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USING A HOT DRY ROCK GEOTHERMAL RESERVOIR FOR LOAD FOLLOWING

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ABSTRACT

Field measurements and modeling have shown the potential for using a Hot Dry Rock (HDR) geothermal reservoir for electric ***load following***: either with Power-Peaking from a base-load operating condition, or for Pumped Storage of off-peak electric energy with a very significant thermal augmentation of the stored mechanical energy during periods of power production. For the base-load with power-peaking mode of operation, an HDR reservoir appears capable of producing over twice its nominal power output for short -- 2 to 4 hour -- periods of time. In this mode of operation, the reservoir normally would be produced under a high-backpressure condition with the HDR reservoir region near the production well highly inflated. Upon demand, the production backpressure would be sharply reduced, surging the production flow.

Alternatively, for Pumped Storage, the reservoir would be operated in a cyclic mode, with production shut-in during off-peak hours. When the produced thermal energy of such a pumped-storage system is considered, an HDR reservoir would be capable of returning considerably more energy to the surface during the production phase than would have been consumed in inflating the reservoir during the off-peak storage phase. Pumped Storage reservoir operation was actually demonstrated experimentally during a brief series of cyclic reservoir tests at the end of the Long-Term Flow Test (LTFT) of the HDR reservoir at Fenton Hill, NM in May 1993.

The analytical tool used in these investigations has been the transient finite element model of the an HDR reservoir called GEOCRACK, which is being developed by Professor Dan Swenson and his students at Kansas State University. This discrete-element representation of a jointed rock mass has recently been validated for transient operations using the set of cyclic reservoir operating data obtained at the end of the LTFT.

INTRODUCTION

The subjects of Power Peaking and Pumped Storage Energy Production, which would offer electric utilities flexibility in load management when using engineered Hot Dry Rock (HDR) geothermal systems, are very timely as concerns the commercialization of HDR geothermal technology. This is because one or the other of these load following concepts may provide an initial "niche" market application which would allow HDR geothermal energy to become economically competitive earlier in the commercial demonstration phase, before HDR technology would have had sufficient time for the anticipated engineering refinements that will be necessary to make HDR power generation an accepted option in the presently very competitive electric power marketplace. In both of these applications, one would use the large fluid capacitance of a highly pressurized HDR reservoir to store and then rapidly produce energy. The resulting flexibility offered by these engineered HDR systems may be the ultimate key to the development of HDR geothermal energy as a commercial reality.

The first concept is that of on-demand power peaking using an HDR geothermal system. In this concept, the HDR reservoir would be continuously produced in a high-backpressure base-load operating mode with the ability -- and flexibility -- to almost instantaneously double the power output by dropping the production backpressure to a much lower level. In practice, this might be accomplished by reducing the backpressure from a base-load level of 3000 psi to 700 psi in less than a minute, effecting a very significant increase in the production flow rate, as well as an increase in the produced geofluid temperature, as the inflated portion of the reservoir surrounding the production wellbore is rapidly vented.

The second concept is that of using an HDR reservoir for pumped storage and power peaking as follows: The reservoir would be shut-in and pressurized with an electrically driven pump during off-peak hours, inflating the reservoir with fluid and storing mechanical energy through the elastic compression of the rock comprising the HDR reservoir region. Then, the reservoir would be partially vented during the subsequent period of peak power demand, returning the previously stored mechanical energy in the form of a much larger amount of thermal energy. This augmented energy production, with the mechanical energy being returned as thermal energy, obviously results from the increase in the enthalpy of the injected fluid as heat is extracted from the HDR reservoir during the storage phase of the cycle. This recovered thermal energy, during the production phase of the cycle, would then be converted to electrical energy in a conventional geothermal power plant.

In this "pumped-storage" mode of operation, an HDR reservoir is capable of returning to the surface significantly more thermal energy than was stored as mechanical energy during the hours of off-peak pressurization. This behavior is not unlike that of a heat pump, which is capable of providing several times its electric power input as space heat during winter months.

