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Reservoir Simulation of Brady's Geothermal Field, Nevada

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ABSTRACT

Brady Power Partners (BPP) has operated a 20 MWe dual-flash electrical power plant at Brady's since 1992. BPP's operations obtain geothermal water from pumped production wells drilled into the Brady's fault zone. From the beginning of operation, cooling of production by breakthrough from injectors drilled into the fault zone about a mile north has been a problem. To aid in finding an optimal operation of the resource, BPP initiated a comprehensive technical assessment of the geothermal resource at Brady's in the late 1990's. The result was the location and development of an unconnected injection field to the southeast of the producers and development of a fully calibrated TETRAD numerical model of the resource. The model was used to make quantitative forecasts of reservoir performance under various scenarios, balancing remote injection to arrest the cooling versus required pressure support for productivity. These scenarios were compared and the final operating plan consisted of diverting a specific amount of injection to a remote area and installing a 5.0 Mw binary bottoming cycle plant to operate on the effluent of the existing flash plant. With several years of operating history, including two of binary operation, the numerical model continues to closely match the measured data and the installation of the binary has been successful.

Conceptual Geologic Model of Brady's Geothermal Field

The first phase of this modeling effort was the integration of available geologic and temperature data into a conceptual model of the field. The distribution of temperature and permeability are discussed together because they are related. In a convecting geothermal resource venting to the surface, such as Brady's, thermal fluid flows upward from depth through permeable structures, i.e. fault zones, to ground level. Defining the three-dimensional pattern of temperature, therefore, also helps in specifying the permeable zones.

All downhole temperature data for Brady's wells were collected and reviewed to identify surveys that represent static, initial conditions before the BPP power plant started. These pre-startup records define the natural state temperature distributions which is required for later comparison to the numerical model output. Temperatures were contoured on horizontal sections drawn at seven elevation intervals between +3,900 and +1,000 ft (msl). Vertical temperature sections have also been constructed from the temperature profiles and combined with the geologic sections. Collectively, these drawings show the three-dimensional distribution of temperature and the manner in which geologic structures control the temperature pattern and define the Brady's reservoir. The following features summarize the conceptual geologic model of the Brady's field:

- The permeability consists mainly of fractures associated with major faults. Three major faults comprising the Brady's Fault Zone strike northeast through the field. These faults are offset westward by northwest trending cross-faults that appear to dip steeply northward.
- Seven stratigraphic units exist in the Brady's field. All of these units have been structurally displaced and rotated by the faults. The only effect the different lithologies have on the resource is that limited matrix permeability occurs in near-surface siltstones in BPP's northern injection area and in shallow basalt lavas that appear to be micro-fractured away from the faults creating matrix-like permeability. An additional effect may be caused by a marble bed in the basement that could allow secondary calcite to seal deeper portions of the faults.
- The parent ~410 °F reservoir is located in the basement stratigraphic unit which appears to be micro-fractured. Water from the parent reservoir at ~410 °F enters permeable fractures associated with the Middle and Brady's Faults and migrates upward along these fault planes.

Numerical Model of Brady's Geothermal Field

The numerical model was built using the latest version of TETRAD reservoir simulator. TETRAD is a commercial, state-of-the-art reservoir simulator that is widely used in the geothermal industry.

The numerical model is based on a rectangular grid system that is oriented in a direction rotated 26.5 degrees to the northeast. This scheme allows the y-axis of the grid to be in approximate parallel alignment with the Brady's fault zone. The model covers a total area of nearly 11 square miles: 15,000 feet in the NW-SE direction (x-axis), and 20,000 feet in the NE-SW direction (y-axis). The location of the model with respect to the BPP lease area is shown in Figure 1. The top of Layer 1 is the ground surface. The bottom of Layer 18 reaches a depth of 10,000 ft. Figure 2 shows a cross-section of the vertical grid system.

