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RESULTS OF RESERVOIR ENGINEERING TESTS, 1977, EAST MESA, CALIFORNIA

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ABSTRACT

The East Mesa KGRA (Known Geothermal Resource Area) is located in the Imperial Valley of Southern California. Geothermal fluids at temperatures of 160°C to 177°C have been successfully tapped by fourteen geothermal wells, ranging in depth from 1800 to 2800m. During 1977 several production and interference well tests were performed on the East Mesa wells in order to assess the reservoir potential. The results of these tests are summarized in this paper.

INTRODUCTION

The East Mesa KGRA (Known Geothermal Resource Area) (Figure 1) is located in the Imperial Valley of Southern California close to the Mexican border. In addition to the U.S. Bureau of Reclamation (BUREC) which owns lands in the central part of the geothermal anomaly, two private companies have leased lands for the exploitation of the geothermal fluids: Republic Geothermal, Inc., to the north and Magma Power Co. to the south. By late 1977, a total of fourteen wells had been drilled to explore the resource: five by the BUREC, six by Republic and three by Magma. Lawrence Berkeley Laboratory has been carrying out well tests since early 1976 in order to assess the characteristics of the East Mesa geothermal reservoir. The results of tests conducted during 1976 have been discussed elsewhere.[1] The purpose of this paper is to present the results of the well tests conducted during 1977. These tests, carried out in collaboration with BUREC and Magma (February to June, 1977) and with Republic (July to October, 1977), included production and interference as well as injection tests. Valuable information was obtained concerning the the reservoir parameters and geometry. This paper, however, will focus attention primarily on the interference tests. Injection tests are outside the scope of its presentation.

GEOLOGY

The East Mesa resource occurs in a young (tertiary) and geologically active sedimentary basin filled with over 6,000m (20,000 feet) of sandstones, siltstones and shales. Structurally the basin is considerably faulted within the East Mesa area. At least three faults, varying in trend from NNW-SSE to WNW-ESE, have been positvely identified.[2] Growth faults, penecontemporaneous with deposition and trending northeast have also been inferred (J.L. Smith, Republic Geothermal Co., personal communication). There is reason to believe that some of the faults may be discontinuous, either laterally or vertically. The disposition of isotherms at a depth of 1,800m (6,000 feet) suggest that the hot-spot of the geothermal anomaly is centered in the BUREC property (Figure 2). The wells tested vary in depth from 1,800m (6,000 feet) to a little over 2,770m (9,000 feet). The well-head temperatures, which are dependent on flow rates, varying from ~160°C (320°F) ~177°C (350°F). All the wells are under artesian head with well-head pressures ranging from 3.4475×10^5 Pa (50 psi) to 8.274×10^5 Pa (120 psi). The available data on the different wells at East Mesa are summarized in Table I.

References and illustrations are at the end of paper.

DESCRIPTION OF WELLS TESTS

The tests were conducted in two parts. The first part, extending from February to June 1977, consisted of producing BUREC Wells 6-2 and 6-1 for over 10 weeks and monitoring pressure drawdowns in BUREC Well 31-1 and Magma Well 44-7. During the second part of the well testing activity, from July to October 1977, several production and interference tests were carried out in the northern part of the anomaly and data was collected from seven wells. Two of the wells, Republic 38-30 and 16-29, were used alternately as production wells. The produced fluids were then reinjected, after suitable treatment, into Republic Well 18-28. The other wells, BUREC 31-1 and Republic 16-30, 56-30 and 78-30 were used as observation wells.

A description of the tests is presented in Table II. All the tests involved variable flow rates. In the case of BUREC tests, flow rates were measured on Well 6-2 by passing the unflashed discharge through an aperture plate and measuring the pressure drop across the plate. In order to measure discharge from BUREC Well 6-1, the fluid was first passed through a steam separator and the liquid phase then passed through a calibrated Weir box. Appropriate corrections for the vapor-phase were made using steam quality estimates corresponding to the temperature and pressure measured at the well-head.