This study represents only a first analysis of these two HDR load-following concepts. A more definitive study must await a comprehensive experimental data set supported by further numerical modeling. The presently available data is from a 3-day sequence of cyclic flow experiments performed in May 1993, at the end of the Long-Term Flow Test (LTFT) of the Fenton Hill HDR reservoir. The modeling results presented here will allow us to better define and plan the sequence of HDR production flow experiments planned for the summer of 1995.

ADVANTAGES AND DISADVANTAGES OF THESE TWO METHODS OF LOAD FOLLOWING

Advantages of operating an HDR system in a high-backpressure base-load mode with the option of power peaking:
• This mode of operation would add significantly to the flexibility of an HDR-based geothermal power plant.
• The revenue potential would be increased due to the doubling of the power output during periods of peak demand and the premium price paid for peaking power.
• Injection pumping costs during high-backpressure base-load operation would be reduced because elevated production pressures would, with proper surface-system design, significantly reduce the pumping power required for any given injection pressure.

Disadvantages:
• The base-load power production at a backpressure of 3000 psi would be only about 60% of that at 1400 psi.
• Production wellhead equipment would be subjected to marked pressure fluctuations.
• A more complicated power plant design would be required, with more injection pumping capacity and with attendant increased capital costs to accommodate the doubling of the production thermal power output during the relatively short periods of enhanced production.

Advantages of Cyclic Reservoir Operation Associated with Pumped Storage:
• During the production portion of the cycle, significantly more power would be generated than during comparable base-load operation, partially compensating for the reduced period of power production.
• Heat removal from the less-fluid-accessible portions of the reservoir volume would be enhanced.
• Cyclic operation would reduce the tendency for reservoir flow short-circuiting.

Disadvantages:
• This method of operation could adversely affect power plant and wellhead equipment due to pressure *and* temperature fluctuations.
• The capital investment in the power plant, wells and reservoir would be underutilized. However, enhanced reservoir power production and peaking-power revenue would at least partially compensate for lost revenue during shut-in periods.
• Borehole heat losses would be accentuated since the production well(s) would be shut-in for up to 16 hours per day. This would have the effect of markedly reducing the surface production temperature for the first few hours of each production interval, as discussed later. An insulated production tubing string would reduce these heat losses, but at an added cost.
• To best utilize the pumped-storage aspect of this mode of operation, it would be most advantageous if the reservoir were produced open-loop, with the fluid stored above ground for later reinjection. However, this would add to the overall capital costs and would result in the evolution of some of the gas dissolved in the geofluid and the precipitation of minerals during the time of storage.

MODEL REPLICATION OF EXPERIMENTAL CYCLIC RESERVOIR PERFORMANCE

The GEOCRACK model was first validated against the cyclic reservoir performance measured near the the end of the Long Term Flow Test in May 1993. The injection and production pressure profiles for these three cycles are shown in Figure 1 while the corresponding injection and production flow rates are shown in Figure 2. It should be noted that because freezing nighttime temperatures were still anticipated at Fenton Hill during May, a small (about 25 gpm) production flow was maintained during each 16-hour overnight production "shut-in" to prevent damage to the air-cooled heat exchanger.

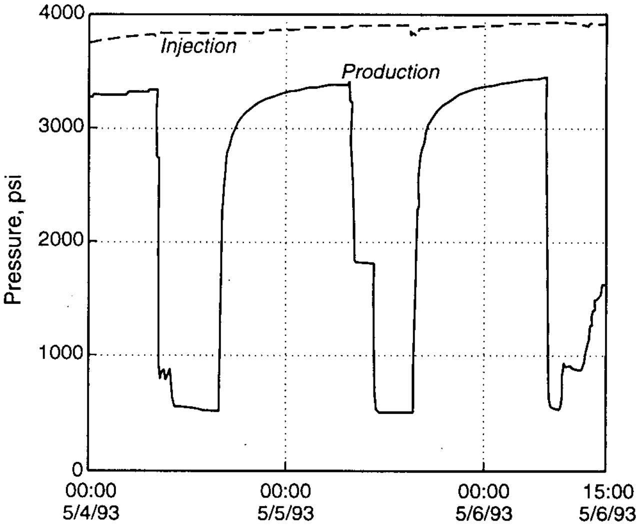

Figure 1. Injection and Production Pressure Profiles During the 3-Day Cyclic Flow Experiment in Early May, 1993.

