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SUMMARY OF HOT DRY ROCK GEOTHERMAL RESERVOIR TESTING 1978 TO 1980

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Abstract Experimental results and re-evaluation of the Phase I Hot Dry Rock Geothermal Energy reservoirs at the Fenton Hill field site are summarized. This report traces reservoir growth as demonstrated during Run Segments 2 through 5 (January 1978 to December 1980). Reservoir growth was caused not only by pressurization and hydraulic fracturing, but also by heat extraction and thermal contraction effects. Reservoir heat-transfer area grew from 8000 to 50 000 m^2 and reservoir fracture volume grew from 11 to 266 m^3. Despite this reservoir growth, the water loss rate increased only 30%, under similar pressure environments. For comparable temperature and pressure conditions, the flow impedance (a measure of the resistance to circulation of water through the reservoir) remained essentially unchanged, and if reproduced in the Phase II reservoir under development, could result in "self pumping." Geochemical and seismic hazards have been nonexistent in the Phase I reservoirs. The produced water is relatively low in total dissolved solids and shows little tendency for corrosion or scaling. The largest microearthquake associated with heat extraction measures less than -1 on the extrapolated Richter scale.

Introduction The HDR reservoirs at Fenton Hill are located in the Jemez Mountains of northern New Mexico. The reservoirs were formed between two wells, GT-2B and EE-1, drilled into hot, low permeability rock and hydraulically fractured. Reservoir performance was first evaluated by a 75-day period of closed-loop operation from January 28 to April 13, 1978 (Tester and Albright, 1979). The assessment of this first reservoir in EE-1 and GT-2B is referred to as "Run Segment 2" or the "75-day test." (Run Segment 1 consisted of a 4-day precursor experiment conducted in September 1977.) Hot water from GT-2B was directed to a water-to-air heat exchanger where the water was cooled to 25°C before reinjection. Makeup water, required to replace downhole losses to the rock surrounding the fracture, was added to the cooled water and pumped down EE-1, and then through the fracture system. Heat was transferred to the circulating water by thermal conduction through the nearly impervious rock adjacent to the fracture surfaces.

Run Segment 3 (Expt. 186), the High Back-Pressure Flow Experiment (Brown, in preparation) was run during September and October 1978 for 28 days. The purpose of this experiment was to evaluate reservoir flow characteristics at high mean-pressure levels. The high back pressure was induced by throttling the production well. Following Run Segment 3, the EE-1 casing was recemented near its casing bottom to prevent leakage of fluid into the annulus. An enlarged reservoir was then formed by extending a hydraulic fracture from an initiation depth of 2.93 km (9620 ft) in EE-1, about 200 m deeper than the first fracture in EE-1. The fracturing was conducted in March 1979, with two fracturing experiments. These experiments are referred to as "massive" hydraulic fracturing (MHF) Expts. 203 (March 14) and 195 (March 21). Preliminary evaluation of the new reservoir was accomplished during a 23-day heat-extraction and reservoir-assessment experiment that began October 23, 1979 (Murphy, 1980). This segment of operation with the EE-1/GT-2B well pair was Run Segment 4, or Expt. 215.

The long-term reservoir characterisics were investigated in Run Segment 5, or Expt. 217, which began March 3, 1980 (Zyvoloski, 1981). Because of the large size and resulting slow thermal drawdown, a lengthy flow time of 286 days was necessary to evaluate the reservoir. Run Segment 5 ended with the 2-day Stress Unlocking Experiment (SUE) (Murphy, 1981).

In the three years during which these reservoir tests were conducted, our understanding of reservoir behavior has steadily improved. Simplified models that were developed for Run Segment 2 were significantly modified by the time of Run Segment 5. Consequently, the previous tests were reanalysed in a consistent manner using the latest models. Further, the growth of the reservoir with time was traced and periods of growth attributed to thermal contraction and heat extraction effects were identified as apposed to growth caused by pressurization and hydraulic fracturing.