In order to begin running a natural state model, an estimate is needed of the natural inflow of geothermal water from depth. It is assumed that prior to field development, the Brady's system was in a steady-state condition. In this natural state, energy and mass that leave the system are exactly balanced by energy and mass that enter the system. Therefore, the energy that leaves the ground surface through the Brady's thermal anomaly is balanced by energy that enters from the bottom

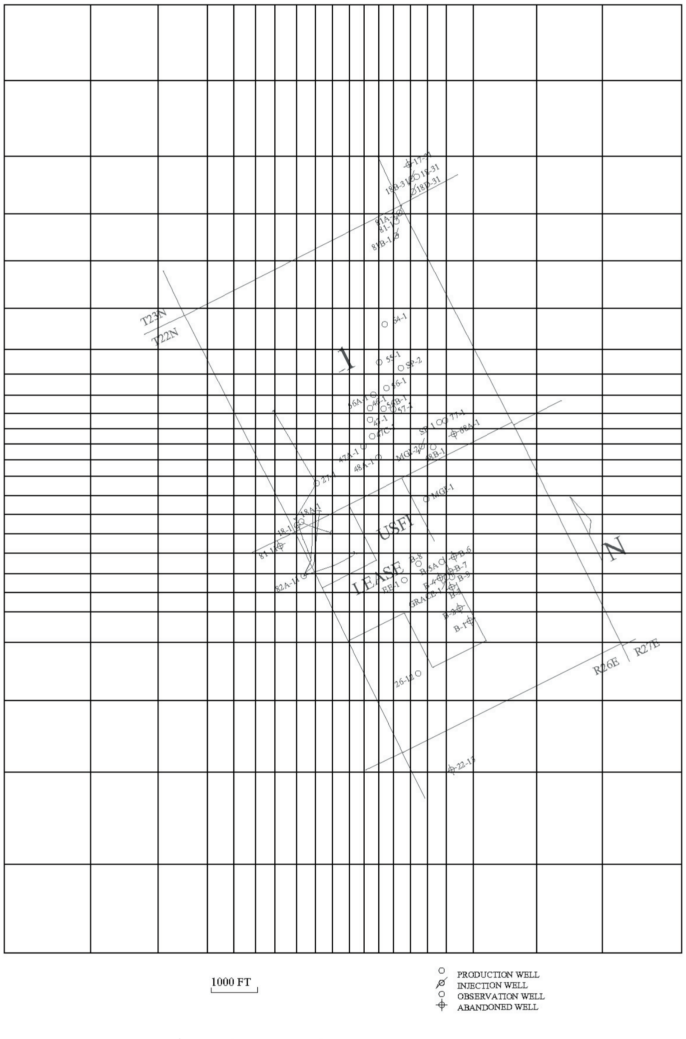

Figure 1. Layout of simulation grid.

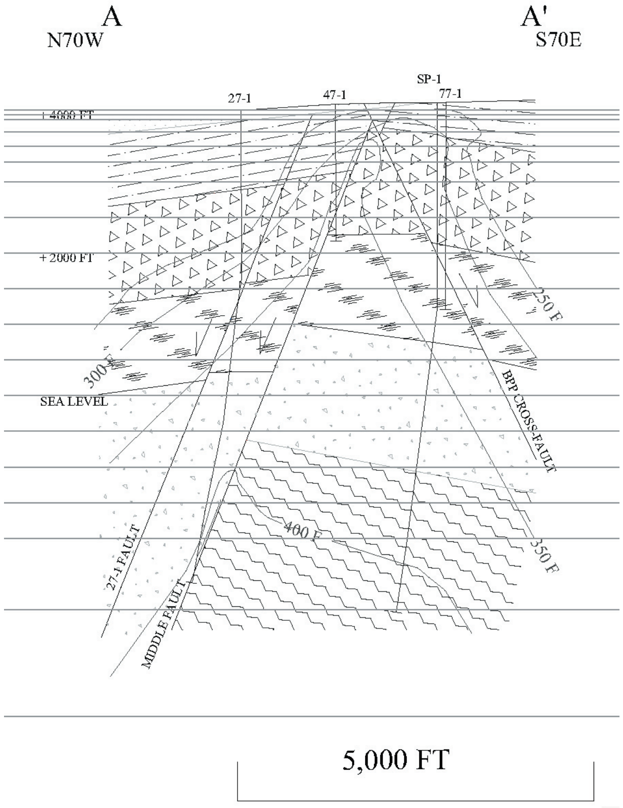

Figure 2. Layers in simulation grid.

