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1982 THERMAL SHALLOW RESERVOIR TESTING

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ABSTRACT

An extensive study of the Thermal Shallow Reservoir at The Geysers was performed in 1982 to improve our understanding of the source and flow patterns of steam in the shallow anomaly and how they relate to the Thermal 4 blowout. This project included gathering and analyzing pressure transient, enthalpy, tracer and chemical data and developing a reservoir model that was consistent with this data.

Following the pressure transient testing and analysis, a convection-plume with lateral-flow model was proposed. Subsequent analysis of enthalpy, tracer and chemical data corroborated this model. The high flowrate wells - Thermal 4, Thermal 10, Thermal 11 and Magma 1 - produce from the high-pressure, high-permeability upflow zone. The source of this upflow is a limited fracture system connecting the shallow anomaly with the underlying main reservoir. The outlying low-pressure, low-permeability wells are supplied by lateral flow of steam from the central area. The pressure gradient from the core to the periphery is caused by condensation in the flanks.

INTRODUCTION

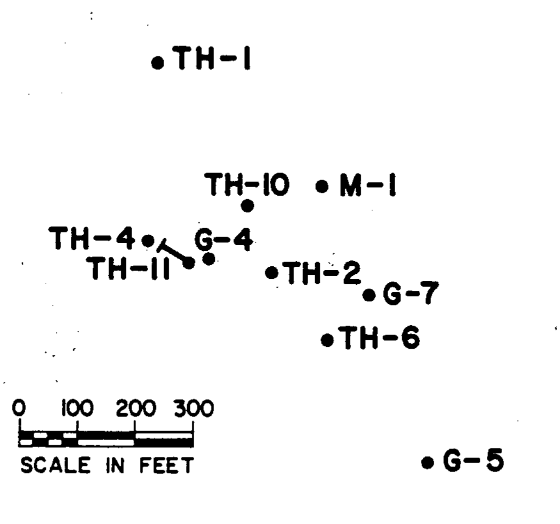
The Thermal Shallow Reservoir was the first part of The Geysers to be utilized for commercial electrical generation, primarily because of its associated surface manifestations and shallow depth. The early development and production history of this area is discussed in detail by Raasch (1985). Figure 1 is a map of the surface locations of the ten wells included in the study. Directional surveys are not available for most of these wells, and the wellcourses are assumed to be vertical. The only well that is directionally drilled is Thermal 11, a relief well for the Thermal 4 blowout.

To improve our understanding of the Thermal Shallow Reservoir and the Thermal 4 blowout system, an extensive reservoir study was undertaken in 1982. The small scale of this reservoir allowed us to include pressure transient, tritium tracer, noncondensible gas and enthalpy data in the analysis. The objective was to develop a simple model of the reservoir and its steam flow patterns that was consistent with each of these analytical approaches.

Wellhead pressure, temperature and flowrate of each of the wells were monitored from January to August, 1982 using a portable, computerized, data-gathering system. Wells monitored were: Thermal 4 (the blow-out); three wells producing to Unit 2 - Thermal 10, Thermal 11 and Magma 1; three idle wells completed only in the shallow zone - Thermal 1, Thermal 2 and Thermal 6; and three wells drilled in the

FIGURE I

1982 THERMAL RESERVOIR STUDY



DISCLAIMER

1920's - Geysers 4, Geysers 5 and Geysers 7. These wells range in depth from 416 ft to 936 ft and are all within 650 ft of Thermal 4.

PRESSURE TRANSIENT TESTING AND ANALYSIS

Flowtesting of the wells began in January, 1982 after the data gathering network and flowlines were installed. A typical test included a three-day flow period followed by a shut-in period of comparable length. The active and observation wells were monitored continuously to obtain pressure buildup and interference data.