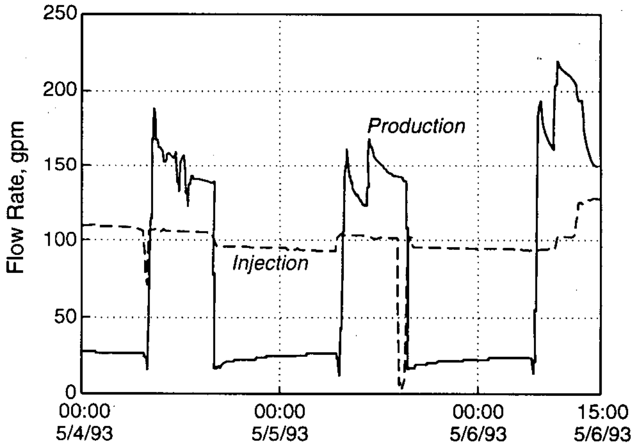

Figure 2. Injection and Production Flow Rate Profiles During the 3-Day Cyclic Flow Experiment.

Analysis efforts were concentrated on the second cycle which began the morning of May 5 (at the first sharp drop in production backpressure) because this cycle contained all the necessary components for an adequate model validation:

- Two unique levels of production backpressure during the 8-hour production interval: 1800 psi and 500 psi,
- A 16-hour period of reservoir inflation while the production well was nearly shut-in and,
- A near-constant injection pressure of 3900 psi.

As shown in Figure 2, the most significant feature regarding production enhancement is that the *average* flow rate during the second 8-hour production interval was about 145 gpm. This flow rate is about 60% greater than the previous steady-state production flow rate of 90 gpm measured two weeks earlier at the end of the second phase of the Long-Term Flow Test (Brown, 1994a).

Figure 3 shows the production temperature variation during these three one-day cycles. The initial production temperature of only 107°C (225°F) at the beginning of the first 8-hour production interval shows the significant cooling effect resulting from having shut-in production for the previous 13 days. At the beginning of the next two intervals, the geofluid production temperature is still depressed, but not as much as for the first cycle. For the second and third cycles, the initial geofluid temperature was in the range of 130°C (260 to 270°F) compared to the 184°C (363°F) geofluid production temperature near the end of the second phase of the LTFT in April 1993 (Brown, 1994a). These temperatures clearly show the effects of wellbore cooling during the preceding 16-hour shut-ins. This reduced geofluid temperature for the first 3 to 4 hours of each production interval points up an obvious disadvantage with this mode of reservoir operation which, however, could be mitigated by using an insulated production tubing string.

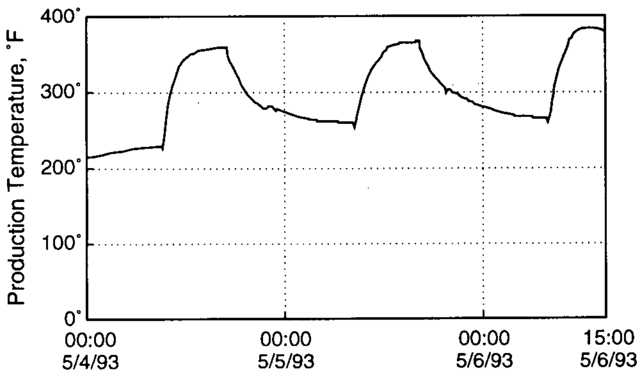

Figure 3. Production Temperature Variation During the 3-Day Cyclic Flow Experiment.

