becomes higher than in the open system after about eight years.

Owing to the restricted water entry, the mass and heat flow rates in this case are significantly smaller than in the open case (Figs. 1 and 4). Therefore, the total thermal energy extracted from the system is only about 2.0×10^{16} Joules (640 MW-year), 40 percent of what was extracted in the open case.

The results of the two radial systems clearly indicate the importance of recharge on the performance of a liquid-dominated system. If the permeability of the outer region had been reduced below 5 md, further decreasing the recharge into the inner core of the reservoir, the boiling would have been more intense and the mass produced would have dropped to minimal levels.

Two-Dimensional Model

The two-dimensional model simulates the behavior of a fault-controlled geothermal system (Fig. 5). It consists of a 100 m-thick reservoir (k = 100 md, porosity = 20 percent) overlain and underlain by an impermeable caprock and bedrock. The system is connected to a permeable (k=100 md, porosity= 20 percent) fault and an infinitely large aquifer. Hot (280°C) water recharges the reservoir by way of the fault that is fed from a constant pressure and temperature boundary located 3 km below. The colder (210°C) groundwater aquifer is connected to the lower 50 m of the reservoir, 2 km from the fault.

Two lines of wells, open in the upper 50 m of the reservoir, are located 100 and 300 m from the fault zone (Fig. 5). In this model we also assumed constant well productivity indices (5×10^{-12} m^3) and downhole pressures (51.5 bars).

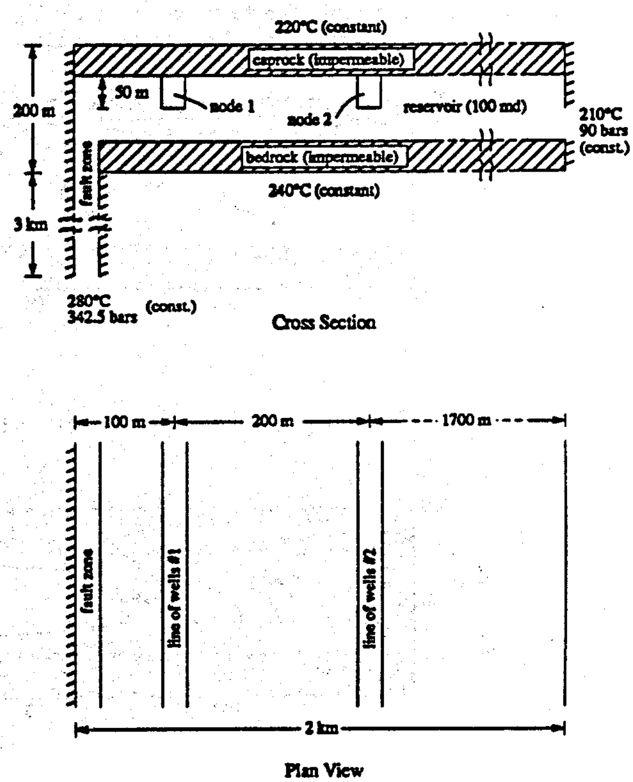

Figure 5. Cross-section and plan view of the two-dimensional model.

In contrast to the radial cases discussed earlier, this two-dimensional model allows for thermal conduction. Constant temperatures are assumed above the caprock (220°C) and below the bedrock (240°C; Fig. 5). The permeable layers are assumed to have a thermal conductivity of 3.0 W/m/°C, and the impermeable ones, 2.0 W/m/°C.

To show a more realistic initial temperature distribution, as a first step in our simulations we allowed the system to be heated up until steady state conditions were reached. That is, 280°C water flows up the fault into the reservoir and then horizontally toward the groundwater aquifer (at the right edge of Fig. 5). The water cools by conduction as it flows through the system.

Again two cases were simulated. In one the permeability of the groundwater aquifer was 100 md, equal to that of the reservoir. In the other it was only 10 md, reducing the hydraulic communication between the reservoir and the aquifer.

Open Two-Dimensional System

In this system the permeability (and porosity) of the fault, reservoir and aquifer are identical, enhancing the natural-state circulation of hot water from the fault out into the aquifer. Under steady state conditions, 4.2×10^{-3} kg/s (per meter of fault length) of 280°C water recharge the system. The resulting initial temperature distribution is shown in Fig. 6.

