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Results of Interference Tests From Two Geothermal Reservoirs

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Introduction

An important facet in the problem of geothermal energy development is assessing the productivity and size of a geothermal reservoir. Modern techniques of well-test analysis (pressure drawdown, buildup, and interference tests) developed in petroleum engineering and hydrogeology have been applied successfully to two liquid-dominated geothermal reservoirs in the U.S.: one in the Raft River Valley of Idaho and the other at East Mesa in the Imperial Valley of California. These tests gave reasonable estimates of the permeability and storage parameters for the two reservoirs. In addition, the tests also illustrate the type of instrumentation that can be used in testing geothermal wells as well as the nature of the data that can be collected.

A large body of literature is available on well testing in both petroleum engineering and hydrogeology. Ramey[1] recently has summarized the practical aspects of modern well-test analysis.

This paper reviews the results of interference tests performed with a very sensitive pressure-measuring device on two geothermal reservoirs. As used in this paper, the term "interference test" denotes the fluid production from one well and measurement of pressure transients in a nearby observation well. The geologic setting for each reservoir is given and the instrumentation is presented. Some unusual features of the data are discussed, followed by the methods of interpretation that were used.

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Description of the Geothermal Reservoirs

Raft River Valley Field, Idaho

The Raft River Valley geothermal field (Fig. 1) is located on a graben filled with Tertiary and Pleistocene sediments and volcanics, with an aggregate thickness of about 5,000 ft. The sediments rest on a basement of quartzites, schists, and quartz monzonites of Precambrian age.

Wells RRGE 1 and RRGE 2 were drilled in 1975 and successfully produced hot water at approximately 295°F from a geothermal reservoir occurring at the base of the sediments at 3,500 to 5,000 ft below the land surface. Well RRGE 2 is northeast and 4,000 ft from Well RRGE 1. Both wells are artesian with wellhead pressures of about 150 psi when shut in. During construction, both wells indicated free flows of about 400 gal/min. The completion details for the two wells are summarized in Table 1.

Subsurface correlations of borehole data suggest that the sediments dip toward Well RRGE 2 with apparent northeasterly dips increasing from about 3° in the upper portion to about 7° toward the bottom. Also, it is known that Well RRGE 1 pierced a fault zone between 3,800 and 4,500 ft. Apparently, Well RRGE 2 did not intercept any faults.

East Mesa Field, California

The East Mesa geothermal field (Fig. 2) is located on the eastern part of the Salton Trough in the Imperial Valley of California. The Salton Trough is a young, geologically active sedimentary basin filled with more than 10,000 ft

Results are presented from interference tests on two liquid-dominated geothermal reservoirs in the U.S. The collected pressure data show that interference effects can be masked by earth tides and other effects. Well known techniques of petroleum engineering and hydrogeology are used to estimate hydraulic characteristics and to infer the presence of barrier and leaky boundaries.

TABLE 1—COMPLETION DATA FOR THE RAFT RIVER VALLEY GEOTHERMAL WELLS

Well Number	Total Depth (ft)	Total Depth (m)	Bottom-Hole Temperature (°F)	Bottom-Hole Temperature (°C)	Production Interval (ft)	Production Interval (m)	Casing OD	Casing Depth	Well-head Pressure (psi)
RRGE 1	4,989	1,521	294	146	3,620 to 4,200	1,105 to 1,280	13⅜-in. (34 cm) Uncased	Ground level to 3,620 ft (1,105 m) to bottom	150
RRGE 2	5,988	1,826	294	146	4,230 to 5,000	1,290 to 1,520	13⅜-in. (34 cm) Uncased	Ground level to 4,230 ft (1,290 m) to bottom	150

of sediments composed of sandstones, siltstones, and clays. Structurally, the sediments of the East Mesa field are faulted considerably, and three intersecting faults (Fig. 2) have been mapped so far. Five wells, varying from 6,000 to 8,000 ft, have been drilled at East Mesa by the U.S. Bureau of Reclamation. The bottom-hole temperatures of the East Mesa wells were distinctly higher than those in the Raft River field and varied from 309 to 399°F. In addition, other geothermal wells also have been drilled on neighboring leases by private companies. We will be concerned with only one of these (Well RG 38-30), used during the interference tests and owned by the Republic Geothermal Co. As at Raft River, the East Mesa wells are also artesian, but with smaller shut-in wellhead pressures of about 70 psi. The completion data for the East Mesa wells are summarized in Table 2.

Reservoir Tests and Instrumentation

Tests

Both interference tests and production well tests were conducted during these studies. The interference tests provided relatively more important information on the reservoir conditions and are the only tests discussed.