Example: Thermal 11 Flowtest

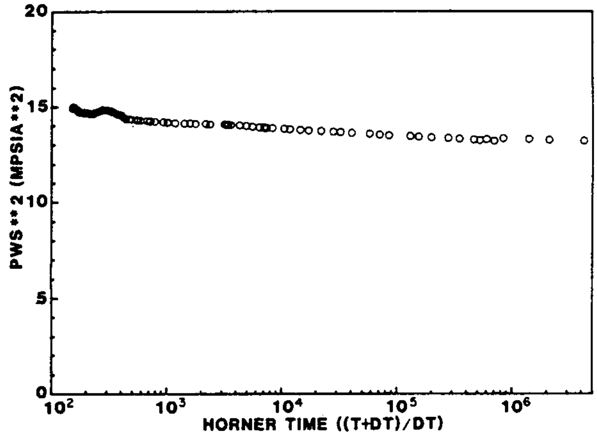
The Thermal 11 flowtest is discussed in detail to provide an example of the nine flowtests performed. Thermal 11 flowed at 81,400 lb/hr with all neighboring wells shut in (except Thermal 4). Figure 2 shows the Horner plot of the Thermal 11 pressure buildup following this flowtest. Pressure-squared analysis is used to account for the compressibility of steam. A line with the slope of 320 psi^2/cycle intersects the data for over three log cycles, yielding a very large kh of 2.1 million md-ft.

In addition to the buildup data, pressure interference was observed at three observation wells: Thermal 2, Thermal 10 and Magma 1. Figure 3 shows the response at Thermal 10, plotting Δp vs Δt. Type-curve matching this response with the line-source solution yields two distinct matches, an early- and late-time match. As stated in Earlougher (1977), the late-time match is the appropriate one to use when analyzing naturally fractured reservoirs. Type-curve analysis yields a kh of 1.2 million md-ft and a Øh of 10 ft.

Results of Flowtests

Pressure buildup results were obtained from nine flowtests performed during the study. The results for kh shown in Table 1 range from 10,000 md-ft at Thermal 1 to 2.1 million at Thermal 11. The Unit 2 wells had very high kh products of 1 million md-ft or more, and the surrounding wells had much lower values. Figure 4 contours the kh values, depicting a decreasing trend of permeability-thickness away from the central wells.

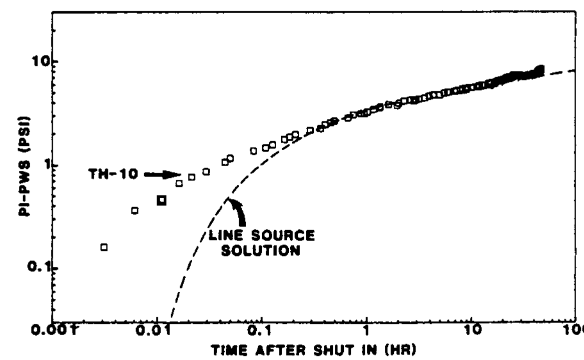
FIGURE 2
THERMAL-11 HORNER BUILDUP RESPONSE



The same trend can be observed in the variation of p*, the extrapolated reservoir pressure of the semi-log straight line. The p* values for the Unit 2 wells ranged from 120 to 126 psia. Both Thermal 2 and Thermal 6 pressures were close to 100 psia, and the remaining wells had pressures below 80 psia. Figure 5 shows the estimated isobars of the Thermal Shallow Reservoir, again showing a decreasing trend away from the center.

During these nine flowtests, several pressure interference responses were observed at neighboring wells. The results for kh and Øh from these tests are shown in Table 2. Each of the Unit 2 wells responded to each other, and the values for kh averaged approximately 1 million md-ft, which is comparable to the results from the buildup tests. The Øh values for the Unit 2 wells ranged from 6 to 20 ft. Assuming a porosity of 5%, this range of Øh indicates a producing thickness of 120 to 400 ft, which

FIGURE 3: THERMAL 10 PRESSURE INTERFERENCE RESPONSE DURING TH-11 BUILDUP



compares reasonably with the drilling data.

