A RESERVOIR ENGINEERING STUDY OF THE EAST MESA KGRA

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The East Mesa area is located on the east side of the Imperial Valley approximately seven miles southeast of Holtville and 110 miles east of the San Diego metropolitan area. This area presently contains ten deep geothermal wells, five of which have been drilled by the Bureau of Reclamation, three by Republic Geothermal and two by Magma Power Company. Four older, abandoned deep holes are also in the general area.

Summary

The East Mesa Reservoir has been analyzed from a reservoir engineering point of view using a three-dimensional Geothermal Reservoir Simulation Model (1). The model treats transient two-phase (steam-water) flow in permeable rock and solves the energy and mass equations using finite-difference methods.

The basic objectives of the study were to determine the following:

1. Expected reservoir life when fluids at temperatures greater than 300°F are produced at flow rates of

   10,000 lb/min (600,000 lb/hr)
   100,000 lb/min (6,000,000 lb/hr)
   1,000,000 lb/min (60,000,000 lb/hr)

2. Optimum production and injection well spacing design for the above flow rates.

Results of the study showed that under certain assumptions concerning the level of permeability and the extent of the reservoir, all of the above rate objectives could be met for a period in excess of 30 years.

Basic Data

1. Petrophysics and Geology

Basic petrophysical characterization of the reservoir (porosity and permeability distribution) were obtained from the following sources:

(a) flow test data from the five Bureau of Reclamation wells and the three Republic wells,

(b) interwell interference data obtained by Lawrence Berkeley Laboratory using an ultra-sensitive pressure gauge, and

(c) analysis of all the log and core data in the Bureau of Reclamation and Republic wells.

2. Subsurface Temperature Distribution

A three-dimensional subsurface temperature distribution was determined by TRW using measured temperature profiles in deep wells and heat flow determinations in numerous shallow holes throughout the area.

Two-Dimensional Areal Calculations

A network of 40 acre (1320' x 1320') grid blocks was set up to enclose the 300°F isotherm at a depth of 6000 ft. The grid network comprised 14 grid blocks in the x (east-west) direction and 20 grid blocks in the y (north-south) direction. A northwest-southeast fault was accounted for by zeroing interblock transmissibilities along a series of grid block interfaces approximating the fault. (See Figure 1.)

A total thickness of 1000' representing the interval from 5000' to 6000' was simulated. This is approximately the interval in which all of the Bureau wells are completed with the exception of the 6-1 well which is completed below 6000'. The average temperature in this interval is 355°F.

Heat lost to or gained from the rock volume above and below the interval being simulated is computed from the one-dimensional heat conduction equation:

$$K_{ob} \frac{\partial^2 T}{\partial Z^2} = (\rho C_p)_{ob} \frac{\partial T}{\partial t}$$

where

K_{ob} = rock thermal conductivity (BTU/°F-ft-day)

ρ = rock density (lb/cu.ft.)

C_p = rock specific heat (BTU/lb-°F)

This equation is solved numerically in conjunction with the mass and energy balance equations.

In practice, the over and underburden almost always supplies heat to the reservoir in that injected fluid is almost always cooler than the in-place reservoir fluid. Accordingly, the reservoir either remains constant in temperature or declines, and as a result, the heat flux is from the over and underburden into the reservoir. It should be noted that the over and underburden heat supply is completely independent of heat supplied to the reservoir by convection.

The two-dimensional simulation runs were made under either of two assumptions: The reservoir is closed and limited to the 11,200 acres of the grid model or the reservoir is effectively infinite so that the 11,200 acre grid model is only a part of a much larger hydrologic system. The portion of this system outside the grid will be referred to as the "aquifer," although, strictly speaking, the total system is an aquifer and the grid is simply a region of anomalous temperature.

The pressure support supplied by the aquifer to the grid has been calculated using the method of Carter and Tracy (2) which is, in turn, an approximation of the rigorous superposition calculation described by Van Everdingen and Hurst (3) for an infinite circular system.