In all, three interference tests were conducted, one at Raft River and two at East Mesa. The Raft River test was the longest and Well RRGE 2 flowed at the rate of 400 gal/min (13,700 B/D) for nearly 26 days. During this production period and the subsequent buildup, pressure changes were monitored in Well RRGE 1, the observation well. The two interference tests at East Mesa (EM) were of relatively shorter duration, with production lasting for only 10 or 11 days. The first test consisted of producing Well EM 6-2 at a near constant flow rate of about 90 gal/min (3,100 B/D) for 11 days and monitoring pressure change at the observation wells, EM 6-1 (1,500 ft away) and EM 8-1 (2,300 ft away). The second interference test was conducted in the northern part of the field, with Well EM 31-1 producing at approximately 130 gal/min (4,450 B/D) for 10 days and the Republic Geothermal Well RG 38-30 acting as the observation well. Because all the pressure observations were made on shut-in wells with positive wellhead pressures and because only the pressure differentials are critical for well-test analysis, it was not necessary to obtain pressure-transient data opposite the reservoir itself. Instead, it was feasible to collect such data from any convenient intermediate depth. Pressures were monitored in the observation wells at 1,000 and 1,500 ft. In addition, accurate pressure monitoring also was carried out simultaneously

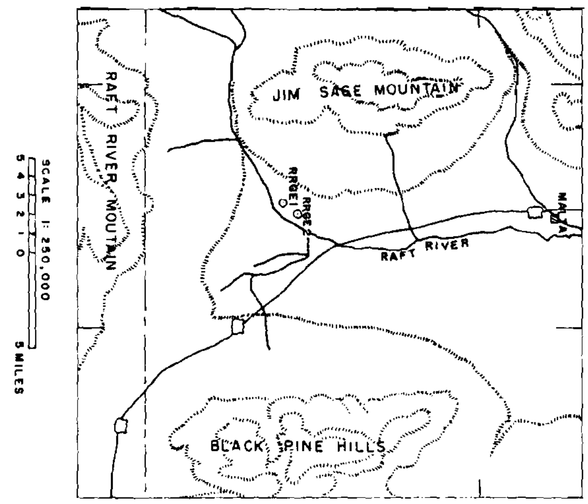

Fig. 1—Location map of the Raft River Valley geothermal field, Idaho.

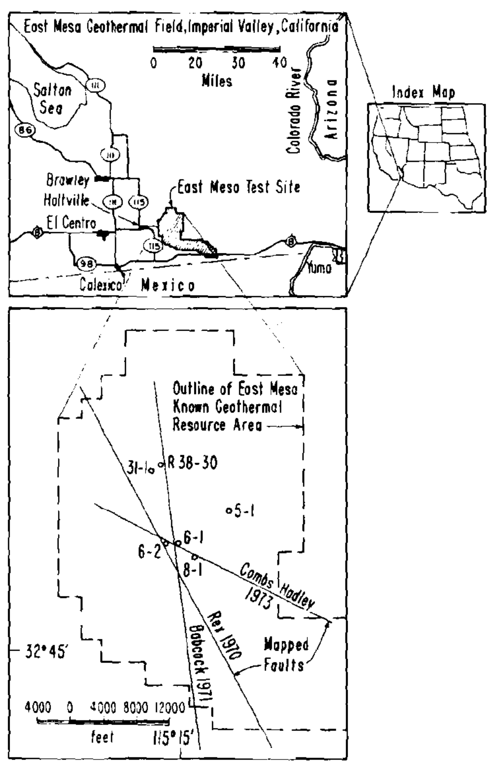

Fig. 2—Location map of the East Mesa geothermal field, California.

TABLE 2—COMPLETION DATA FOR EAST MESA GEOTHERMAL WELLS (After Mathias,[7] 1975)

Well Number	Total Depth (ft)	Total Depth (m)	Bottom-Hole Temperature (°F)	Bottom-Hole Temperature (°C)	Production Interval (ft)	Production Interval (m)	Lower Casing* OD (in.)	Lower Casing* Depth	Well-head Pressure (psi)
EM 6-1	8,015	2,443	399	204	6,201 to 7,982	1,890 to 2,433	7	To bottom	66
EM 6-2	5,958	1,816	340	188	4,790 to 5,959	1,460 to 1,816	7⅝	To bottom	110
EM 5-1	6,004	1,829	315	157	5,007 to 6,004	1,526 to 1,830	7⅝	To bottom	68
EM 8-1	6,001	1,829	354	179	4,948 to 6,001	1,508 to 1,829	7⅝	To bottom	71
EM 31-1	6,175	1,882	309	154	5,420 to 6,175	1,652 to 1,882	7⅝	To bottom	65
RG 38-30	8,890	2,710	N/A**	N/A	6,383† to 7,022	1,945† to 2,140	7	To 7,020 ft (2,140 m)	N/A

*Casing includes blank, perforated, and slotted sections.
**Not available.
†Casing partially filled in.

at the wellhead in the Raft River test. All observation wells at Raft River and East Mesa had remained quiet for several weeks to several months before the interference tests and hence were essentially under thermal equilibrium. For various reasons, production-well bottom-hole pressures could not be measured during the interference tests. The detailed data collected during these tests have been reported elsewhere.[2,3] The data pertaining to the individual tests are summarized in Table 3.