MODELING RESULTS

Replication of Actual Cyclic Reservoir Behavior

The behavior of the Phase II HDR reservoir during transient operations has been modeled with the finite-element coupled fluid-flow and deformation portion of the GEOCRACK model. In particular, the reservoir behavior during the second 24-hour cycle shown in Figures 1 and 2 (from 08:00 on May 5 through 08:00 on May 6) has been simulated with GEOCRACK. As shown in these two figures, there were essentially two phases to this second cycle which can be represented as follows: A two-stage high-rate production interval starting at 08:00 on May 5 and lasting 8 hours, followed by a low-production/very-high-backpressure phase lasting 16 hours.

The model input parameters and results for the simulation of the second cycle are shown in Figure 4. It should be noted that the initial half-day "lead-in" period shown in this figure was used to establish the array of converged steady-state solutions throughout the reservoir region before the sharp transient drop in the production backpressure at 0.5 days. For the entire period modeled, a constant injection pressure of 3700 psi (25.5 MPa) and the time-varying production backpressure profile shown in Figure 4 were used as model inputs. For the 8-hour high-production phase, two stepwise decreases in the production backpressure, from an initial value of 3500 psi (24.2 MPa), were specified: first to 1800 psi (12.5 MPa) for 3 hours and then to 500 psi (3.5 MPa) for the next 5 hours. For the subsequent 16-hour phase of this cycle, a very rapid increase in the production backpressure from 500 psi to 2980 psi (20.5 MPa) was specified, followed by a much more gradual approach to a near-constant backpressure of 3500 psi (24.2 MPa) by the end of 16 hours.

Figure 4 also presents the principal outputs from the model simulation of the cyclic behavior of the reservoir for an 8-hour high-production-rate phase followed by a 16-hour near shut-in phase -- the temporal variation of the production flow including a constant production flow rate of 25 gpm for the second 16-hour phase. When compared to the measured production flow behavior during the second cycle as shown in Figure 2, the high degree of replication by the GEOCRACK model is evident.

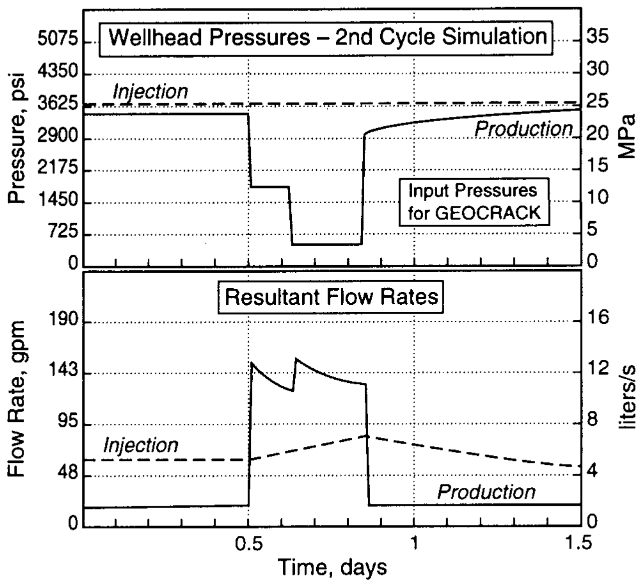

Figure 4. Modeling Results for the Second Cycle of the Cyclic Flow Experiment.

CYCLIC RESERVOIR OPERATION ASSOCIATED WITH POSITIVE-GAIN PUMPED STORAGE

The actual behavior of the Fenton Hill reservoir under an 8-hour on and 16-hour off mode of cyclic production has already been experimentally determined. This behavior is best represented by the second production cycle starting May 5, 1993 as discussed above. During continuous commercial operation of such an HDR load-following system, it would be anticipated that a very similar approach would be taken: a high production rate during daytime hours followed by a near shut-in condition during off-peak hours. To minimize the effects of thermal transients on the production piping and to prevent freezing during winter operations, it would be anticipated that a modest production flow would be maintained during the "shut-in" periods, as was used at Fenton Hill. Thus, the measured behavior as shown in Figures 1, 2, and 3 as well as the modeling results shown in Figure 4 can be used to better understand cyclic HDR system operation associated with a positive-gain pumped storage mode of reservoir operation.