Production wells produce fluid at an assigned rate or whatever the well is capable of producing against a flowing bottomhole pressure of 1000 psi, whichever is less. In most cases, the assigned rate was 500,000 lb/hr. For a water specific gravity of 1.02, 500,000 lb/hr. is equivalent to 981 gpm or 33,634 barrels per day. The production capability of a well is calculated as follows:

$$Q = \frac{.001127\ 2\pi kh}{\mu_w \left(\ell n \frac{r_e}{r_w} - 1/2\right)} \left(p_{i,j,k} - p_{wf}\right)$$

where

Q = flow rate (B/D)

k = grid block permeability (md)

h = formation thickness (ft)

$p_{i,j,k}$ = grid block pressure (psi)

p_{wf} = flowing bottomhole pressure (psi)

r_w = wellbore radius (ft)

r_e = $\frac{\sqrt{\Delta x \cdot \Delta y}}{\pi}$

Δx = x-direction grid block dimension (ft)

Δy = y-direction grid block dimension (ft)

Low Rate

For the low rate case (600,000 lb/hr), one producing well and one injection well were employed. The wells were in the central portion of the reservoir, a distance of 1-1/4 miles apart. All of the produced fluid was reinjected at a temperature of 200°F. The average reservoir permeability was 50 md. After 30 years, the production well had sustained its initial rate and initial temperature of 355°F. The temperature front created by the bank of 200° F water had only progressed approximately 1/4 the distance between the two wells. Results for this case were similar, for an average permeability of 10 md.

Intermediate Rate

For the intermediate rate case (6,000,000 lb/hr) 12 production wells were employed. These wells were placed within the central portion of the grid model. For an average permeability of 50 md and assuming that the system is *infinite*, the total rate can be sustained for at least 30 years. If the reservoir is closed and limited to the 11,200 acres within the grid model, then the production rate drops very rapidly and within 6 years the average reservoir pressure falls to the limiting bottomhole pressure of 1000 psi.

With twelve injection wells located around the periphery of the 300°F contour and the twelve production wells in the interior as before, the intermediate rate can be maintained for 30 years. The cooling caused by the reinjection is limited to the regions immediately around the injection wells so that the producing wells remain essentially at the initial temperature of 355°F.

High Rate

For the high rate case (60,000,000 lb/hr) both peripheral and pattern injection were looked at. In the peripheral injection case, 60 producing wells were located in the central portion of the reservoir and 60 injection wells were located around the periphery of the 300°F contour. As before, the minimum flowing bottomhole pressure was 1000 psi and the injected water temperature was 200°F. For both the 10 md and 50 md case, the production rates dropped rapidly at first and then stabilized at rates below the desired 60,000,000 lb/hr. These stabilized rates were 48,000,000 lb/hr and 33,000,000 lb/hr for the 50 md and 10 md cases, respectively. The stabilized rates could be higher if a lower limiting bottomhole pressure could be tolerated.

Since there was some question as to whether the high rate case was feasible with peripheral injection, a series of pattern injection cases was run. For all pattern cases, a 5-spot pattern was assumed.

Simulation runs were made for 5-spot patterns with wells drilled on 20, 40 and 80 acre spacing. All runs were made using a 2-D areal 10 x 10 grid for 1/4 of a 5-spot. Production and injection rates were approximately 500,000 lb/hr per well. In each case, the temperature of the produced water was determined as a function of time. For 80 acre spacing, there was no decline in the temperature of the produced water, even after 30 years. For 40 acre spacing the produced water temperature dropped to 250°F after 27 years and for 20 acre spacing, the produced water dropped to 250°F after about 15 years. (See Figure 2.)

A summary of the Two Dimensional Areal Calculations is presented in Table 1.

Two-Dimensional Cross-Sectional Calculations

The two-dimensional areal simulations assume uniform permeability in the vertical direction. In order to look at the effects of vertical heterogeneity, a two-dimensional x-z cross-sectional grid was utilized. The grid has four layers in the vertical direction and 19 columns in the x-direction. Fluid was injected at one end (x=1) and produced from the other end (x=19). Thickness in the y-direction decreases from the center toward the injection and production ends to represent approximately the shape of the area that would be swept in a 5-spot pattern. The distance between the production and injection wells is 933 ft. corresponding to a 40 acre 5-spot (wells drilled on 20 acre spacing). (See Figure 3.)