At time zero, production starts simultaneously in both lines of wells. In response to the resulting pressure drawdown, there is some increase in the upward flow of hot fluids through the fault zone. The entry of colder water into the reservoir is not immediate; for it to occur the pressure gradient in the outer reservor region has to be reversed (under initial conditions, the pressures in the reservoir are higher than in the aquifer).

At the end of 20 years of production there is significant cooling in the region to the right of the first line of wells (Fig. 7), the result of groundwater recharge (conductive losses are not important). On the other hand, there are only small temperature changes in the region between the fault and the first line of wells (node 1). Even though the influx of 280°C water has increased (see below), the resulting heating seems to be cancelled by cooling due to boiling. Checking the recharge at about 10 years, 14 percent of the fluid extracted by the wells is replaced by water flowing up the fault (1.3×10^{-2} kg/s/m), while the remaining 86 percent enters via the groundwater aquifer. Similar values are obtained after 20 years.

The temperature histories of the produced fluids are shown in Fig. 8. The first line of wells exhibits minimal changes. The second line (node 2) clearly shows a temperature decrease as progressively cooler waters from the outer regions of the reservoir move toward the well.

Boiling occurs only near the hotter first line of wells and is continuous over the 20 years (Fig. 9). Following an initial sharp rise and fall (for $t < 1.5$ years), the steam saturation (at bottomhole conditions) decreases slowly indicating that the heat recharge into that part of the reservoir is smaller than the thermal losses.

The mass flow rates for both lines of wells are given in Fig. 10. At early time a restricted mass recharge to node 1 causes its flow rate to drop. Because of its position, most of the mass recharge to node 1 comes from the fault zone. It takes some time to establish an adequate pressure gradient between the fault and the node 1 area, which is attained at about two years. After that, the node 1 flow rate rises very slowly. Node 2, which has good access to the outer regions of the reservoir, shows initial mass flow rate about four times larger than node 1. With the cooling of the outer regions (and decrease in the kinematic mobility of the water) there is a progressive drop in node 2 flow rates.

The heat flow rate histories of both lines of wells (Fig. 11) reflect the changes shown in Fig. 10. Node 2 extracts more heat from the system than node 1, and exhibits only a small rate decrease with time. Over the 20 years of simulated production the total heat

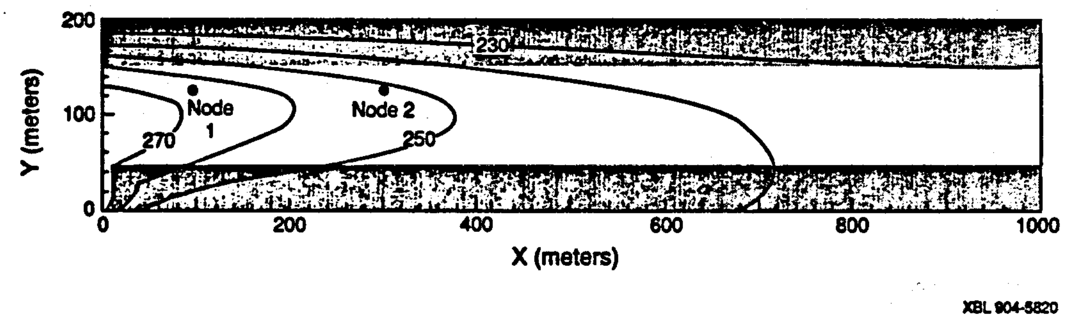

Figure 6. Two-dimensional Open System - Initial temperature distribution.