A first observation is that the amount of mechanical energy stored during 16 hours of reservoir inflation is small compared to the electrical energy generated during the 8 hours of high-production flow. For a combined 2-well injection rate of 272 gpm at 5200 psi (Brown, 1994b), only 10 MW-hours of mechanical energy would be stored during the 16-hour reservoir inflation (shut-in) phase. During the 8-hour production phase, however, up to 40 MW-hours of electrical energy could be produced, representing a net gain of a factor of 4 over the stored mechanical energy. This number was derived as follows from the previously reported 20 MW(th) potential power output from the Fenton Hill Reservoir when using a 2-production-well system (Brown, 1994b):

Average production flow enhancement for 8 hours = 1.6 (145 gpm/90 gpm)

Peaking power production = 1.6 x 20 = 32 MW(th)

Using a net 16% power conversion efficiency for a geofluid production temperature of about 210°C (410°F), and with no injection pumping losses, the peaking electrical power generation would be about 5 MW for 8 hours, or 40 MW-hours of electrical energy -- 4 times the stored mechanical energy.

A second observation is that if the Fenton Hill reservoir were to be operated in this load-following mode for 8 hours a day, one would need to sell this peaking power for at least twice the base-load rate to produce the same revenue as continuous base-load operation (assuming other plant costs were comparable).

However, the absence of flow short-circuiting, the enhanced thermal recovery from the entire reservoir region, and the fact that the reservoir would experience only half the draw-down (or, conversely, twice the lifetime) when compared to base-load operation may add to the desirability of this cyclic mode of reservoir operation.

Operation in a High-Backpressure Base-Load Mode with the Capability for Power Peaking

Operation of the Fenton Hill reservoir in a high-backpressure base-load mode of operation, with periodic flow surging to approximate the system response to a peaking power demand, has also been simulated with the GEOCRACK model. Steady-state reservoir operating conditions as measured during the LTFT and the two higher backpressure portions of the Interim Flow Test (Brown, 1994a) were used to determine reservoir flow parameters and boundary conditions. However, the model had to be adjusted in the far-field region to account for the significantly larger capacitance of the Phase II reservoir than had previously been replicated by the GEOCRACK model. The simulations were performed as if the HDR system were being operated in flow control, with the backpressure being continuously adjusted to produce a constant elevated flow rate during periods of peak power demand. These periods of enhanced power production were assumed to be for either 4 or 8 hours each day.

Figure 5 shows the predicted behavior of the Fenton Hill HDR system operated in a high-backpressure mode, with 4-hour power surges each day produced by significantly reducing the production backpressure from a 3000 psi baseline level. This figure shows the specified production flow parameters: 63.5 gpm (4 l/s) for 20 hours and then 127 gpm (8 l/s) for the next 4 hours. Using a flow control system to produce a constant power output by controlling the production backpressure, the base-load flow rate was easily doubled during the 4-hour period of peak power demand. It should be noted that since the production backpressure only dropped to 1820 psi (12.5 MPa) during this period of enhanced power production, the overall system performance could be further improved in either of two ways: By reducing the backpressure level during base-load operation, the base-load power output could be increased and the minimum backpressure would still not drop below the desired 500 to 700 psi level during the period of flow surging. Alternatively, the production flow rate could be increased by more than a factor of 2 during peaking operations, increasing the power output and still not dropping below the 500 psi backpressure limit after 4 hours of enhanced production.

