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ROOSEVELT HOT SPRINGS RESERVOIR MODEL APPLIED TO FORECASTING REMAINING FIELD POTENTIAL

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ABSTRACT

The Roosevelt Hot Springs geothermal field has maintained a capacity of approximately 25 megawatts (gross) since 1984. Ten years of field data and reservoir pressure history are used to calibrate a computer model of the Roosevelt geothermal reservoir. The basic features of this model are described, and the history matching process is reviewed. The model is used to estimate the remaining potential of the field in terms of capacity versus sustainability. Wellhead pressure is used as the pressure constraint in the forecasts. These simulations indicate that the current capacity of 25 megawatts is sustainable throughout the forecast period (to the year 2026), and that a capacity of 50 MW is sustainable for 18 years. Higher capacities decline sooner, but all decline rates decrease toward asymptotic limits approaching 40 MW of capacity.

INTRODUCTION

The purpose of this paper is to document the basic features of the Roosevelt reservoir model and provide estimates of the remaining potential of the field. Roosevelt offers an excellent opportunity to use reservoir simulation as a means of applying what is known about the field to forecasting because of its long production history and wealth of field data.

The Roosevelt geothermal reservoir occurs in a fractured complex of Tertiary granitic and Precambrian metamorphic rocks on the west side of the Mineral Mountains in Beaver County, Utah. The discovery well for Roosevelt was drilled in 1975, and the field began commercial production in 1984. During the 10 years of production between 1984 and 1994, power generation has remained at approximately 25 megawatts (gross). Power is generated by a single-flash plant supplied by 400 thousand pounds per hour (kph) of steam. The total mass rate has stayed relatively constant at 2300 kph, and is provided by three production wells at any given time (four active production wells are available).

This paper focuses on the description of the reservoir model, history matching, and forecasting, but does not cover the regional setting or conceptual model of Roosevelt in depth, which are ablely addressed elsewhere (i.e., Faulder, 1991; Benoit and Butler, 1983; Parry et al., 1980).

MODEL DESCRIPTION

The current Roosevelt reservoir model has been constructed using Tetrad software, a commercially available simulation program widely used in the geothermal industry and independently validated (Shook and Faulder, 1991). The model includes an area of approximately 5.3 by 3.5 miles and is made up of a rectangular grid system consisting of 2,016 grid-blocks divided into five layers. The model is a single-porosity representation of the fractured formation, which pressure transient data indicates is a valid characterization of the bulk properties of the reservoir.

The source of heat for the reservoir appears to be provided by upwelling along intersecting faults, which influence the shape of the initial state temperature and pressure contours (figures 1 and 2). Permeability and porosity in the model are controlled by these steeply dipping faults, as is the primary recharge. Geothermal recharge in the model is supplied by constant-pressure, constant-temperature aquifers attached to four grid-blocks on the bottom layer at the fault intersection. The temperature of these recharge aquifers is 500°F, which is also the highest temperature defined in the model. The pressure of the recharge aquifers is determined from initial state modeling and exploitation history matching, and is approximately 150 psi greater than the initial pressure in the bottom layer of the model, which supplies the pressure differential that drives the geothermal system.

The initial state modeling used here consists of running the model for a simulated period of 10,000 years without production or injection and adjusting permeability, porosity, and boundary conditions such that the initial state temperature and pressure conditions remain reasonably stable. The simulated fluid throughput under stable initial conditions is approximately 180 kph. Boundary conditions other than geothermal recharge include outflow to the north and south, indicated by the shape of the temperature isotherms, and shallow leakage through the alluvium (top layer) on the western margin of the model. The top and bottom of the model are isothermal no-flow boundaries (except for recharge from the bottom layer).

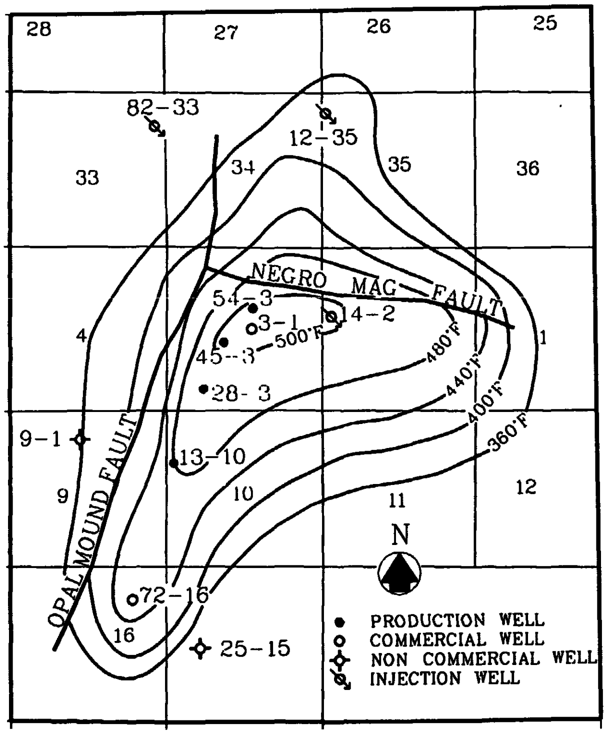


FIGURE 1: Initial state isothermal map at +1800 feet above sea level (roughly 4200 feet of depth).