Heat Production and Heat-transfer Modeling

Heat-transfer modeling of the reservoirs has been performed with two numerical models. Both models use two-dimensional simulators in which heat is transported by conduction within the rock to the fractures. The most recently developed model (the multiple-fracture model) assumes that the reservoir consists of three parallel fractures idealized as rectangles in which the flow is distributed uniformly along the bottom of each fracture and withdrawn uniformly across the top. The flow is thus one-dimensional, and the streamlines are straight vertical lines. Consequently fluid dynamic considerations do not directly enter into the heat-extraction process, the sweep efficiency is implicitly assumed to be 100%. However, a rigorous two-dimensional heat-conduction solution is incorporated for the rock between the fractures, and this permits valid consideration of thermal-interaction effects between the fractures. In contrast, the older model (the independent-fractures model), assumes that the fractures (two in number) are circular and allows proper local positioning of the inlet and outlets, i.e., the point-like intersection of the injection well with the fracture can be modeled, as can the intersection of the main hydraulic fractures and the slanting joints that provide the connections to GT-2B. However, as was cautioned earlier, while the fluid dynamic effects of the joints/outlets can be faithfully modeled, the heat-transfer effect of the joints cannot; the area of the joints must be lumped with the main fractures. In view of this more faithful representation of inlet and outlets, and the fact that a complete two-dimensional solution to the Navier-Stokes fluid dynamic equations is incorporated, the independent-fractures model results in a more realistic assessment of the effect of fluid dynamics and sweep efficiencies upon heat extraction. The penalty, however, is that in the present two-dimensional version of the code, thermal interaction as the temperature waves in the rock between fractures overlap cannot be realistically represented, as it is with the multiple-fracture model.

Independent-Fractures Modeling The first application of this model was to the earlv research reservoir, when only a small single hydraulic fracture existed. This reservoir was tested extensively during Run Segment 2. Based upon spinner and temperature surveys in the production well, the depths of the intersections of the production well with the slanting joints were estimated as well as the flow rates communicated by each joint. In the calculations, the actual temporal variations of production and injection flow rates were utilized. With this information, estimates of the thermal drawdown were calculated with the model for various trial values of fracture radii and vertical position of the fracture inlet. A fracture radius of 60 m with an inlet located 25 m above the fracture bottom resulted in a good fit to the measurements. A radius of 60 m implies a total fracture area (on one side) of 11 000 m^2; however, because of hydrodynamic flow sweep inefficiencies the net area effective in heat exchange was only 8000 m^2.

During Run Segment 3 (the high back-pressure experiment) thermal drawdown suqgested that, according to the independent-fractures model, the effective heat area was nearly the same. However, flow rate (spinner) surveys in GT-2 indicated that because of the higher pressure level most of the flow was entering GT-2B at positions that averaged 25 m deeper than during Run Segment 2. In effect the reservoir flow paths were shortened about 25%. It was concluded that while pressurization did indeed result in partial short circuiting of the streamlines, it also resulted in a notable decrease in impedance, which afforded better fluid sweep and bathing of the remaining area. The reservoir was enlarged during the fracturing operations of 1979, the MHF Expts. 195 and 203. For the independent-fractures model the enlarged reservoir is portrayed as two fractures, the old one operative in Run Segments 2 and 3, with a new and larger one. The enlarqed reservoir was evaluated during Run Segment 4 and Run Segment 5. To summarize the Run Segment 4 studies, it was found that the old fracture had an effective heat-transfer area of 15 000 m^2 and the new fracture had an effective area of at least 30 000 m^2. The area determined in Run Segment 4 for the old fracture was at least twice that determined in Run Segment 2. This trend of increasing area is now attributed to thermal stress cracking effects (Murphy, 1979).

Better estimates of the total effective heat-transfer area of both fractures were obtained in Run Segment 5, during which the thermal drawdown was only 8°C. The mean outlet temperature actually increased slightly during the early portion of Run Seqment 5. This temporary increase is due to transport of deeper, hotter water to the production well, as well as to some interaction of the fractures. For simplicity the effect was neglected in the independent-fractures model as it is fairly small, less than 2°C. The data are fit very well by a model with a combined area of 50 000 m^2, some 5000 m^2 greater than the area tentatively estimated during Run Segment 4.

A summary of the heat-exchange areas determined with the independent-fractures model is presented in Fig. 1. As can be seen, a steady increase, from 8000 to 50 000 m^2, is indicated. As indicated by the question marks in Fig. 1, the area increase due to the MHF experiments (195 and 203), is uncertain. The heat-transfer area was not measured until the later stages of Run Segment 4. Consequently, the area increase measured is due to the combined effects of all the fracturing and Run Segment 4 operations, and cannot be individually ascribed to the separate operations.

Multiple-Fracture Modeling For the multiple-fracture model the following procedure was used to fit the data.