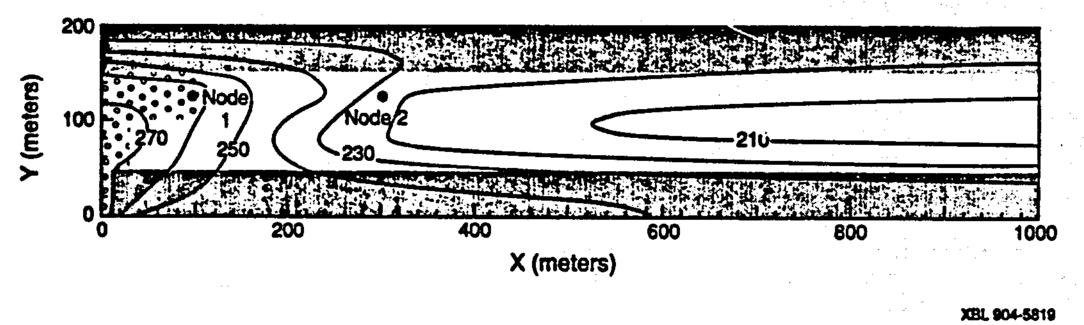

Figure 7. Two-dimensional Open System - Temperature distribution after 20 years of simulated production (boiling zone indicated by small circles).

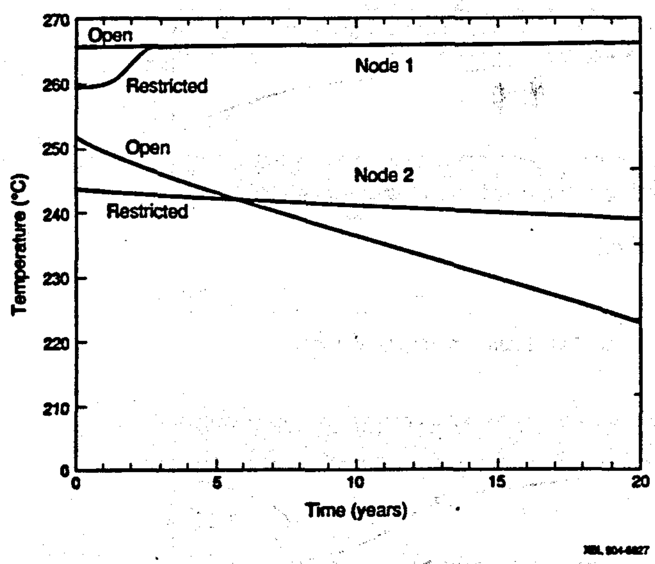

Figure 8. Two-dimensional Model - Bottomhole temperature versus time for the Open and Restricted Cases.

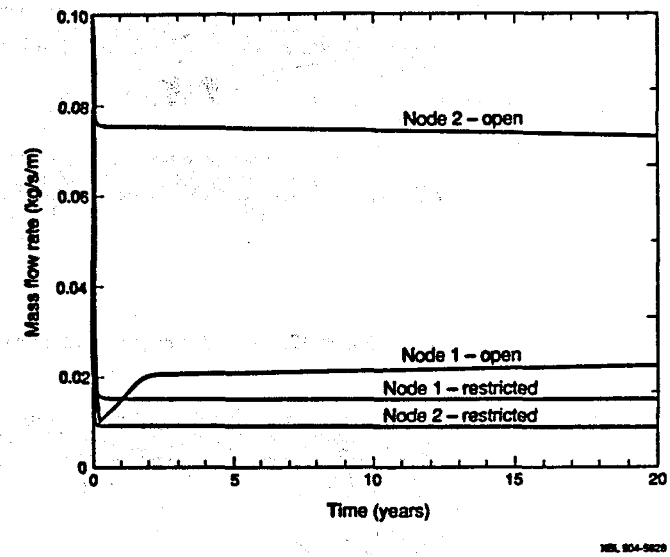

Figure 10. Two-dimensional Model • Mass production rate versus time for the Open and Restricted Cases.