In the case of the Republic well test, flow rates were measured by first separating steam and water and then passing each phase through separate orifice meters.

Two different methods were employed in order to measure fluid pressures. Bottomhole pressures in self-flowing production wells were measured using the Sperry-Sun system in which a small diameter tube is filled with nitrogen gas. In the unpumped, quiet observation wells, well head pressures were automatically monitored by means of Paro Scientific quartz-crystal pressure transducers.

Figure 3 presents a segment of the data collected from BUREC Well 6-2 using the Sperry Sun system (a .066cm (0.26 inch) inner-diameter tube extended to a depth of ∿1,525m (5,000 feet) below ground level). The figure shows that during the first 90 minutes after commencement of production on 2/10/77, the measured pressures increased by nearly 8.62×10^5 Pa (∿125 psi), during which time the well-head temperatures rose from atmospheric to approximately 160°C (320°F). Because the Sperry Sun system operates by transmitting the pressure sensed at the bottom of the gas column upwards through a compressible gas, the observed increase in pressure during the early stages of production is obviously to be attributed to a gradual heating of the gas-filled tube. This pronounced perturbation of pressure leaves the initial reservoir pressure difficult to define. Consequently, early drawdown data, so valuable for the interpretation of well bore storage, fracture, and other effects, is completely lost.

Additional difficulties arose when, during this test, over 325m (1,000 feet) of excess tubing remaining on the spool were exposed to the atmosphere protected by only crude insulation. The effects of diurnal temperature on the gas in this part of the tubing are reflected in the three prominent peaks seen in Figure 3 once daily between 2/11/77 and 2/13/77. In a subsequent test on Well 38-30, the use of larger I.D. tubing (.14 cm; 0.054 inch) significantly minimized the magnitude of the pressure perturbations immediately after the commencement of production.

TECHNIQUES FOR INTERPRETATION

All of the tests were conducted with the reservoir remaining in single-phase with liquid water. Because the time scale in which temperature changes occur within the reservoir is much greater than the duration of the well tests, it is practical to apply the widely known techniques for isothermal systems developed by petroleum engineers and hydrogeologists for purposes of analysis.

It is well known that the conventional type-curve or a semi-log plot analysis requires that well tests be conducted with constant flow rates. However, for practical reasons it is often extremely difficult to assure constant or near-constant production during geothermal well tests. Since all the tests in the present study involved variable flow rates, it was clearly not feasible to utilize the conventional methods to interpret the data. Instead, a computer assisted curve-matching procedure[3] developed at the Lawrence Berkeley Laboratory was employed.

In the case of a few observation wells (e.g. Well 31-1, Fig. 4; Well 16-29, Fig. 5) which experienced only small pressure drawdowns, the data collected was sufficiently sensitive to reveal the presence of small pressure perturbations induced by earth tides. In such cases, the effect of the earth tides on the pressure transient was first eliminated by smoothing the data through eye judgement.

RESULTS

I. TESTS ON BUREC WELLS

Our tests first began by producing Well 6-2 for 12 days, during which time well head pressures were monitored on Wells 6-1, 8-1 and 31-1. Flow rates from Well 6-2 varied from $2.524 \times 10^{-3} m^3/sec$ to $6.31 \times 10^{-3} m^3/sec$ (40 to 110 gpm). After this 12 day period, production was continued without interruption on 6-2 while, at the same time, Well 6-1 was also opened to production. The total production from the two wells remained steady at approximately $6.94 \times 10^{-3} m^3/sec$ (110 gpm) for over 10 weeks.

Downhole measurements taken in Well 8-1 during the first weeks of the test showed no appreciable drawdowns, thus indicating a lack of communication between Wells 6-1, 6-2 on the one hand and 8-1 on the other. This observation agrees with the data collected during an earlier test in 1976.[1] The precise geologic cause of this lack of communication has not yet been determined.