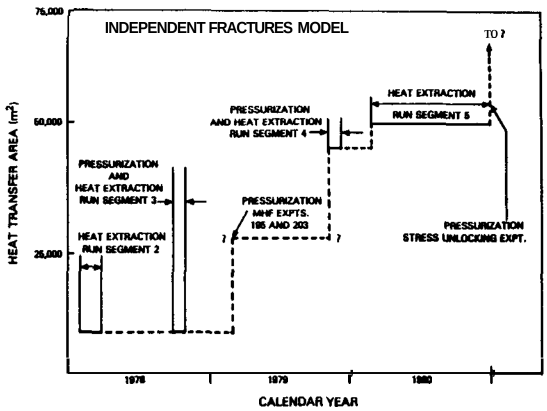

Figure 1 Heat transfer area growth determined by the independent fractures model in the Phase I reservoirs during Run Segments 2 through 5

- o The measured GT-2B flow rate and estimated reservoir inlet temperature were programmed as functions of time.
- o The initial fracture area was adjusted to obtain the best fit at early times.
- The fracture area was allowed to increase so as to provide a good fit to the remaining data. For computational simplicity, the area increase was assumed to occur in discrete steps rather than in a smooth, piece-wise linear, fashion.

As indicated earlier, the independent-fractures model was not able to detect any increase in the effective heat-transfer area during actual drawdown, but the multiple fracture model indicates that the heat-transfer area increased by a factor of two.

Similar modeling was carried out for Run Segments 3, 4 and 5. Figure 2 summarizes the growth of the heat-exchange area, according to the multiple-fractures model, throughout Phase I. The general similarity with the summary of the independent-fractures model, Fig. 1, is noted, but there are differences in detail.

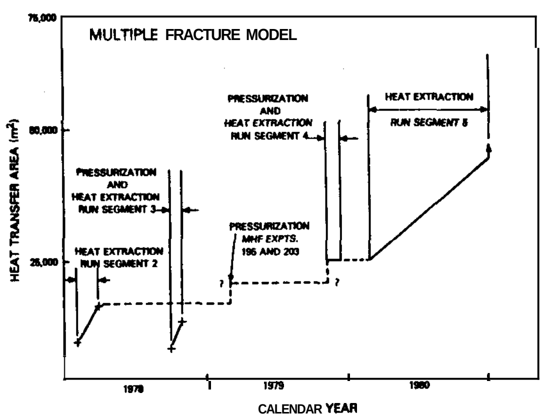

Figure 2 Heat transfer area growth determined by model fits to drawdown data and wellbore temperature logs in the Phase I reservoirs during Run Segments 2 through 5

The initial area of 7500 m^2 was established by many pressurizations and some cooling. This area grew to 15 000 m^2 in Run Segment 2. As indicated earlier the high back pressure of Run Segment 3 caused a redistribution of flow resulting in fluid dynamic short-circuiting. However, unlike the independent-fractures model, the new model indicates that the initial heat-exchange area was actually less than that of Run Segment 2, starting at 6000 m^2; but it then grew to 12 000 m^2 during the 28-day test. The system was pressurized to high pressures several times during MHF Expts. 203 and 195 and Run Segment 4 but no area or volume measurements were made until Run Segment 4. After Run Segment 4, the EE-1 temperature logs indicated that between 6000 and 9000 m^2 had been added to the lower part of the reservoir by the recementing and pressurization prior to and during Run Segment 4. This increased the measured heat-exchange area to between 21 000 and 24 000 m^2. The area measurements during Run Segment 5 are somewhat uncertain. The best estimates are that the heat-exchange area was qreater than 45 000 m^2 at the end of the experiment. The lack of recovery of the outlet temperature indicates that the additional area is in the depleted upper half of the reservoir or was partly added to the lower half as Run Segment 5 proceeded.

Tracer Studies and Fracture Volume Growth The main objectives of reservoir tracer studies are to assess the volume changes associated with the creation of the Phase I system and to determine dynamic behavior of the system volume as the system undergoes long-term heat extraction. The fracture modal volume is simply the volume of fluid produced at GT-2B between the time the tracer pulse was injected and the time the peak tracer concentration appeared in the produced fluid. The wellbore volumes are subtracted from the total volume produced to give the true fracture modal volumes. The modal volume is considered the most reliable indicator of reservoir volume change. Large changes in the modal volume are observed after the hydraulic fracturinq of the system between Run Segments 3 and 4 and during the SUE, which followed Run Segment 5.