Thermal 2 and 6 showed pressure communication with the Unit 2 wells, but their static pressures were 20 psi lower. Strong pressure communication in the presence of such a large pressure difference indicates a regional flow pattern away from the Unit 2 wells. The values for kh were similar to those between the Unit 2 wells, but the Øh products were much higher, ranging from 75 to 387 ft. One possible explanation for this difference may be presence of water near Thermal 2 and 6, causing the total compressibility of the system to increase.

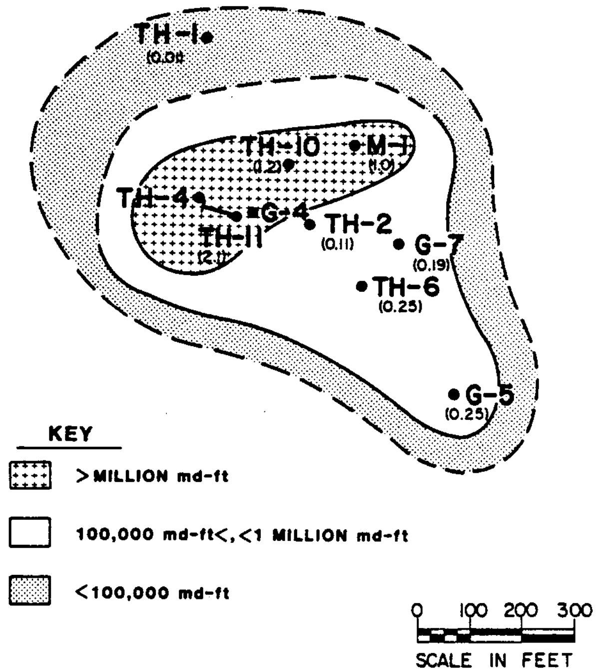
Interference responses were also observed at Geysers 5 and Geysers 7, which are two low-pressure wells in the periphery of the reservoir. This pair showed similar responses to each other, but did not respond to any other flowtests.

Because Thermal 4 vents to the atmosphere continuously, its wellhead pressure cannot be monitored to test for interference. Its flowrate, however, is dependent on production from the Unit 2 wells, thereby indicating communication. On March 25, 1982, the Thermal 4 flowrate increased 6% when Thermal 11 and Magma 1 were shut in. Considering that Thermal 4 communicates with the Unit 2 wells and also has a large flowrate, it is probably completed in the high-pressure, high-permeability area of the Thermal Shallow Reservoir.

FIGURE-4

1982 THERMAL RESERVOIR STUDY

AREAL DISTRIBUTION OF FLOW THICKNESS, kh (MILLION md-ft)



PRELIMINARY RESERVOIR MODEL

From the pressure transient analysis alone, enough information is available to propose a model of the Thermal Shallow Reservoir. The most pertinent results from the analysis are the identification of:

TABLE 1

SUMMARY OF PRESSURE BUILDUP ANALYSIS

Well	kh (md-ft)	P* (psia)	Test Date
Thermal 1	0.0105×10^6	78	4/08/82
Thermal 2	0.108×10^6	99	1/27/82
Thermal 6	0.251×10^6	103	3/19/82
Thermal 10	1.23×10^6	126	5/10/82
Thermal 11	2.1×10^6	120	5/05/82
Magma 1	0.97×10^6	123	5/21/82
Geysers 4	0.084×10^6	78	2/04/82
Geysers 5	0.25×10^6	60	2/01/82
Geysers 7	0.19×10^6	61	2/10/82

TABLE 2

SUMMARY OF INTERFERENCE ANALYSIS

Observation Well	Active Well	Kh (md-ft)	Øh[1] (ft)
Thermal 2	Thermal 10	1.07×10^6	387
Thermal 2	Thermal 11	0.73×10^6	75
Thermal 6	Thermal 10	3.4×10^6	146
Thermal 10	Thermal 11	1.25×10^6	10.2
Thermal 10	Magma 1	0.92×10^6	14.4
Thermal 11	Thermal 10	1.24×10^6	6.2
Thermal 11	Magma 1	0.64×10^6	9.6
Magma 1	Thermal 10	1.1×10^6	21.3
Magma 1	Thermal 11	0.89×10^6	15
Geysers 5	Geysers 7	0.24×10^6	20
Geysers 7	Geysers 5	0.41×10^6	34.4

1) Assumes single phase steam compressibility (c_t = .0093 psi^{-1})

1) A high-permeability, high pressure core of the reservoir, containing Thermal 4, Thermal 10, Thermal 11 and Magma 1.