The analysis of the data collected from Well 6-1 with Well 6-2 in production was rendered difficult because of the uncertainty in establishing the initial reservoir pressures with reference to which drawdowns are calculated (Fig. 6). This uncertainty results from the fact that Well 6-1 was heated up briefly a few days prior to the interference test and was still cooling down when the test commenced. Subject to this uncertainty, by a reasonable estimate of the initial pressure the reservoir kH was computed as $7.50 \times 10^{-12} m^3$ (25,000 md-feet) with a reservoir ϕcH of 2.65×10^{-7} m/Pa (6×10^{-3} ft/psi). The estimated kH, it should be pointed out, is much higher than the earlier[1] estimate of $\sim 3.31 \times 10^{-12} m^3$ (11,000 md-feet).

The drawdown responses observed in Wells 31-1 and 44-7 with Wells 6-2 and 6-1 simultaneously producing were extremely small. The former (Fig. 4), approximately 2,750m (9,000 feet) away indicated a drawdown of $\sim 1.379 \times 10^3$ Pa (0.2 psi); the latter, approximately 1280m (4,200 feet) away, a drawdown of $\sim 3.45 \times 10^3$ Pa (0.5 psi). Data from both wells showed considerable earth tide influence. Although the qualitative evidence of clear drawdown effects suggests the hydraulic continuity of the reservoir, a strictly quantitative interpretation must be viewed with caution due to the long distances between the production and observation wells.

When we posit a linear leaky boundary trending slightly to the west of north and passing a little to the west of 8-1, an interpretation assuming a single production well located midway between 6-2 and 6-1 yielded a kH of $7.94 \times 10^{-12} m^3$ (26,400 md-feet) for the 31-1 data and a kH of $6.91 \times 10^{-12} m^3$ (23,000 md-feet) for the 44-7 data. Although a leaky boundary had also been inferred from the earlier tests in 1976[1], the quality of the data collected thus far has not been good enough to positively establish the presence of this leaky boundary.

The results of our interpretations of the BUREC test data are summarized in Table III.

II. TEST ON REPUBLIC WELLS

Three tests were conducted on the Republic wells. In the first, a production-interference test, Well 38-30 was subjected to step-wise flow rates for four days, by throttling the well flow. During this test, downhole pressures were monitored in the production well using the Sperry Sun system, while well head pressures were monitored in the different observation wells indicated in Table II. The second and third tests were interference tests. The second test consisted of producing Well 16-29 for four days, allowing it to sustain production by free flow. The third and final test was a long duration (7 weeks) interference test in which Well 38-30 was produced with a downhole pump set at 126m (410 feet) below ground level.

The flow history of Well 38-30 during the first test and its corresponding downhole pressures are given in Figure 7. The prominant increase in pressure seen at the start of the test and the subsequent appearance of spikes every time the flow rate was stepped up are due to the aforementioned temperature effects on the gas column in the small diameter tube. During this test, the production well experienced a maximum drawdown of about 1.03×10^6 Pa (150 psi). Pronounced drawdowns were measured in all three observation wells: 9.65×10^4 Pa, 14 psi (Well 31-1); 1.52×10^5 Pa, 22 psi (Well 56-30); and 8.96×10^3 Pa, 1.3 psi (Well 16-29). The pressure response from Well 56-30 is presented in Figure 8 for purposes of illustration.

Study of the results indicates that the Productivity Index of Well 38-30 was $\sim 4.6 \times 10^{-8}$ m^3/sec Pa; 5.0 gpm/psi. Analysis of the drawdown data indicates a reservoir kH of 24,000 md-feet in the vicinity of 38-30.

In analyzing the interference data from this test, rough calculations indicate that injection into Well 18-28, located a considerable distance to the east, will not create significant drawdowns in any of the observation wells throughout the duration of the tests. Hence the effect of injection on the observation wells can conveniently be neglected.

Interpretation of the observation well data led to estimates of kH ranging from 6.31×10^{-12} to $1.052 \times 10^{-11} m^3$ (21,000 to 35,000 md-feet) and ϕcH from 1.77×10^{-8} m/Pa (4×10^{-4} ft/psi) to 1.77×10^{-7} m/Pa (4×10^{-3} ft/psi). For details, please refer to Table IV.