A complete review of the tracer-test data from Segments 2 through 5 has revealed pertinent information regarding the growth of the reservoir due to heat extraction and pressurization effects. The reservoir growth due to heat extraction is, to be precise, really a thermal-contraction effect -- as the rock surrounding the fractures shrinks, the fractures, and consequently, the measured volumes, expand. In spite of nonlinear coupled effects of thermal contraction, pore and fracture inflation due to sustained pressurization, and local irreversibilities resulting in fracture propagation, a simple correlation between ΔV and ΔE exists. Furthermore, this simple relationship persists even in the presence of the confining stresses surrounding the active reservoir, which induce a constrained behavior. For practical purposes, the region between the low-pressure data and the free thermal volume lines defines an envelope of reservoir operating conditions. As stresses are relieved, for example during SUE, or the high back-pressure test of the original reservoir (Run Segment 3), or the high-pressure, hydraulic-fracturing stage at the beginning of Run Segment 4, one moves away from the normally constrained condition toward the free thermal expansion line.

Perhaps the most promising aspect of the tracer tests is their potential for estimating the effective heat-transfer surface area of a reservoir. This becomes clear when the modal volume (plotted vs time in Fig. 3) is compared to the corresponding heat-transfer area (plotted vs time in Figs. 1 and 2); the similarities of the growth of area and volume are quite striking. This can be quantified by considering the relationships between area, volume, and aperture (or effective fracture opening). The volume, V, is simply the product of the area, A, and the mean aperture, w: $V = A \cdot w$. During heat extraction and/or pressurization, the area and aperture can both vary; therefore the volume is a function of two variables rather than one. For constant aperture, the tracer volumes should scale directly with heat-transfer area. Further development of this empirical correlation could provide a direct and independent method of determining reservoir heat-transfer area without requiring thermal drawdown, which is time consuming and expensive to obtain, particularly so for the larger Phase II reservoir under development.

Impedance Characteristics The impedance of a circulating geothermal reservoir is usually defined as the pressure drop between the inlet and outlet of the fracture caused by flow in the fracture, divided by the exit volumetric flow rate. Its units are pressure-s/volume, and in this report we typically use Giga Pascals per cubic meter per second (GPa s/m^3) or in English customary units, pounds per square inch per gallon per minute (psi/gpm). Because pressures are usually measured at the surface, a "buoyancy" correction should be made for the difference in hydrostatic pressures in the hot production well and the cold injection well. The depth at which this correction is calculated corresponds to the bottom of the injection well, that is, buoyancy inside the fracture is included in the hot leg. Impedances of about 1 GPa s/m^3 are considered desirable. For example, in the deeper and hotter Phase II reservoir being completed now, such a low value of impedance could actually result in "self-pumping" of the reservoir because of buoyancy effects.

Figure 4 summarizes the impedance history over Segments 2 through 5 and the SUE experiment. Impedance is dependent on fracture aperture, w. Theoretically, it decreases as $1/w^3$ in both laminar and turbulent flow. Aperture may be increased in several ways: (1) by pressurization of the fracture, (2) cooling of the surrounding rock, (3) dissolution of minerals lining the crack by chemical treatment of the fluid, and (4) by geometric changes resulting from relative displacement of one fracture face with respect to the other. Run Segments 2 and 3 were especially useful in demonstrating the correlation between impedance and pressure and temperature. The impedance changes observed after SUE were probably due to additional "self-propping" caused by slippage along the fracture faces near the exit or by other pressure-induced geometric changes.

The concentration of impedance near the exit, shown in all the low back-pressure flow experiments, may be desirable when the system impedance is reduced by multiple fractures. In this mode of reservoir development, the possibility of unstable "runaway" (one fracture cooling and taking much of the flow) exists, and the exit impedance concentration will prevent this until reservoir cooling has been extensive. Eventually, the problem of flow control in the individual fractures may arise,

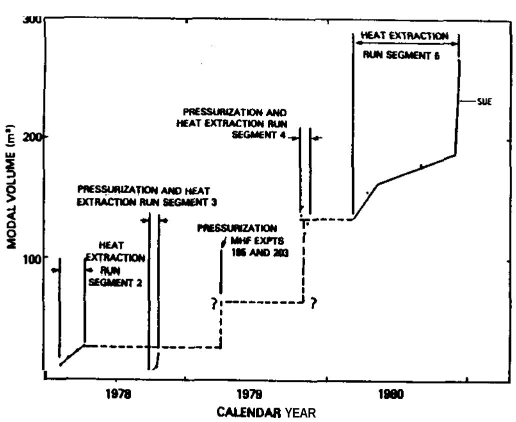

Figure 3 Growth of tracer modal volume in the Phase I reservoirs during Run Segments 2 through 5