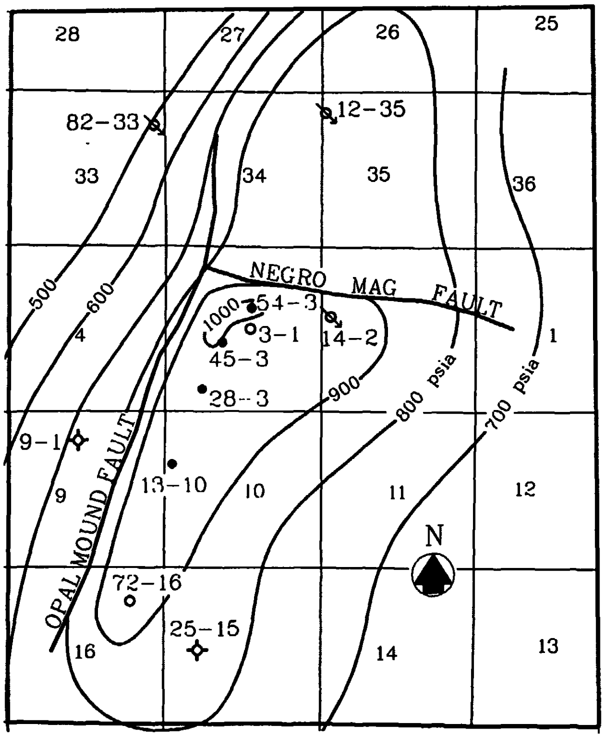


FIGURE 2: Initial state isobar map at +4000 feet above sea level (roughly 2000 feet of depth).

HISTORY MATCHING

Calibration of the model is an iterative process between satisfying initial state stability requirements and matching the history of reservoir pressure decline during exploitation. Factors which control the shape and slope of the pressure decline trend include:

- ☐ The rate of mass withdrawal
- ☐ The amount of recharge
- ☐ Reservoir pore volume
- ☐ Permeability (magnitude and distribution)
- ☐ Evolution of a two-phase zone (steam cap)
- ☐ Location of injection

The rate of mass withdrawal is measured in the field and prescribed in the model as monthly averaged rates. Recharge, pore volume, and permeability are interrelated and all affect the evolution of the steam cap, so a unique solution is impossible. However, each of these parameters can be constrained within some limits, as discussed below.