2) A decreasing permeability and pressure gradient outward from the core.

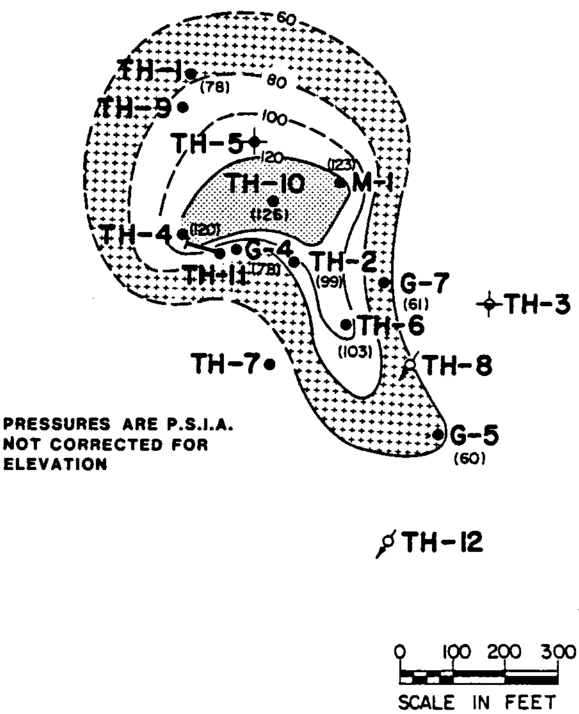
3) Pressure communication between the core and some periphery wells.

The combination of pressure communication and pressure gradient requires lateral flow from the core to the periphery wells. The core area is the direct source for lateral flow. This area in turn must have its own source when considering the number of pore volumes of steam produced from the Thermal Shallow Reservoir. The steam source must be from below rather than from the sides considering that pressure decreases radially from the core. Some sort of limited communication must exist with the main Geysers reservoir, creating an upflow zone in the central area. Figure 6 provides a schematic of this upflow, lateral-flow model.

FIGURE-5

1982 THERMAL RESERVOIR STUDY

ISOBARS FROM BUILDUP DATA



CORROBORATING EVIDENCE OF UPFLOW-CONDENSATION MODEL

Enthalpy, tritium tracer and chemical analyses were evaluated for consistency with the upflow-condensation model suggested by permeability and pressure data. Individually these analyses were inconclusive, but combined with permeability and pressure gradient information, they complemented well the working model of the Thermal Shallow Reservoir.

Enthalpy

Enthalpies in the Thermal area were generally stable during the study, with exceptions at Thermal 4, Thermal 6, Geysers 5 and Thermal 10. Variations at Thermal 4 are probably attributable to grounawater fluctuations (Vantine, 1985), at Thermal 10 to instrumentation error, and at Thermal 6 to water injection from Thermal 8 and Thermal 2 (verified by dye and tritium tracers, respectively). Geysers 5 may have been affected by injection water as was Thermal 6, but mechanical configuration prevented verification of this.

In the model proposed, the highest enthalpies would be expected in the vicinity of the Unit 2 wells (the proposed upflow zone), decreasing toward the periphery (through the proposed condensation zone). Figure 7 shows enthalpy trends for the Thermal Shallow Reservoir. The superheated region is that around the proposed upflow zone. The area surrounding the superheated region varies between saturation and superheat. The periphery is consistently at saturation conditions. The possibility of peripheral water boiling and becoming superheated as it moves towards the Unit 2 wells is precluded by the observed pressure gradient in the opposite direction.