The interpretation also suggested the possible presence of a barrier boundary. The distance to the image well was estimated to be 1,400m (4,600 feet) from Well 56-30 and 800m (2,600 feet) from Well 31-1. These distances result in two possible positions for the barrier boundary. However, when during subsequent tests it became known that Well 16-30 did not show any pressure response to production from either 38-30 or 16-29, it became possible to infer that a linear boundary trending NNE passes a little to the east of Well 16-30, as shown in Figure 9. We should note that the presence of a barrier boundary had also been inferred during an earlier test in 1976.[1]

The data collected during the second test in which Well 16-29 was produced failed to yield any definitive information. During this test none of the observation wells, namely, 56-30, 31-1 and 16-30, experienced any pressure response to 16-29 production. Moreover, downhole pressures taken from Well 16-29 were available for only a limited duration just before and after shutting down production. The build-up data, which was of doubtful quality, led to an estimate of 9.62×10^{-12} m^3 (32,000 md-feet) for the reservoir in the vicinity of Well 16-29.

Data collected from observation Wells 56-30 and 31-1 during the long duration interference test corroborated the interpretations drawn from the first test. Well 56-30 suggested a kH of $7.1 \times 10^{-12} m^3$ (23,600 md-feet); Well 31-1, a kH of $9.53 \times 10^{-12} m^3$ (31,700 md-feet). The distance from Wells 56-30 and 31-1 to the image well were computed to be 1,100m (3,500 feet) and 740m (2,400 feet) respectively.

Careful measurements on Well 16-30 indicated that it did not experience any pressure response to production from Well 38-30. In addition, the pressure response of Well 78-30, drilled in August 1977, to production from Well 38-30 was considerably slower than that which one might have expected from already established estimates of reservoir kH on the assumption of clear communication between the two wells. The pressure response in Well 78-30 rather suggests that there may exist a discontinuous barrier of some kind (either vertical or horizontal) between Wells 38-30 and 78-30.

The results of the Republic tests are summarized in Table IV. The pressure communications thus far established between different wells in the East Mesa geothermal field are depicted in Figure 10. This figure also includes those barriers or leaky boundaries that have been inferred to affect the reservoir. Of these, the barrier boundary near Well 16-30 is the most pronounced and the most firmly established. The two barriers in the vicinity of 56-30 and 78-30 have been qualitatively inferred from the limited communication that exists between wells in that area. The leaky boundary inferred to exist near Well 8-1 requires additional confirmation based on more definitive well test evidence, should such evidence be forthcoming.

SUMMARY

The interference tests conducted on the BUREC wells suggest that the kH of the reservoir in the vicinity of Wells 6-2 and 6-1 is $\sim 6.01 \times 10^{-12} m^3$ (20,000 md-feet). This value is somewhat higher than the $3.61 \times 10^{-12} m^3$ (~12,000 md-feet) previously estimated in 1976.[1] It should be noted that interpretation of data from 6-1 during the present test must be considered tentative because of the difficulty in estimating the initial reservoir pressure. Interference data from Wells 31-1 and 44-7, which are farther removed from the center of geothermal anomaly, indicate kH values of 7.81×10^{-12} m^3 and $6.91 \times 10^{-12} m^3$ (26,000 and 23,000 md-feet) respectively, possibly suggesting that the reservoir transmissivity generally increases as one moves away from the hot spot. From a geological perspective, this appears to be quite realistic, since one expects permeability degradation in the hot spot due to the increased metamorphism and deposition of minerals.

The Republic tests indicate that in the northern part of the reservoir, kH values generally range from $7.21 \times 10^{-12} m^3$ to $1.05 \times 10^{-11} m^3$ (24,000 to 35,000 md-feet). These tests have also indicated the presence of a pronounced barrier trending NNE and passing a little to the east of Well 16-30. The possible presence of two discontinuous barriers in the Republic lease area and an as yet ill-defined leaky boundary in the BUREC property have also been inferred from the available data.