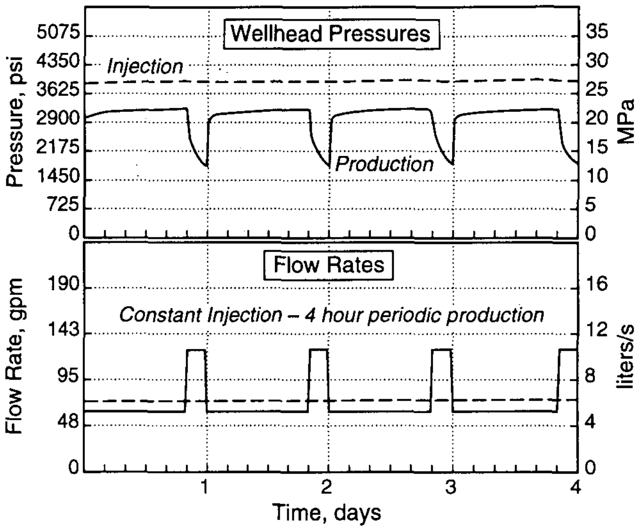

Figure 5. Simulated Reservoir Behavior for High-Backpressure Base-Load Operation with 4 Hours of Low-Pressure Production Every 24 Hours.

Figure 6 presents the results from simulating a similar peaking-power mode of reservoir operation, but with an 8-hour high-rate production interval rather that the 4-hour period discussed above. In order to produce the same level of enhanced power production for 8 hours instead of 4 hours, it was necessary to increase the mean injection pressure by 300 psi, to 4250 psi (29.3 MPa). As a consequence, the base-load production flow rate increased from 63.4 gpm (4 l/s) to 85.6 gpm (5.4 l/s), resulting in only a 48% gain in power during the period of enhanced power production, but now from a considerably higher initial power level.

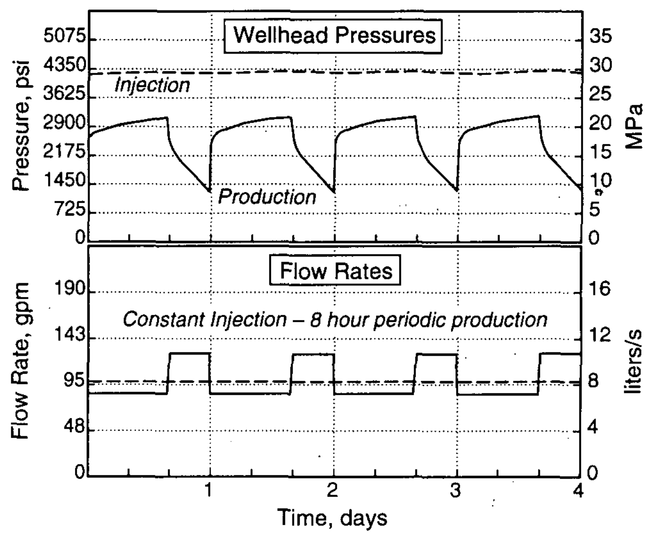

Figure 6. Simulated Reservoir Behavior for High-Backpressure Base-Load Operation with 8 Hours of Low-Pressure Production Every 24 Hours.

Hopefully, questions regarding how best to operate an HDR reservoir in a base-load mode with extended power surges will be answered experimentally during the reservoir flow testing planned for the summer of 1995.

DISCUSSION AND CONCLUSIONS

These preliminary experimental and modeling results suggest that load-following methods of HDR reservoir operation could be very attractive from a commercial power-production standpoint.

The HDR load-following concept which maintains the system in a high-backpressure base-load operating condition except for periods of peak demand, when the reservoir is produced in a rapid venting mode with at least twice the power output for 4-hour intervals, appears to offer the most attractive method of load following.

However, positive-gain pumped storage using an HDR reservoir appears to offer several advantages over conventional pumped storage concepts now being used by the electric utility industry -- the principal one being an energy output several times greater than the off-peak energy storage.

As now planned, the initial results obtained from this study will be confirmed during the summer of 1995 when a sequence of cyclic flow tests will be performed in association with additional numerical modeling using a model with a more detailed representation of the jointed rock region in the vicinity of the production wellbore. This region of the model is the most important for modeling cyclic reservoir production, since a significant fraction of the produced fluid will have been stored in the pressure-dilated region within 100 m or so of the production wellbore prior to each low-backpressure production interval.

References

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