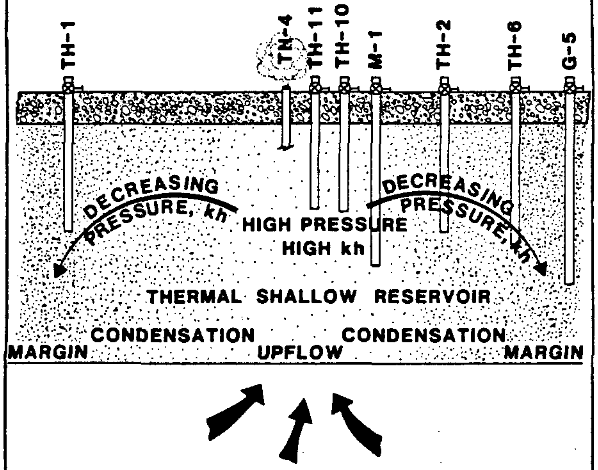
Tritium Tracer

Fluid flow in the Thermal Shallow Reservoir was further investigated with the use of a tritium tracer. All study wells except Thermal 2 were flowed, followed a few weeks later by injection of condensate into Thermal 2 at a stabilized rate of 60 gpm. This rate was maintained for approximately eight weeks.

Thermal 6 was producing superheated steam prior to injection at Thermal 2. Six days after the start of injection, Thermal 6 temperature fell to saturation. Three weeks later, Thermal 6 began producing large amounts of water and was shut in. Geysers 5 also fell to saturation conditions after producing superheated steam during previous flows. No other wells were similarly affected by Thermal 2 injection.

FIGURE 6

THERMAL SHALLOW RESERVOIR UPFLOW - CONDENSATION MODEL



After the first 12 days of injection into Thermal 2, two curies of tritium were injected. All other wells were monitored for tritium production. Monitoring continued for approximately seven months, at which point 41% of the tritium injected had been recovered.

Both Geysers 5 and Thermal 6 had tritium breakthrough within three hours. In just 16 days, these two wells produced half of the total tritium recovered over a seven month perioa. They were shut in due to excessive water production. Thermal 4 had low tritium concentrations, but large total recovery due to its high relative flowrate and constant production. Geysers 7 haa the third highest tritium concentration, which increased dramatically when Thermal 6 and Geysers 5 were shut in. Unit 2 wells produced some tritium, but in very small concentrations.

Figure 8 shows tritium recovery with isochronal lines. The major fluid flow during injection into Thermal 2 is away from the Unit 2 wells and toward the periphery. While injection may have altered fluid flow characteristics somewhat, these results indicate that normal fluid flow is away from the Unit 2 wells.

Chemical Data

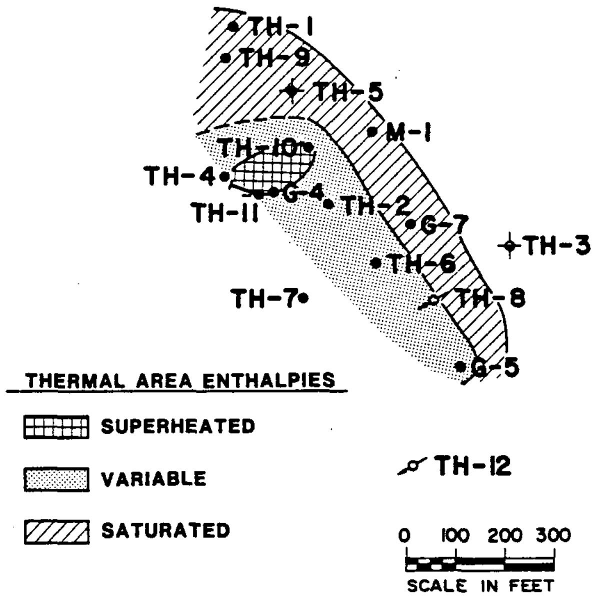
Chemical data was also analyzed within the framework of the model proposed. The data available fell into three categories; non-condensible gases, dissolved solids, and isotopes.