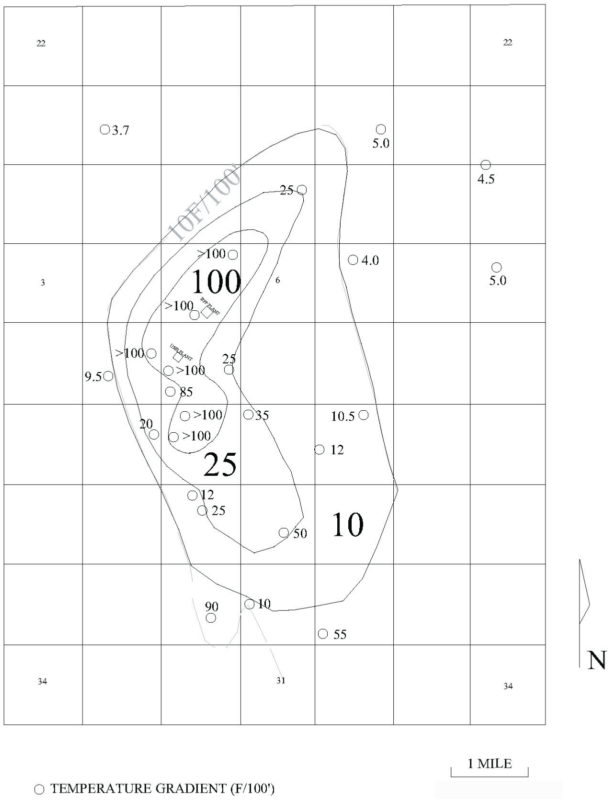

Figure 3. Temperature gradient map, Brady's Field, NV.

through recharge to the Brady's fault. There are likely other ways that energy either enters or leaves the system, however, as a first approximation to begin the iterative modeling process, the technique is reasonable.

The energy leaving the surface was estimated using the temperature gradient data. As shown in Figure 3, the temperature gradients were contoured for 10, 25, and 100 °F/100 ft. Planimetry was then used to measure the areas bounded by each contour. Next, the literature was surveyed for data on the thermal conductivity of various rocks. The thermal conductivity of rocks and soils varies over a substantial range. However, for water saturated rocks, many studies report values in the range of 1.0 to 2.0 Btu/ft °F hr. A mid-range value of 1.5 Btu/hr °F ft gives a total surface heat flux that implies a source inflow rate of 452,000 lbm/hour at 410 °F. This estimation of thermal influx was used as the initial starting point, but the final value used in the model was somewhat lower (400,000 lbm/hour at 410 °F). The boundary conditions used in the model are as follows:

- Inflow from a deep source: Heat and mass inflow to the bottom of the model was set by injecting 100,000 lbm/hour at 410 °F into each of four gridblocks located at the believed point of inflow. Total source inflow was 400,000 lbm/hour at 410 °F.
- Ground surface: Heat loss from the top of the model to the atmosphere was modeled by specifying a conductive heat loss term for each block in Layer 1. The rate of heat loss is proportional to the temperature difference between the ground surface and an assumed atmospheric temperature of 80 °F.
- Peripheral aquifers: Steady-state aquifers were attached to the north, west, east, and south periphery blocks in each layer of the model.

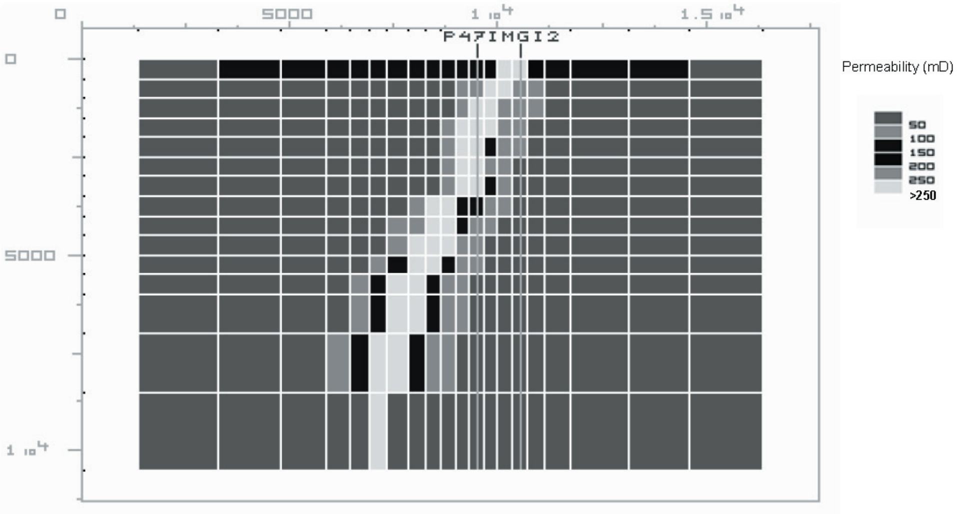

Figure 4. Cross section through model showing fault zone permeability.