NOMENCLATURE

k = permeability [L^2]

H = reservoir thickness [L]

ϕ = porosity

c = total compressibility; is equal to water compressibility plus pore volume compressibility of the rock [LT^2/M]

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2. U.S. Bureau of Reclamation, "Geothermal Investigations, East Mesa Test Site, Imperial Valley, California, Status Report 1974," November 1974.

3. Tsang, C.F., D.G. McEdwards, T.N. Narasimhan and P.A. Witherspoon, "Variable Flow Well Test Analysis by a Computer Assisted Matching Procedure," Paper No. 6547, SPE, AIME, Bakersfield, California, April 1977.

ACKNOWLEDGEMENTS

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Table I

WELL	OWNER	TOTAL DEPTH	SLOTTED INTERVAL	NET SAND IN OPEN INTERVALS	REMARKS
6-1	BuRec	2447m	1890m to 2444m	152m	
6-2	BuRec	1830m	1460m to 1816m	320m	
5-1	BuRec	1829m	1526m to 1829m	210m	
8-1	BuRec	1891m	1508m to 1829m	210m	
31-1	BuRec	1899m	1652m to 1882m	158m	
44-7	Magma	2240m	2239m to 2240m	NA	
48-7	Magma	2300m	1828m to 2194m	NA	
46-7	Magma	943m		NA	Shallow injection well
38-30	Republic	2770m	1920m to 2412m	152m	Filled to 2140m
56-30	Republic	2292m	1615m to 2292m	561m	
16-29	Republic	2437m	1950m to	255m	
16-30	Republic	2438m	1950m to 2438m	340m	
18-28	Republic	2438m	1557m to 2438m	70m	No water entry between 1950m and 2438m
78-30	Republic	2268m	1798m to 2268m	383m	

Table II

TEST	DATE	PRODUCING WELL	METHOD OF PRODUCTION	FLOW RATE m^3/sec (bbl/day)	PRESSURE MEASUREMENT IN PRODUCING WELL	OBSERVATION WELLS (wellhead, quartz crystal pressure transducer) 1	2	3	4
BUREC	1/27/77 to 4/13/77	6-1, 6-2	Artesian Flow	Combined 3.7×10^3 bbl/day (6.9×10^{-3} m^3/sec)	6-2 Sperry Sun Pressure Transmission System	6-1	31-1	44-7	
Republic Test 1	7/14/77 to 7/18/77	38-30	Artesian Flow	Five Rate 1.72×10^4 bbl/day (3.2×10^{-2} m^3/sec) 2.97×10^4 bbl/day (4.7×10^{-2} m^3/sec) 3.08×10^4 bbl/day (5.7×10^{-2} m^3/sec) 1.72×10^4 bbl/day (3.2×10^{-2} m^3/sec) 8.57×10^3 bbl/day (1.6×10^{-2} m^3/sec)	Sperry Sun Pressure Transmission System	56-30	31-1	16-29	
Republic Test 2	7/26/77 to 7/30/77	16-29	Artesian Flow	Highly Variable 6.85×10^3 bbl/day (1.2×10^{-2} m^3/sec) to 2.4×10^4 bbl/day (4.4×10^{-2} m^3/sec)	Build-up only Sperry Sun Pressure Transmission System	56-30	31-1	16-30	
Republic Test 3	8/22/77 to 10/5/77	38-30	Downhole Pump	~1.37×10^4 bbl/day (~2.5×10^{-2} m^3/sec)	None	56-30	31-1	16-30	78-30