D'Amore, et. al. (1982) described an upflow-condensation model and the corresponding geochemical characteristics. In this model, an upflow zone shows maxima in temperature, permeability, boron, chlorides, H_2, H_2S and $\delta^{18}O$, while a condensation zone shows maxima in total NCG's and NH_3, and minima in boron, chlorides, and $\delta^{18}O$. A marginal zone will have temperature and permeability minima.

Table 3 shows the relative rankings of the study wells in each of the categories which help to identify the various zone types. The Unit 2 wells appear to be in an upflow zone, Thermal 6 in a condensation zone, and Geysers 4, 5 and 7 in a marginal or condensation zone. Thermal 4 is not classified, as groundwater influx may limit the applicability of the model there.

FIGURE 7

1982 THERMAL RESERVOIR STUDY



CONCLUSIONS

The Thermal Shallow Reservoir appears to be a convection cell consisting of an upflow zone in the vicinity of the

TABLE 3

SUMMARY OF D'AMORE, ET. AL. UPFLOW-CONDENSATION MODEL PARAMETERS AS APPLIED TO THE THERMAL SHALLOW RESERVOIR

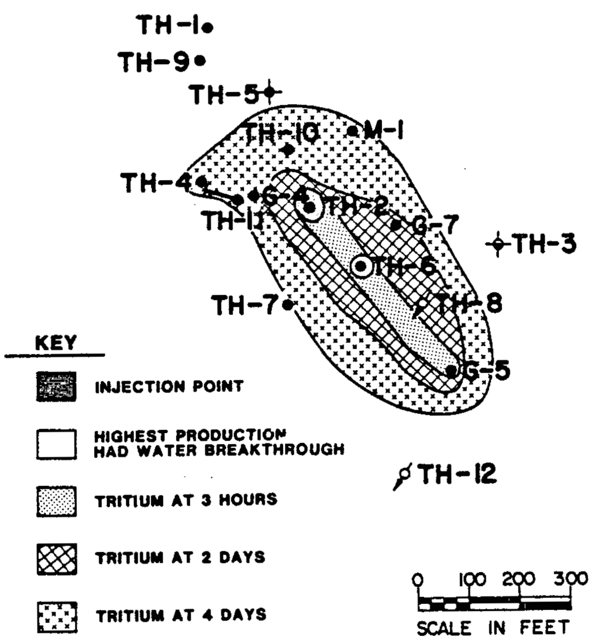
	QUALIFYING WELL
UPFLOW ZONE	
Maxima	
Temperature	Thermal 11
Permeability (kh)	Thermal 11
Boron	Thermal 10
Chlorides	Thermal 10
Hydrogen	Magma 1
Hydrogen Sulfide	Magma 1
$\delta^{18}O$	Thermal 10
CONDENSATION ZONE	
Maxima	
Total NCG's	Thermal 6
Ammonia	Thermal 6
Minima	
Boron	Thermal 6
Chlorides	Geysers 7
$\delta^{18}O$	Thermal 6
MARGINAL ZONE	
Minima	
Temperature	Geysers 5
Permeability (kh)	Geysers 4

Unit 2 wells and Thermal 4, a condensation zone around Thermal 6, and a marginal zone as distance from the Unit 2 wells increases. The deep reservoir appears to be the source of upflow steam. Pressure and permeability data suggest this, and enthalpy, tritium tracer and chemical data support the suggestion.

FIGURE-8

1982 THERMAL RESERVOIR STUDY

TRITIUM RECOVERY FROM THERMAL 2 INJECTION



Based on this model, a relief well was targeted for the upflow zone near Thermal 4 with the intention of intercepting the source of Thermal 4 steam, thereby reducing emissions from the blowout.

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