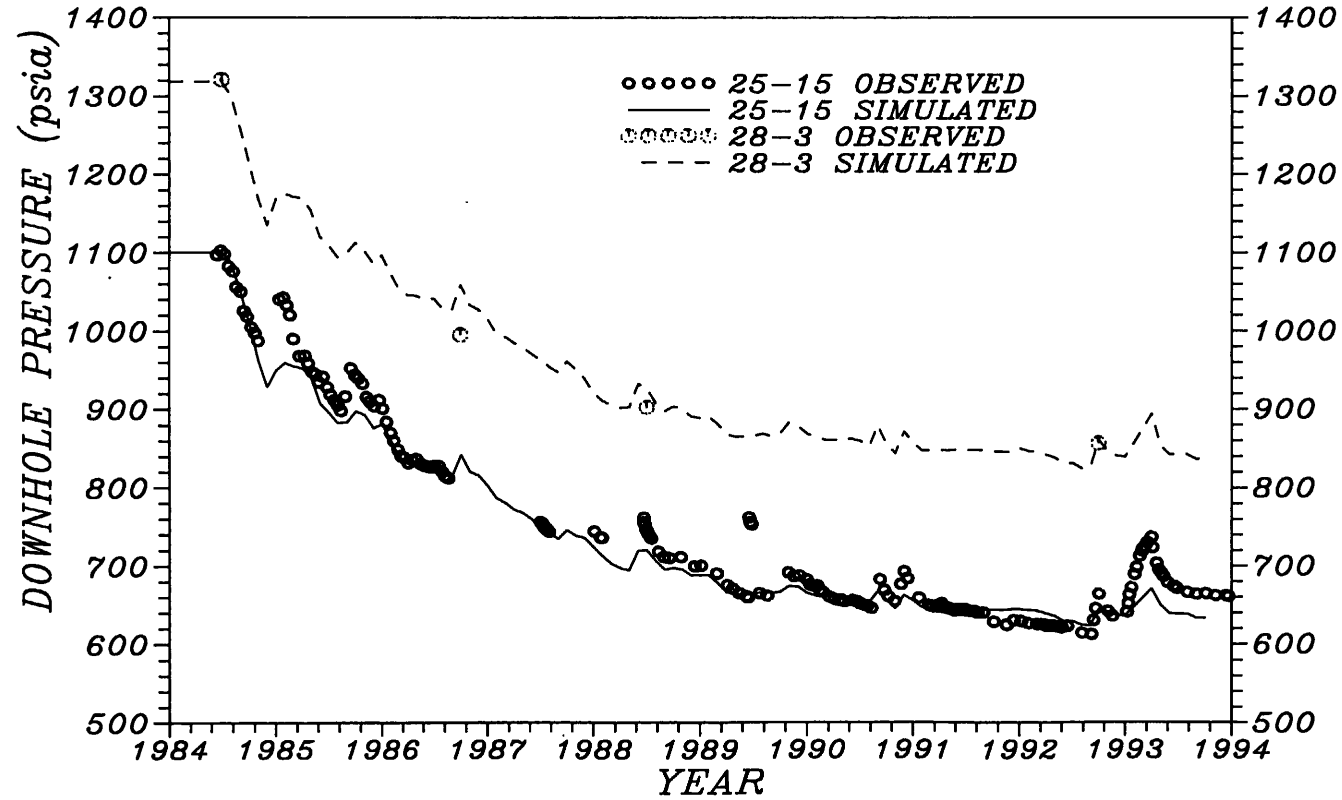
Figure 3 shows the observed and simulated pressure histories for wells 25-15 and 28-3 (see figures 1 and 2 for location). Observation well 25-15 has been instrumented with capillary tubing for much of the 10 years of production history, and while not a production well, is in good hydraulic communication with the reservoir. Production well 28-3 has four static surveys that define the general shape of its pressure decline curve, which does not differ significantly from that of 25-15, although separated by 1.6 miles. Pressures were also matched in 3 other observation wells (not shown).

Total pressure decline in 10 years of production has been approximately 500 psi, but 90% of that decline occurred before 1988, and the current rate of decline is negligible. Evidence of a steam cap is apparent in static surveys since 1988, and the current steam cap is estimated to be about 2000 feet thick over an area of approximately one square mile. The existing production wells have feed depths in the liquid below the steam cap, so the presence of the steam cap is not apparent from their production enthalpy. However, the evolution and extent of the steam cap as observed from static surveys and snow melt is reproduced in the simulations, and is an essential element in the history matching process.

The increases in pressure in figure 3 represent periods when the field was shut in (for plant maintenance). One of the shut-in periods spanned the first three months of 1993 and resulted in an observed pressure increase of 100 psi in 25-15. The simulated pressure recovery during this period is less than observed, indicating that recharge may be underestimated in the model. However, the pressure decline history can not be matched with greater recharge (given other constraints), and therefore the recharge parameters represent a compromise between matching pressure decline and pressure recovery.

Reservoir pore volume has a major influence on the rate of pressure decline and the magnitude of pressure recovery. Work presented in a companion paper uses a pre-production long term flow test at Roosevelt to estimate reservoir pore volume (Faulder, 1994). Faulder concludes that the connected pore

FIGURE 3: ROOSEVELT HISTORY MATCHES



volume which represents the Roosevelt reservoir is constrained between 2 and 5 billion barrels, with a most likley estimate of 4 billion barrels. He also presents discussions regarding the inverse relationship between pore volume and the rate of recharge for a given magnitude of pressure recovery. Those discussions indicate that a pressure recovery of 100 psi in 3 months (as observed in 25-15 during the 1993 field shut-in) requires a recharge rate of approximately 315 kph for a pore volume of 3 billion barrels, and a recharge rate of 420 kph for a pore volume of 4 billion barrels. The reservoir pore volume derived from history matching the model is 3.3 billion barrels, and the simulated recharge rate during the 1993 shut-in period is 290 kph, both parameters which are within the constraints suggested by Faulder's work.

Permeability distribution in the reservoir model is derived from a conceptual model developed over the last 20 years by many workers, and refined during the history matching process. Distribution and magnitude of permeability are constrained by well test data, initial state modeling, and reservoir pressure response to injection location. The effect of changing the location of injection on long term pressure decline can be observed in the downhole pressure data, and is matched in the simulations. No cooling of the production wells has occurred during the 10 years of production history.