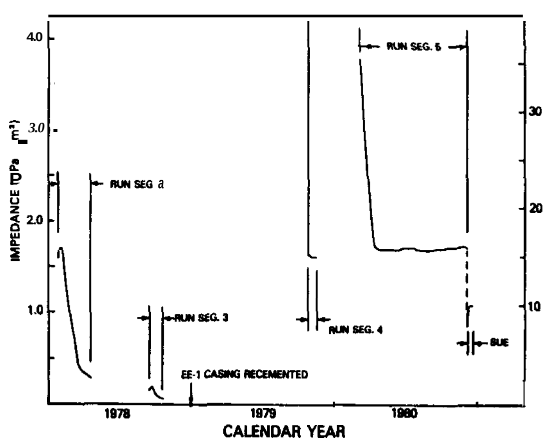

Figure 4 Flow impedance behavior in the Phase I reservoirs during Run Segments 2 through 5

and methods of flow control near the fracture entrance may be required.

During normal, low back-pressure conditions fracture impedance appears to be concentrated near the exit well, at least after a short period of operation, and total impedance does not depend strongly on wellbore separation. Impedances are sufficiently low to allow operation of efficient HDR geothermal energy-extraction systems. The impedance in a large system does not change rapidly, and the prognosis for operation of the multiple-fracture, Phase II system seems favorable.

Water Losses The water loss of an HDR system is very important because this water must be provided from some outside source. This information can be vital for environmental as well as economic reasons. The water-loss rate, that is, the rate at which water permeates the rock formation surrounding the fracture system, is the difference between the injection rate and the produced, or recovered, rate at GT-2B. This loss rate is a strong function of system pressures and flow rate and would also be expected to be a function of reservoir size.

The water-loss flow-rate data of each experiment contain many transients due to operation shutdowns, pump limitations, and various leaks. Consequently, the accumulative volume of water loss is best suited for comparisons since many of the transients are smoothed out, and this comparison is presented in Figure 5, for Run Segments 2, 3, and 5. Run Segment 4, only 23 days long, was excluded from this comparison because of the disparate conditions under which it was conducted.

Comparisons between Run Segments 2 and 5, both conducted under normal, low back-pressure conditions, can be made as follows. Direct comparisons indicate that the water loss for Run Segment 5 is approximately 40% higher than that of Run Segment 2 at comparable times after the beginning of heat extraction. However, because the operating pressure was 10% higher during Run Segment 5, the water

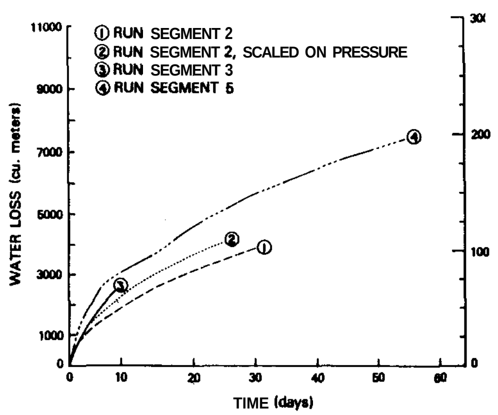

Figure 5 Cumulative water losses vs time for Run Segments 2, 3, and 5

loss for Run Segment 2 should be scaled up by 10% as in curve 2 of the figure, in order to be directly comparable to Run Segment 5. Then it is seen that the Run Segment 5 water loss is only 30% higher than Run Segment 2, despite a several-fold increase in heat-transfer area and volume. An obvious conclusion is that the heat-exchange system utilizes only a small portion of a much larger fracture system that controls water loss. This large, potential fracture system was not altered to any large extent by the MHF experiments of Segment 4. Furthermore, in comparison to the heat-transfer areas, these other areas did not grow siqnificantly from Run Segments 2 throuqh 5.

Fluid Geochemistry Analysis of the fluid-chemistry data from the Phase I reservoirs shows several interesting features that are pertinent to the size of the reservoirs. Strong evidence from each of the Phase I heat-extraction experiments indicates the existence of essentially two parallel flow paths: (1) a fracture-dominated flow path (perhaps consisting of multiple fractures) that includes the heat-transfer surfaces, and (2) a high-impedance flow path consisting of the connected microfractures and pores in the rock surrounding the heat-extraction portion of the reservoir. Displacement of the indigenous pore fluid contained in this high-impedance flow path is the single most important geochemical effect observed in the heat-extraction experiments to date. This is discussed further by Grigsby et al. (1981).