The permeability distribution used in the simulation model was initially estimated by the shapes of the sub-surface temperature contours. The highest permeability in each layer is located within the area enclosed by the highest temperature contours. Using this procedure, a three dimensional representation of the fault zone system was created. Results from numerous well tests run during initial field testing suggested that the flow capacity (transmissivity) of the Brady fault zone was approximately 500,000 millidarcy-feet (md-ft). Away from the fault zone, non-commercial wells typically have tranmissivities of approximately 5,000 md-ft. Figure 4 shows a representative cross section through the model that shows the permeability distribution.

The permeabilities used in the model range from as low as 0.5 md up to greater than 1000 md, although over most of the model the permeabilities are between 5 to 250 md. Assuming a fault zone thickness of several hundred feet, these values are consistent with the range of transmissivities mentioned above.

Natural State Model Results

he calculated temperature distribution based on the final run of the initial state model is shown in Figure 5. These temperatures are in reasonable agreement with the measured data.

Production History Matching Results

The individual production, injection, and monitoring well parameters have been monitored since start of commercial pro-

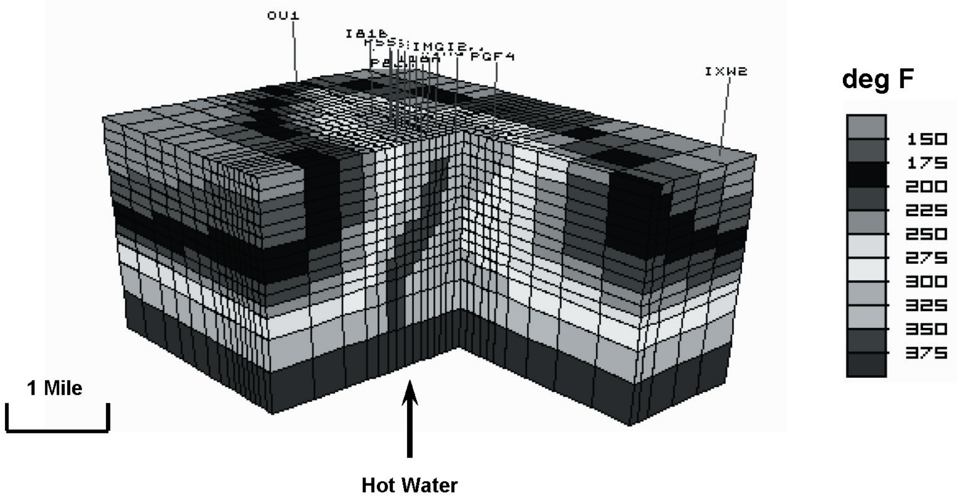

Figure 5. Simulated Initial State Temperatures.

duction. For the production wells, these parameters included flow rate, production temperature, bubble tube pressure, and annulus pressure. For the injection wells, flow rate, wellhead pressure, and injection temperature have been monitored. For several monitoring wells, water levels and/or bubble tube pressures have been monitored. The initial state model was used as the basis for the production history matching, with additional input required to define well locations and the production/injection flow rate histories. The locations of the individual production and injection wells within the model were based on the known well courses with respect to the simulation grid system. The open completion intervals were based on known downhole configurations, and on the location of lost circulation zones. The flow rate histories were converted to 20-day averages and translated into simulation code.

The model was then run for the entire production history with the aim of matching the measured temperatures and pressures in all of the wells in the field. This process required numerous runs, each time making adjustments mainly to the permeability distribution. Following each set of these fine tuning adjustments, the initial model was again run to ensure that it was still possible to obtain a reasonable match to the pre-exploitation conditions in the reservoir. After reasonable matches were obtained to both the measured production data and the initial state conditions, the model was considered to be calibrated.

It should be noted that the remote injection field developed in the late 1990's was not included in the model, as it has no hydraulic connection to the Brady's reservoir. It serves only to allow disposal of part of the cooled plant effluent and thereby reduce the amount of injection breakthrough from the in-field injectors.