The highest permeabilities defined in the model occur along the intersecting faults and are roughly 300 millidarcies over a thickness of 2000 feet. Average permeability that extends from the production wells to 25-15 is roughly 25 millidarcies over a thickness of 2000 feet, which is consistent with a permeability thickness of 50,000 millidarcy-feet derived from interference pressure transient analysis with 25-15 as the observation well.

FORECAST CONSTRAINTS

Historical total mass flow rates are specified in the model, but forecast total mass rates can either be specified or controlled by pressure. A *rate-constrained* well produces at a prescribed rate as long as its pressure remains above a pre-defined pressure constraint. Once a well reaches the pressure constraint, the model decreases the flow rate to maintain minimum pressure, and the well is considered to be *pressure constrained.*

Bottom-hole pressure has commonly been used as the pressure constraint in geothermal modeling. However, the practice of using wellhead pressure as the pressure constraint is growing (Murry and Gunn, 1993; Hadgu et al., 1993). Wellhead pressure constraint offers a more realistic approach to controlling forecast well rates in two-phase reservoirs and is used in these simulations. Wellhead pressure more directly reflects enthalpy-dependent well performance than the does bottom-hole pressure, and minimum wellhead pressure requirements are known in advance.

Simulated wellhead pressures are calculated in Tetrad from lookup tables which are generated by a separate wellbore simulator (Murry and Gunn, 1993). In liquid feed conditions wellhead pressure is dependent on temperature, bottom-hole pressure, and rate. In two-phase feed conditions wellhead pressure is dependent on steam quality, bottom-hole pressure, and rate. A tri-linear interpolation is performed between the appropriate three parameters, depending on flowing conditions. Relative permeability and pressure drop from the reservoir to the wellbore are considered in determining the lookup parameters. The pressure drop is calculated using a volumetric viscosity-dependent productivity index, and is determined iteratively with rate.

The flow rate from the previous time-step is used for the initial estimation of wellhead pressure, which is tested against its prescribed constraint. If below the constraint a lower rate is tried. In some cases no rate will satisfy the constraint, and the well is closed in the model. This can happen for liquid feed wells because of the double-valued characteristic of their output curves (i.e., lower rates result in lower wellhead pressures). Shut-in wells are allowed to re-open if flowing conditions change, for example by increasing steam saturation in the grid-block.

The transition from history to forecast in these simulations is done by assigning a field steam demand at the first forecast time-step which adjusts the prescribed total mass rates of the wells by a factor that maintains the specified field steam demand. The steam demand is no longer in effect when the wells cannot collectively deliver the specified steam demand due to their individual pressure limitations, and the field steam rate is then controlled by the wellhead pressure constraints.