Table III

SUMMARY OF RESULTS FROM BUREC TESTS

TEST NO.	PRODUCTION TEST	OBSERVATION WELL	ESTIMATED* kH (md-feet)	ESTIMATED ϕcH (ft/psi)	REMARKS
BUREC TEST	6-2	6-1	20,000 md-feet (6.1×10^{-12} m^3)	6.0×10^{-3} ft/psi (2.6×10^{-7} m/Pa)	Uncertain initial pressure
	6-2 and 6-1	31-1	26,400 md-feet (8.04×10^{-12} m^3)	2.0×10^{-3} ft/psi (8.8×10^{-8} m/Pa)	Leaky barrier inferred
		44-7	23,000 md-feet (7.0×10^{-12} m^3)	6×10^{-4} ft/psi (2.64×10^{-8} m/Pa)	Leaky barrier inferred

*Assuming a hot water viscosity of .18 cp or $.18 \times 10^{-3}$ kg/msec.

Table IV

SUMMARY OF RESULTS FROM REPUBLIC TESTS

TEST	PRODUCING WELL	OBSERVATION WELL	kH* (md-feet)	ϕcH (ft/psi)	REMARKS
Test 1	38-30	56-30	26,000 md-feet (8.0×10^{-12} m^3)	4.3×10^{-4} ft/psi (1.9×10^{-8} m/Pa)	Image well for barrier boundary 1410m
		31-1	35,000 md-feet (1.06×10^{-11} m^3)	2.0×10^{-3} ft/psi (8.8×10^{-8} m/Pa)	Image well for barrier boundary at 790m
		16-29	21,000 md-feet (6.40×10^{-12} m^3)	4.0×10^{-3} ft/psi (1.7×10^{-7} m/Pa)	
		38-30	24,000 md-feet (7.3×10^{-12} m^3)		Uncertain initial pressure due to temperature effects on nitrogen in tubing
Test 2	16-29	16-29	32,000 md-feet (9.7×10^{-12} m^3)		
		56-30			No communication
		31-1			No communication
		16-30			No communication
Test 3	38-30	56-30	23,600 md-feet (7.2×10^{-12} m^3)	6.4×10^{-4} ft/psi (2.8×10^{-8} m/Pa)	Image well for barrier boundary at 1057m
		31-1	31,700 md-feet (9.66×10^{-12} m^3)	2.4×10^{-3} ft/psi (1.0×10^{-7} m/Pa)	Image well for barrier boundary at 740m
		16-30			No communication
		78-30			Partial barrier of some type affecting pressure response

*Assuming a fluid viscosity of 1.8×10^{-4} kg/msec.

Table V

TABLE OF DISTANCES (METERS) BETWEEN WELLS AT EAST MESA KGRA*

WELL	38-30	56-30	78-30	18-28	16-29	16-30	31-1	6-1	6-2	5-1	8-1	44-7	46-7	48-7
38-30	0	580	800	2,870	1,280	580	380	2,210	2,160	2,260	2,700	3,020	3,280	3,540
56-30	580	0	440	2,500	800	160	690	2,450	2,410	2,380	2,930	3,320	3,580	3,840
78-30	800	440	0	2,060	2,060	960	880	2,130	2,160	1,950	2,560	3,020	3,320	3,570
18-28	2,870	2,500	2,060	0	1,700	2,930	2,950	2,650	2,790	1,310	2,800	3,520	3,830	4,050
16-29	1,280	800	2,060	1,700	0	1,610	1,330	2,470	2,480	1,970	2,850	3,460	2,670	3,930
16-30	580	610	960	2,930	1,610	0	370	2,260	2,120	2,850	3,120	3,400	3,660	3,920
31-1	380	690	880	2,950	1,330	~~370~~	0	2,900	2,700	3,200	3,510	2,490	3,260	3,530
6-1	2,210	2,450	2,130	2,650	2,470	2,260	2,900	0	450	2,160	710	970	1,230	1,460
6-2	2,160	2,410	2,160	2,790	2,480	2,120	2,700	450	0	2,510	1,120	900	1,160	1,430
5-1	2,260	2,380	1,950	1,310	1,970	2,850	3,200	2,160	2,510	0	2,040	2,470	2,600	2,830
8-1	2,700	2,930	2,560	2,800	2,850	3,120	3,510	710	1,120	2,040	0	880	1,200	1,250
44-7	3,020	3,320	3,020	3,520	3,460	3,400	2,990	970	900	2,470	880	0	260	530
46-7	3,420	3,720	3,320	3,830	3,670	3,660	3,260	1,230	1,160	2,600	1,200	260	0	260
48-7	3,820	4,120	3,570	4,050	3,930	3,920	3,530	1,460	1,430	2,830	1,250	530	260	0