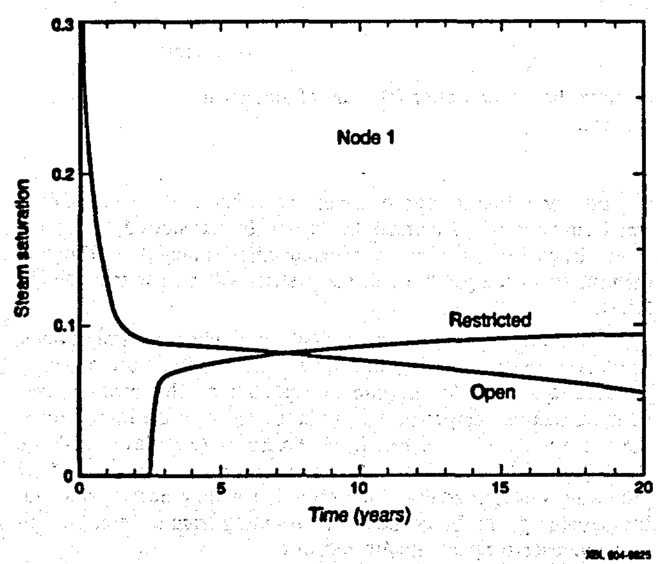

Figure 9. Two-dimensional Model - Bottomhole steam saturation versus time for the Open and Restricted Cases.

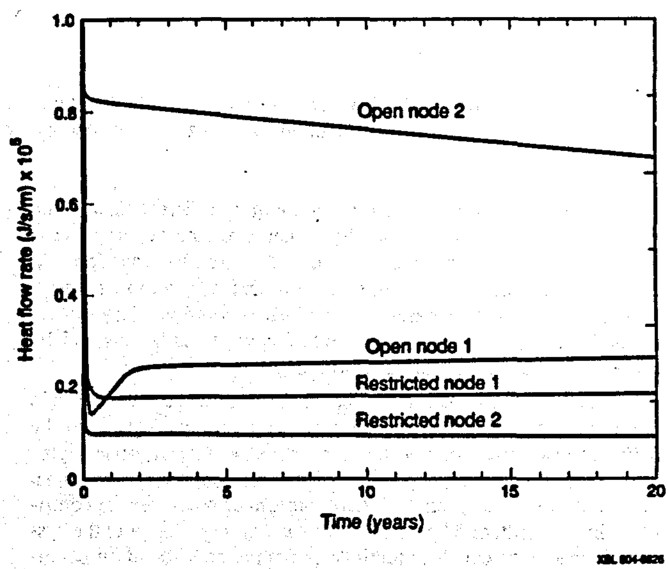

Figure 11. Two-dimensional Model - Heat production rate versus time for the Open and Restricted Cases.

extracted by both lines of wells is 6.5×10^{13} J/m (2.1 MW-year/m).

Restricted Two-Dimensional System

In this system the permeability of the groundwater aquifer (10 md) is a tenth of that of the reservoir, thus restricting the hydraulic communication between both units. In the natural state (Fig. 12) less hot water flows through the reservoir, resulting in a cooler system than in the open case. This is clearly shown by comparing the regions encompassed by the 240°C isotherms in Figs. 6 and 12.

The temperature distribution after 20 years of simulated production is shown in Fig. 13. Since a large proportion of the extracted fluids is contributed by way of the fault zone (see below), there is some heating of the area between the fault and node 1. Some cooling occurs in the region to the right of node 2, but less than in the open system because cool groundwater recharge is restricted.

The bottomhole temperature histories for nodes 1 and 2 are shown in Fig. 8. Except for the first three years, the temperatures in node 1 are similar to those in the open system. In both cases the final temperatures are controlled by the hot water flowing up the fault zone. Initially node 1 is cooler in the restricted system, and at early times it heats up reflecting an increased hot water recharge caused by production-induced reservoir drawdown. In the two-dimensional restricted system node 2 behaves similarly to the well in the radial model discussed earlier. Initially node 2 temperatures are lower than in the open case, but they show a slower decrease. After a time (in this case at about six years) temperatures in the restricted case become higher than in the open system. This indicates that the well is supplied by a smaller amount of cooler waters from the outer reservoir regions; a direct result of less groundwater entry into the system.