In summary, several conclusions should be drawn from geochemistry results to date. First of all, the overall circulating fluid quality in a HDR system is largely fixed by the pore-fluid concentration and displacement rate. Under the very worst conditions (that is, 100% of the produced fluid is pore fluid) the maximum concentration of dissolved solids would be around 5000 mg/ℓ for this reservoir -- within the Environmental Protection Agency (EPA) water quality standard for continuous irrigation of salt-tolerant plants. However, the steady-state concentration of total dissolved solids is typically 2500 mg/ℓ -- similar to water used for human consumption in many parts of the country. The pH of the water is 6.5 ± 0.5, nearly neutral, and problems with corrosion or deposition upon surface equipment such as piping, heat exchangers, and pumps have been minimal.

A second conclusion from the fluid-geochemistry studies concerns the very large volume of pore fluid that has been displaced from the rock surrounding the fracture system into the fracture system. Because this fracture system is everywhere pressurized above hydrostatic pressure, circulating fluid should be continuously lost to the surrounding matrix, which is subhydrostatic. Porefluid from this subhydrostatic pressure field would have to flow against a pressure gradient in order to enter the flowing system. However, secondary flow paths with impedance intermediate to that of the main fracture system and that of the unfractured reservoir rock provide a means for the pressure level in the main fracture(s) to displace the pore fluid into the flow system. Finally, the flow from these secondary paths appears to be partially sensitive to the pressure difference between the inlet and outlet and probably, to the overall level of pressurization of the reservoir.

Seismicity Seismic monitoring was conducted for all the run segments with a surface seismic array and during portions of Run Segments 4 and 5, and SUE, with downhole geophone packages positioned in the reservoir vicinity. The objective of this monitoring was to evaluate potential seismic risks associated with HDR geothermal energy extraction. The largest event detected in Run Segment 4 with the downhole package had a magnitude of -1.5. The energy release of a -1.5 magnitude microseismic event is roughly equivalent to that of a 10 kg mass dropped 3 m. Furthermore, this event occurred during the high back-pressure stage. During the low back-pressure stage, more typical of ordinary heat-extraction conditions, the largest event was -3. During the 286-day Run Seqment 5, 13 microearthquakes ranging between -1.5 and 0.5 were recorded by the surface seismic array. These events were located about 200 m north of EE-2 at a depth of about 1 km. The events are not related to Run Segment 5 activities, but rather to the drilling of EE-2 and EE-3.

Conclusions The reservoirs of the Phase I HDR geothermal energy system have exhibited growth through all segments of operation. This growth resulted from pressurization, cooling (thermal contraction), and fracture-face displacement or movement. During the early time experiments (Run Segments 2 and 3) thermal drawdown was significant due to the small size of the reservoir involved (90°C for Segment 2 and 37°C for Segment 3). In the later experiments, drawdown was much less significant due to the larger reservoir. No drawdown was observed during Segment 4, and during Segment 5 operations, the reservoir sustained only an 8°C thermal drawdown after 286 days. Modeling of the Phase I reservoirs led to an estimated heat-transfer area of 8000 m^2 for Run Segment 2, while by the end of Run Segment 5 the heat-transfer area was estimated to be 45 000 to 50 000 m^2, about six times larger. Measured tracer volumes suggested a fracture area of 80 000 m^2 by the end of Segment 5. Modal volume of the reservoir has grown from 11 to 266 m^3 through the course of Phase I experiments.

Water losses were very encouraging because, for comparable operating pressure conditions, only a 30% increase of water loss was observed for a sixfold increase in heat-transfer area. The impedance remained constant throughout Run Segment 5 at about 1.6 GPa s/m^3. This is in contrast with the Run Segment 2 reservoir that exhibited a sharp decline in the impedance, presumably due to the large thermal drawdown that the system experienced. Geochemical monitoring of the system provided valuable insight concerning pore-fluid displacement and flow connections in the reservoir. The concentrations of dissolved chemicals in the produced water were relatively low and the pH was near neutral, so the produced water was of good quality and problems with corrosion or scaling of surface equipment have been minimal. Seismic activity in the Phase I reservoirs has been insignificant. Events associated with heat extraction have measured less than minus one on the extrapolated Richter scale,

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