The assumed reservoir thickness is 1000 feet with the thickness of each layer being 250 feet. The horizontal permeabilities for the four layers from top to bottom are 111 md, 54 md, 20 md and 15 md, respectively. Vertical permeabilities were assigned as one-half of the horizontal permeabilities. This permeability distribution was based on data from the East Mesa 6-1 well.

Production and injection rates were set at 125,000 lb/hr for the simulated one-quarter 5-spot (500,000 lb/hr for the full 5-spot). For this case, the producing well temperature dropped to 250°F after about 12 years. The producing well temperature was calculated using the temperatures in the four layers weighted by their respective kh's. At the end of 12 years, the top layer has almost been completely swept by the relatively cold 200°F injection water, whereas temperatures in the bottom two layers remain greater than 300°F. Figure 4 shows the temperature distribution after four years.

In order to investigate the effects of a convective heat source from below, this case was repeated with the total injection of 125,000 lb/hr distributed as follows:

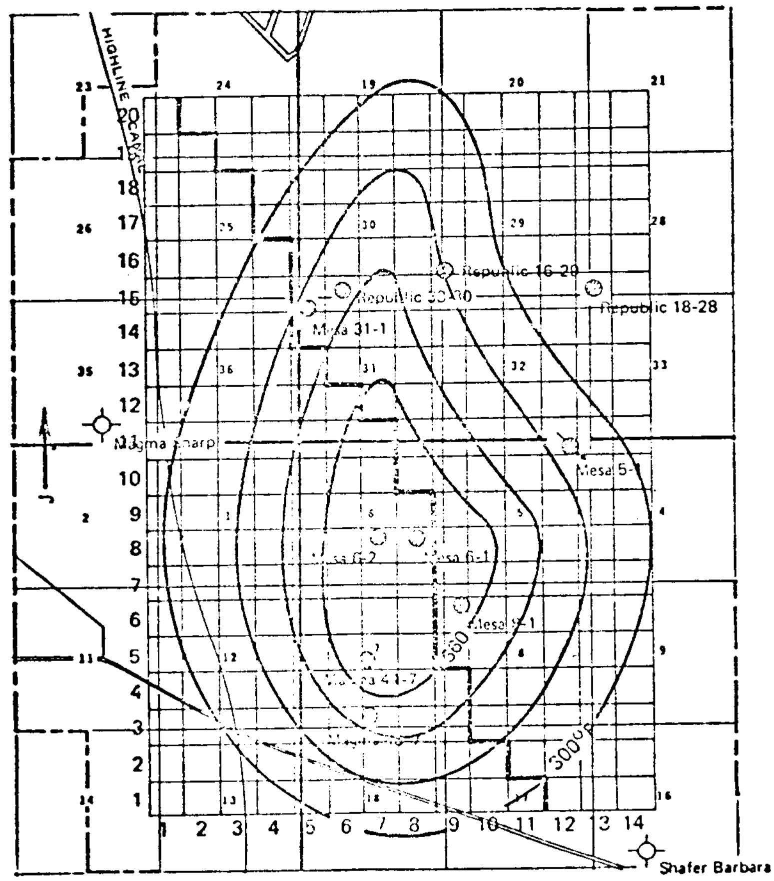