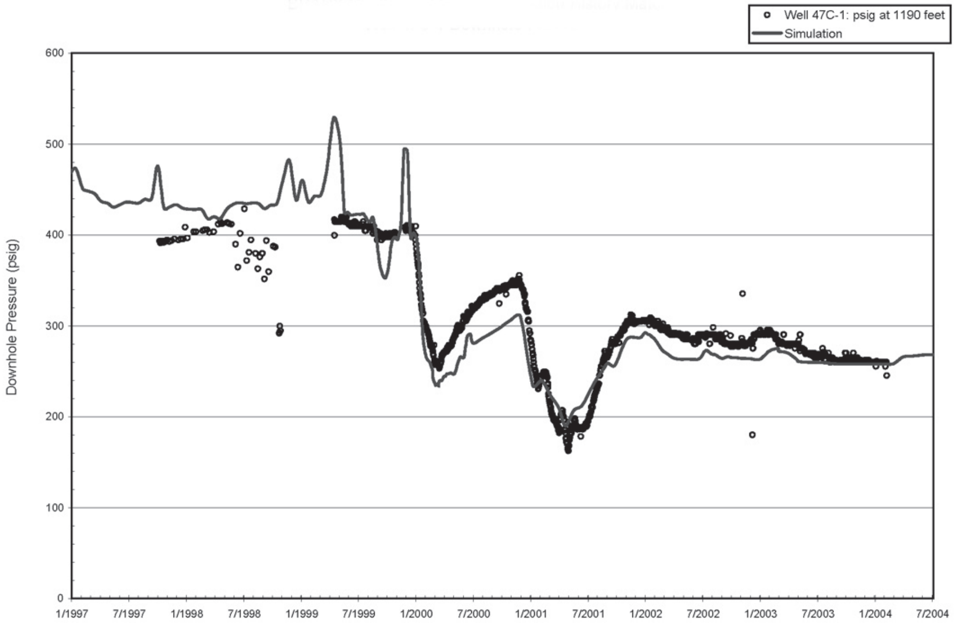

Figure 6. Brady Geothermal Field - Simulation History Match, Well 47C-1 Downhole Pressure.

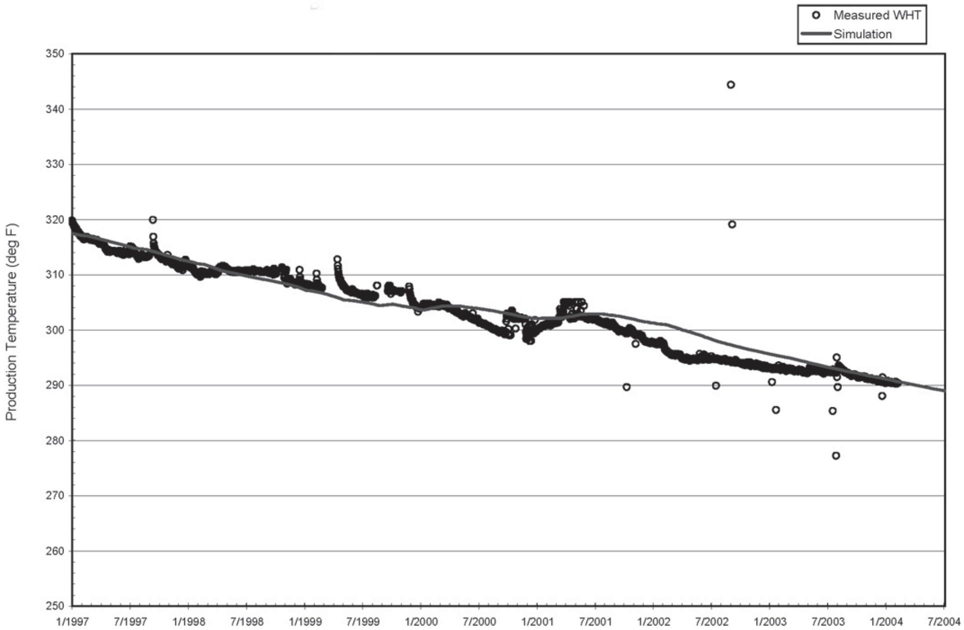

Figure 7. Brady Geothermal Field - Simulation Forecast, Well 47C-1 Production Temperature.

Representative final matches to the measured parameters from the individual wells are presented in Figures 6 and 7. The matches to the temperature and pressure data from the individual wells are considered to be reasonable. However, some discrepancies between the measured and the calculated data were not fully resolved.

Forecast Runs

In early-2000 the numerical model was calibrated and tested. During 2000 and 2001, field tests were made with different levels of diversion of cool injection fluid to the remote injection wells. During these injection diversion tests, the model's calibration continued to be fine-tuned. At this time, wellbore simulation was also integrated into the model such that simulated reservoir pressure changes would effect changes in modeled production flow rates. By late-2001, there was a high level of confidence in the forecasts made with the model.