* Plus or minus 10%

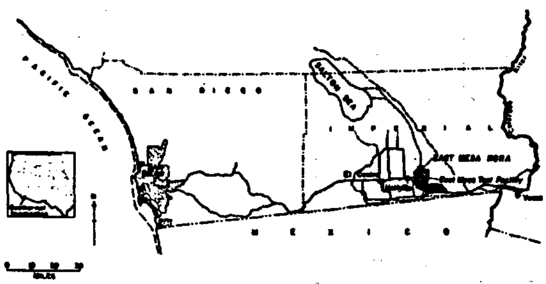

Fig. 1 - Location map of East Mesa KGRA.

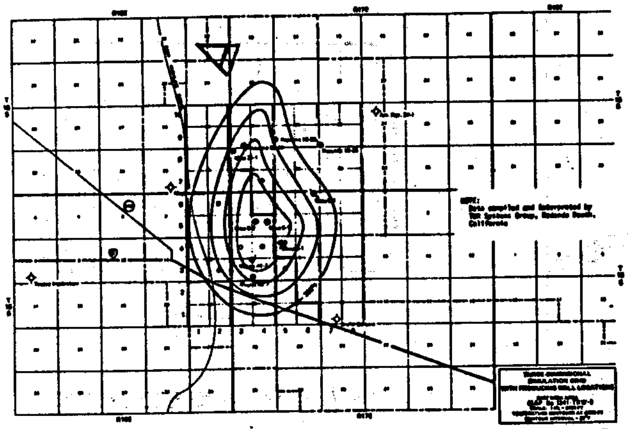

Fig. 2 - East Mesa KGRA: Isotherms at 1,828m (6,00 feet) depth. After U.S. Bureau of Reclamation, 1974.

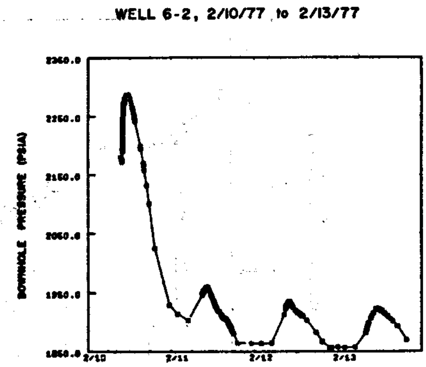

Fig. 3 - Downhole pressure measured with a Sperry-Sun gauge using 0.066 cm (.026 inch) I.D. tube.

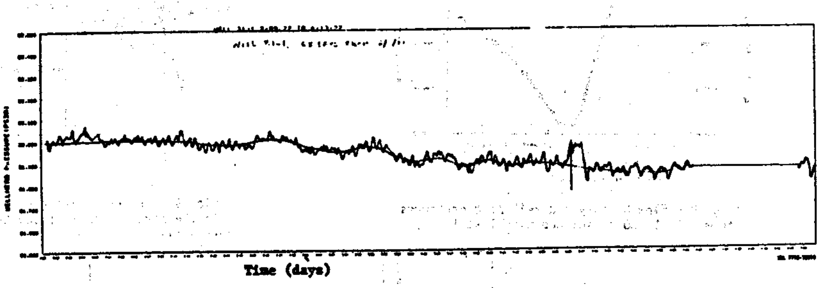

Fig. 4 - Wellhead pressures from well 31-1 with wells 6-2 and 6-1 in production (~2,750 m or ~ 9,000 feet away).