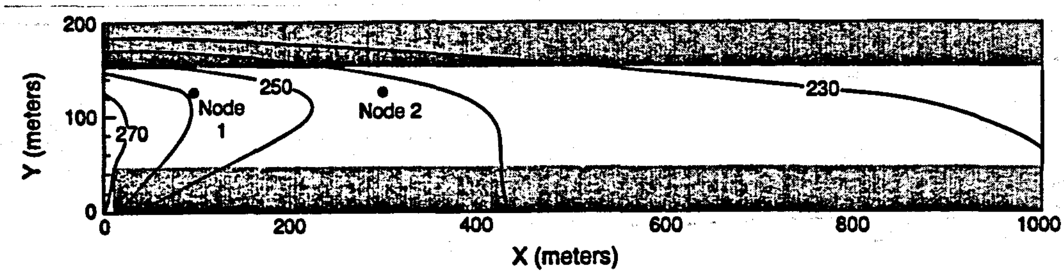

Figure 12. Two-dimensional Restricted System - Initial temperature distribution.

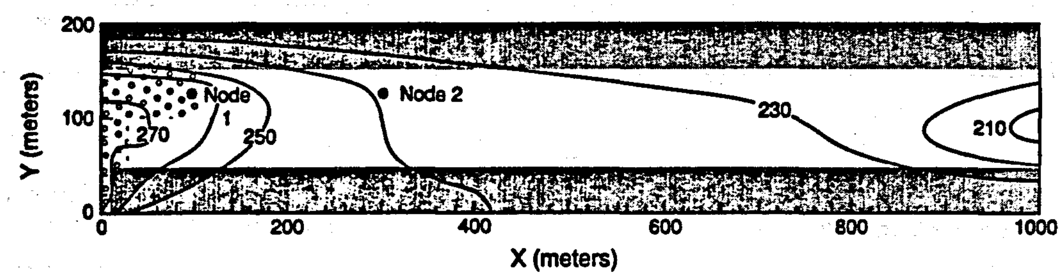

Figure 13. Two-dimensional Restricted System - Temperature distribution after 20 years of simulated production (boiling zone indicated by small circles).

The changes in steam saturation are quite different than in the open system (Fig. 9). In the initially cooler restricted system there is no boiling in the reservoir until about 2.5 years of production. At that time the hotter node 1 begins to boil, and after an initial jump, its saturation slowly increases as more heat is contributed by the hot fluids flowing up the fault zone. Node 2 never boils because of the cooler recharge from the outer regions of the system.

The mass flow rates are much smaller and more stable than in the open system (Fig. 10). Because of the strong recharge from the fault and restricted groundwater entry from the aquifer, node 1 produces more than node 2, opposite to what was observed in the open system. At about ten years, 1.3×10^{-2} kg/s/m of hot water are contributed by the fault, or 54 percent of the total mass recharge to the system. (Because of equal bottomhole pressures and boundary conditions for the fault zone, the rate of hot water recharge is identical in both two-dimensional cases). Cold-water recharge is only 46 percent of the fluid extracted by the wells, compared to 86 percent in the open system. Similar values are obtained at 20 years.

Heat flow rates in both lines of wells (Fig. 11) again reflect the trends shown by the mass flow rate curves (Fig. 10). Node 1 has a higher output rate than Node 2, and exhibits a slow increase with time. The total heat extracted from the restricted system during the 20 years of exploitation is about 1.8×10^{13} J/m (0.56 MW-years/m thermal), only about 28 percent of what was produced from the open system.

CONCLUSIONS

Our numerical simulations show that a good hydraulic communication between reservoir and recharge areas leads to a more productive liquid-dominated system. In the natural state, a strong circulation of hot fluids through the reservoir from the region of deep fluid recharge to the discharge area, where there is mixing with local groundwaters, will result in an initially hotter geothermal system. If the communication is poor (or the source of hot fluids is weak), only small amounts of geothermal fluids will be transferred across the reservoir, cooling significantly by conduction as they flow. The final (natural state) temperatures in the system will be correspondingly lower.

A strong hydraulic connection with adjacent groundwater aquifers increases the entry of cooler-water into the reservoir when pressure is reduced in response to exploitation. This recharge certainly affects the temperature of wells located near the inflow areas, but the overall effect is beneficial. Pressures (and flow rates) are maintained and heat stored in the reservoir rocks is swept toward the producing wells. In addition, the near-well boiling decreases avoiding possible permeability reductions resulting from mineral precipitation in reservoir pores and/or fractures.

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