FORECAST RESULTS

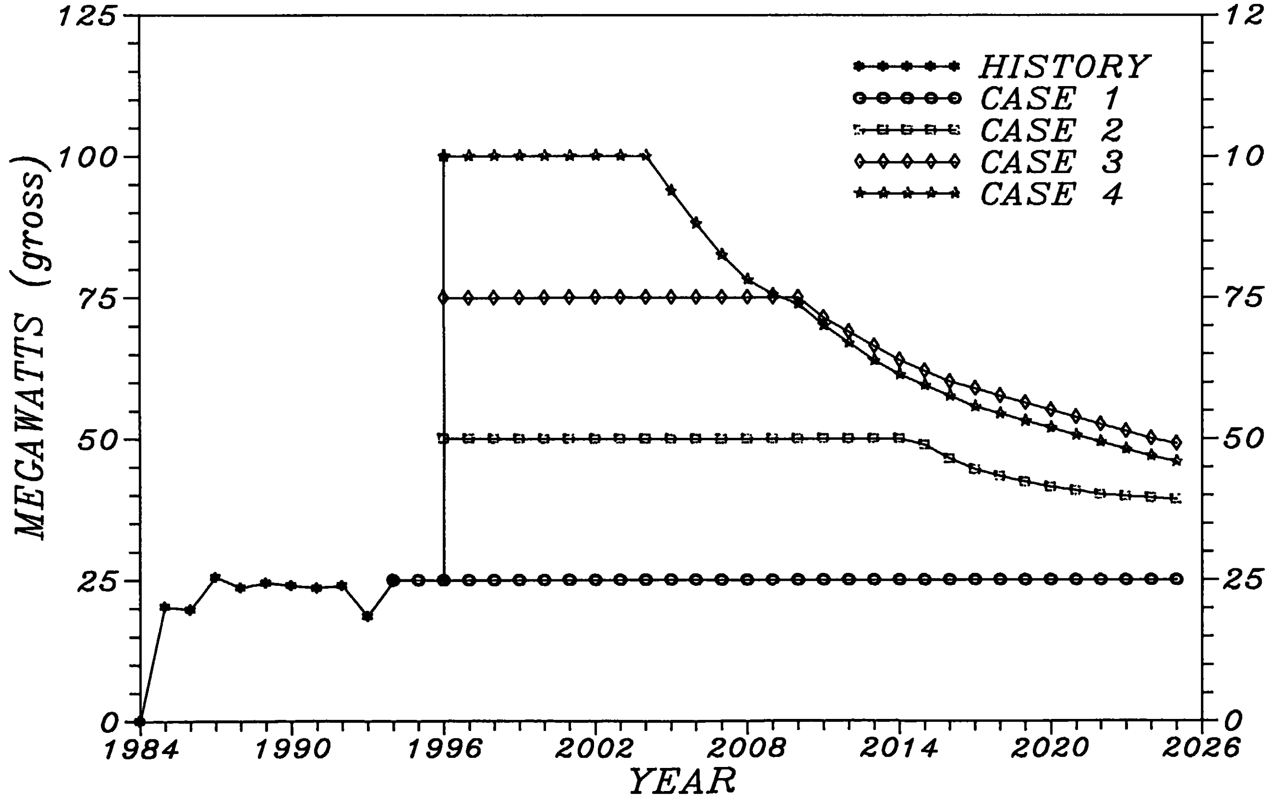
The forecast cases presented in this paper are described in table 1, and the results are presented in figure 4. Case 1 indicates that the current capacity (25 MW) is sustainable throughout the forecast period (to the year 2026). The other cases show that sustainability depends on capacity. With 1996 as the reference year, the time periods for which 100% of capacity can be sustained are listed in table 1. The steeper decline rates are associated with the higher capacities, but decline rates decrease with time toward an extrapolated annual exponential decline rate in the range of 1-2% approaching 40 MW of capacity.

The forecast results shown in figure 4 assume that future plant performance and separator pressures are similar to current operating conditions. The wellhead pressure constraint used for all wells in these simulations is 125 psig, or about 10 psi above the average separator pressure. Greater conversion efficiency from steam to megawatts would increase the power generated per pound of steam, but would not influence the shape and relative position of the curves shown in figure 4. However, changing the wellhead pressure constraint has an important effect on steam rate forecasts, the sensitivity to which is not explored here.

Table 1: Forecast Cases

Case	Steam Demand	Capacity MW (gross)	Prod. Wells	Inj. Wells	Years Sustainable at 100% Capacity
1	400 kph	25	4	3	30
2	800 kph	50	8	4	18
3	1200 kph	75	12	5	14
4	1600 kph	100	16	6	8

FIGURE 4: ROOSEVELT FORECAST RESULTS



Also not explicitly explored in these forecast cases is the sensitivity to factors such as the location and completion interval of the new wells, and the number of make-up wells. One make-up well per 25 MW of capacity for the forecast period is implicit in these simulations, and is reflected in the number of production wells in table 1. New production wells are located in grid-blocks with temperatures from 465°F to 500°F and their completion intervals are staggered so that the forecast cases are not biased toward either liquid or two-phase feeds. New injection wells are located to be useful for pressure support but separated from production wells by at least 1/2 mile. All of the separated water is re-injected.

CONCLUSIONS

Ten years of field data and reservoir pressure history are used to calibrate the Roosevelt reservoir model. The multi-layer model approximately reproduces the principal responses to exploitation, including the pressure decline history, pressure recovery during field shut-in, and the evolution of the steam cap. The model parameters derived from the history matching process are consistent with initial state stability requirements and independent estimates of pore volume and recharge.

The forecast well rates are ultimately controlled by wellhead pressure, which is calculated from lookup tables within the model. The wellhead pressure method of forecast constraint more accurately reflects actual pressure requirements and enthalpy-dependent well performance for two-phase reservoirs compared to the bottom-hole pressure constraint method.

The forecast results show the relationship between capacity and sustainability for the Roosevelt geothermal field. With 1996 as the reference year, the forecasts indicate that the current capacity of 25 MW is sustainable for 30 years, and that 50 MW is sustainable for 18 years. Higher capacities decline sooner, but their decline rates decrease toward an asymptotic limit approaching 40 MW of capacity. For the cases considered here, higher capacities result in greater recoverable energy during the 30 year forecast period, but at the expense of lower capacity factors in the later years of the project life.

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