Figure 1. Grid for Two-Dimensional Areal Calculations

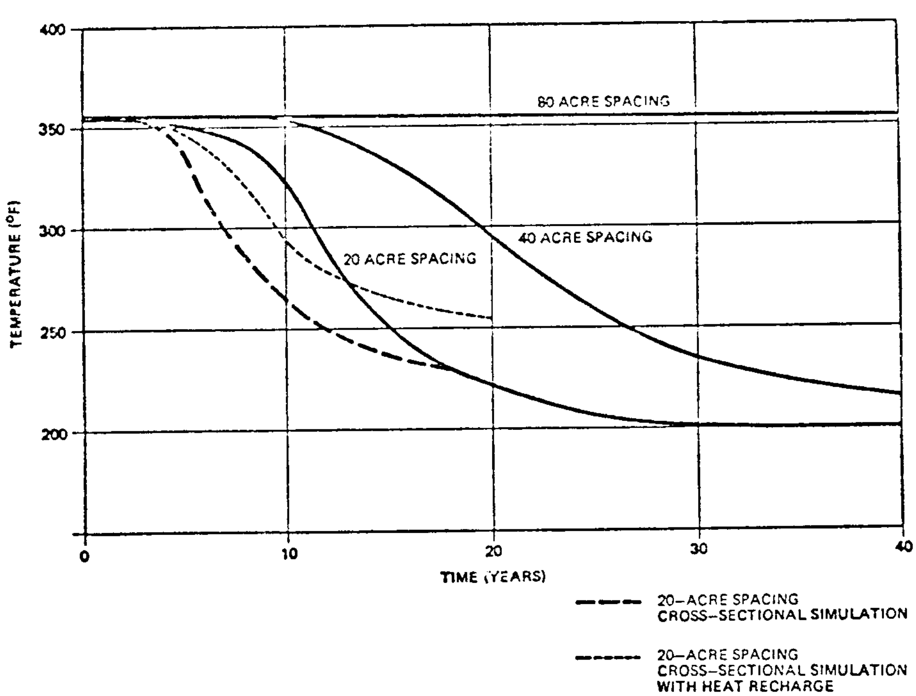

Figure 2. Produced Fluid Temperature as a Function of Time

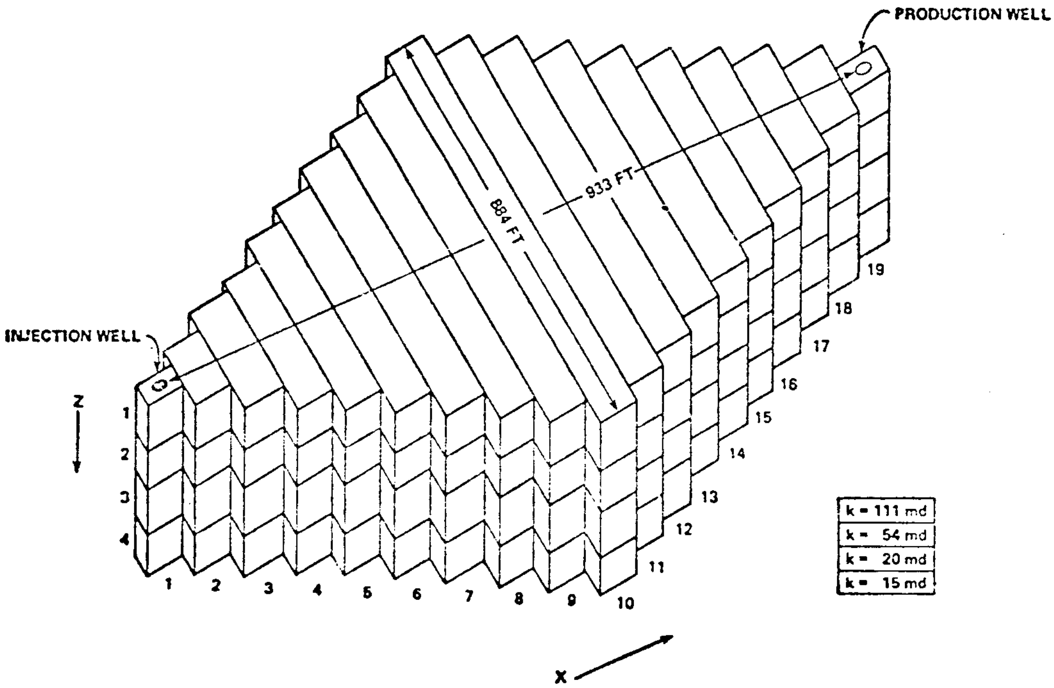

Figure 3. Five-Spot Cross-Sectional Simulation Grid

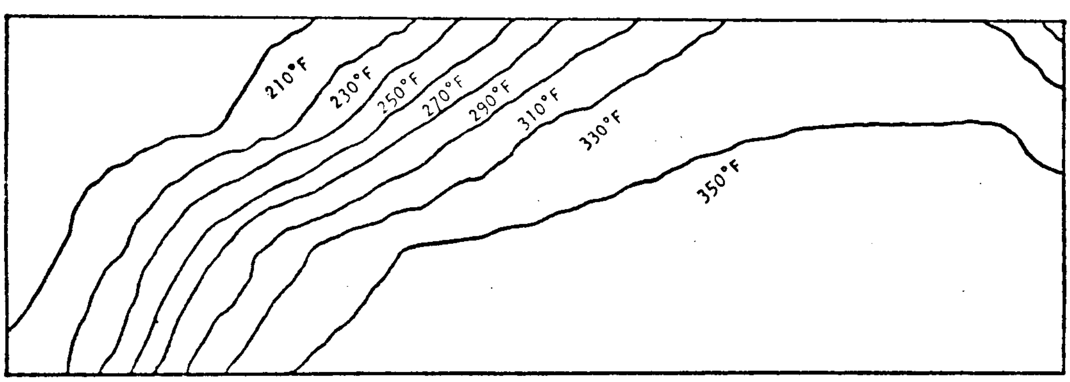

Figure 4. Temperature Distribution Contour Map at 1460 Days: Cross-Sectional Simulation

Table 1. Two Dimension Areal Simulation Summary

Case No.	Permeability (Millidarcies)	Fluid Injection	Aquifer Support	Reservoir Longevity	Notes
Low Flow Rate (10,000 lb/min)					
1	50	No	Yes	Exceeds 30 years	
2	50	No	No	Less than 15 years	Flow not sustained
3	50	Yes	No	Exceeds 30 years	
4	10	No	Yes	Less than 30 years	Flow not sustained
5	10	Yes	Yes	Exceeds 30 years	
6	10	No	No	Less than 30 years	Flow not sustained
7	10	Yes	No	Exceeds 30 years	
Intermediate Flow Rate (100,000 lb/min)					
8	50	No	Yes	Exceeds 30 years	
9	50	No	No	Approx. 6 years	Flow not sustained
10	10	No	Yes	Less than 30 years	Flow not sustained
11	10	No	No	Less than 30 years	Flow not sustained
12	10	Peripheral	Yes	Exceeds 30 years	Flow decreases by 10%
High Flow Rate (1,000,000 lb/min)					