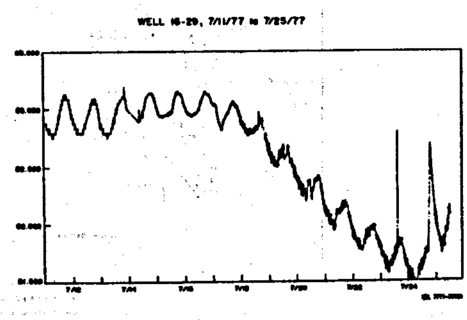

Fig. 5 - Wellhead pressures from well 16-29 with well 38-30 in production (~1,220m; 4,000 feet away).

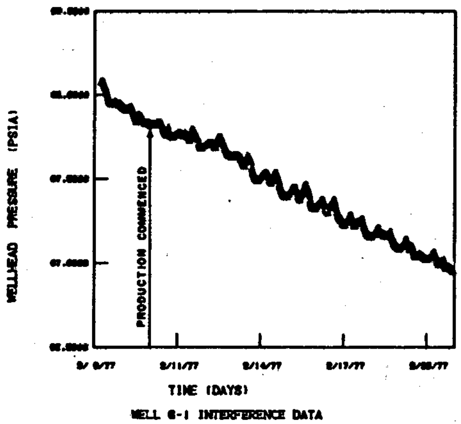

Fig. 6 - Wellhead pressures from well 6-1 with well 6-2 in production (~370m; 1,200 feet away).

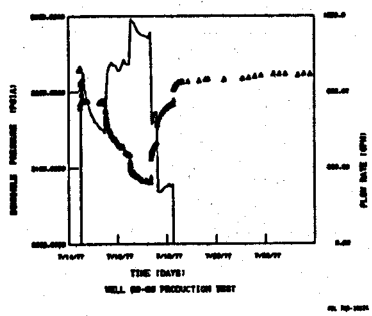

Fig. 7 - Flow history and downhole pressures from well 38-30 during Republic Test 1.

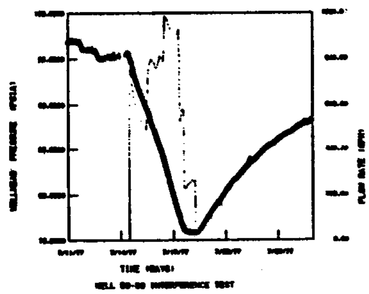

Fig. 8 - Flow history and well head pressures from well 56-30 during Republic Test 1.

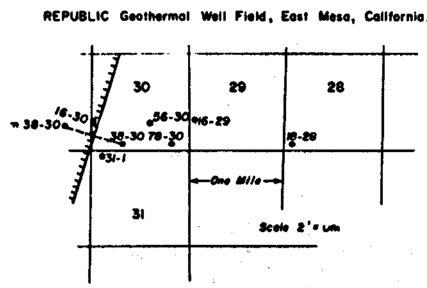

Fig. 9 - Inferred presence of a hydrologic barrier in the northern part of the East Mesa geothermal well field.

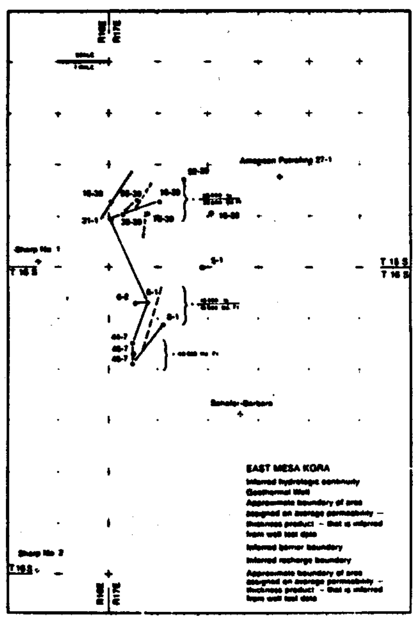

Fig. 10 - Pressure communications between different wells in the East Mesa geothermal field as evidenced by well tests.