Since the plant start-up in 1992, the injection temperature had been approximately 230 °F (equal to the effluent temperature from the dual-flash plant). BPP then used the model

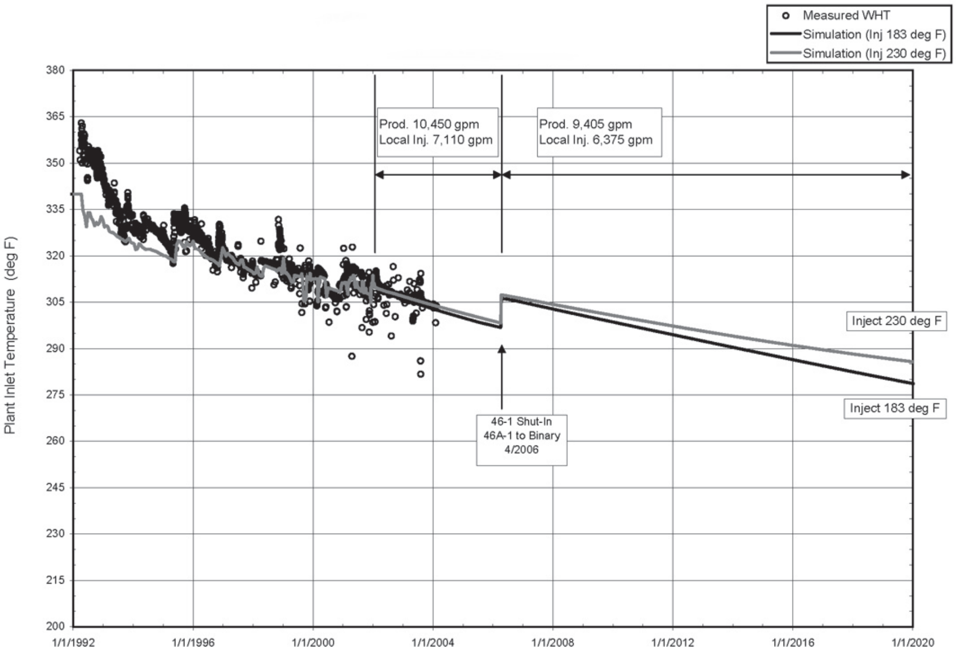

Figure 8. Brady Geothermal Field - Simulation Results, Plant Inlet Temperature.

to explore the possibility of constructing a binary bottoming cycle unit to further extract energy from the 4,125,000 lbm/hour effluent of the dual-flash plant. From a reservoir engineering perspective, the effect of the proposed binary unit would be a drop in injection temperature from 230 to 183 °F.

Using the calibrated numerical model, several operating scenarios involving the binary were explored. The scenarios involved combining the binary (and thus lower injection temperatures) with varying degrees of remote injection diversion. It was found that diversion of 25% of the total injection rate allowed the production flow rates to stabilize at a relatively high level, while causing some beneficial slowing of temperature decline.

Using a fixed injection diversion of 25% of injection, the model was first run 18 years into the future assuming the injection temperature remains 230 °F. Then, for comparison, the same simulation was run with 183 °F injection temperature. Figure 8 shows a plot of the results from both of these simulation runs.

With 230 °F injection, the maximum temperature decline is approximately 1.5 °F per year, and the plant inlet temperature decreases about 20 degrees to 285.7 °F in January 2020.

With 183 °F injection, the maximum temperature decline is approximately 2.0 °F per year, and the plant inlet temperature decreases to 278.6 °F in January 2020.

Therefore, based on these results, the net effect of injecting at 183 °F instead of 230 °F is an additional 7.1 °F of cooling over the course of 18 years. From a reservoir engineering perspective, this is not a large amount of extra cooling. The explanation for the extra cooling being relatively small is as follows:

1. The injected water filters through a significant volume of heated rock and is thus heated as it migrates back to the production wells.
2. The injected water mixes with hotter water as it migrates back to the production wells.
3. The produced water consists of both injection return and also new geothermal recharge entering the system from depth.

Conclusion

The numerical reservoir model has proven to be a very useful tool for managing and optimizing the operation of the Brady's reservoir. A major result was the addition of a binary bottoming cycle unit which came online in August 2002. Thus far, with two years' of operating data, there has been no noticeable increase in the temperature decline rates of the production wells. This is consistent with the reservoir simulation, which shows only a small amount of incremental cooling caused by the cooler injection temperatures.

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