13	10	Peripheral	Yes	Approx. 6 years	Flow not sustained
14	50	Peripheral	Yes	Exceeds 30 years	Flow decreases by 20%
15	50	Pattern 20-acre spacing	—	Approx. 2 years	Pressure not maintained Injected fluid volume not equal to produced fluid volume
16	50	Pattern 20-acre spacing	—	Approx. 12 years	Longevity limited to 300°F
17	50	Pattern 40-acre spacing	—	Approx. 20 years	Longevity limited to 300°F
18	50	Pattern 80-acre spacing	—	Exceeds 30 years	

(a) 100,000 lb/hr @ 200°F into the injection well, and

(b) 25,000 lb/hr @ 500°F at the bottom, half-way between the injection well and the production well.

Performance in this case was considerably improved over the preceding case.

References

1. "Study of the Geothermal Reservoir Underlying the East Mesa Area, Imperial Valley, California," TRW/INTERCOMP Final Report No. 28859-6001-RU-00, prepared for the United States Department of the Interior, December, 1976.

2. Carter, R. D. and Tracy, G. W.: "An Improved Method for Calculating Water Influx," Trans. AIME (1960) 219 p. 415.

3. Van Everdingen, A. F. and Hurst, William: "The Application of the LaPlace Transform to Flow Problems in Reservoirs," Trans. AIME (1949) 181 p. 305.