Instrumentation

A key piece of equipment used in the interference tests was a very sensitive down-hole quartz pressure gauge capable of measuring in-situ absolute pressure with an accuracy of 0.01 psi ranging from 0 to 10,000 psi. This instrument can tolerate temperatures up to 300°F for prolonged periods of time and is capable of yielding pressure data at intervals as small as 1 second. Thus, the instrument is suited ideally for monitoring pressures of shut-in observation wells in geothermal reservoirs, especially when these wells have positive wellhead pressures, such as the Raft River and East Mesa fields. However, the present 300°F limit for the temperature tolerance renders this instrument unsuitable in measuring down-hole pressures in most geothermal reservoirs where temperatures exceed this value. Hence, we are limited at present in using this instrument in producing wells. For example, at the Raft River field where the reservoir temperature is only 295°F, we were able to set the instrument opposite the reservoir in the production well and obtain pressure drawdown and buildup data. However, at the East Mesa field we tried to use the instrument in one well opposite the reservoir at a temperature of 318 °F, but the instrument failed after 40 operating hours.

During the interference test in the Raft River field, we also tested another quartz crystal pressure device that is capable of measuring wellhead pressures. With this surface pressure gauge in position and with the down-hole gauge at 1,000 ft, simultaneous pressure measurements were made during the interference test. The collected data showed that the pressure differentials sensed by the two instruments agreed closely with each other, except that the surface instrument accentuated pressure peaks during early afternoons, probably caused by the thermal expansion of the air-column buffer that protected the crystal from well fluids. It would appear that this problem could be avoided easily by using a buffer of an inert oil, such as silicone oil, instead of air.

Nature of Data Collected

The small magnitude of pressure-transient effects that generally are manifested in observation wells far from the producing well, coupled with the high resolution of the pressure data collected during the interference tests, indicated that raw data often may be masked by small but significant extraneous effects in testing geothermal reservoirs. Appropriate corrections have to be made before a meaningful interpretation of the reservoir parameters can be achieved.

The data collected from the Raft River field showed that the reservoir pressures respond systematically to the earth tides. Fig. 3 presents the variation of pressure in observation Well RRGE 1, as well as the computed changes in the earth's gravitational field for Sept. 28-Oct. 6, 1975. Superposed on the over-all pressure decline caused by interference of the producing well are the periodic pressure changes caused by the earth-tide effects. A cross-spectral analysis of gravity and pressure waves indicated that the crests and the troughs of the pressure wave appear to lead those of the gravity wave by approximately 30 minutes. The maximum perturbation induced by the earth tides is approximately 0.1 psi about the mean, or a total crest-to-trough amplitude of 0.2 psi. Similar earth-tide effects were noticed by Strobel *et al.*[4] in a dry gas reservoir. Note that the total amplitude observed in the gas reservoir is only 0.03 psi or about one-tenth of the amplitude observed at Raft River. The influence of earth-tide effects on groundwater reservoirs has been documented by many hydrogeologists. Marine[5] reports the response of water levels in some deep wells in crystalline rock to earth tides in South Carolina. His study indicates a maximum tidal amplitude of about 0.15 psi. A theoretical study of the response of a well-aquifer system to earth tides has been conducted by Bredehoeft.[6]

Because the pressure data are almost in phase with gravity variation, it is relatively simple to eliminate the

TABLE 3—SUMMARY OF INTERFERENCE TESTS, RAFT RIVER AND EAST MESA GEOTHERMAL FIELDS

Field	Interference Test Number	Producing Well: Well	Producing Well: Rate, Gallons per Minute (B/D)	Producing Well: Duration (hours)	Observation Well 1: Well	Observation Well 1: Distance (ft)	Observation Well 1: Pressure Gauge Setting (ft)	Observation Well 1: Static Pressure (psia)	Observation Well 1: Maximum Drawdown (psi)	Observation Well 2: Well	Observation Well 2: Distance (ft)	Observation Well 2: Pressure Gauge Setting (ft)	Observation Well 2: Static Pressure (psia)	Observation Well 2: Maximum Drawdown (psi)
Raft River, Idaho	1	RRGE 2	400 (13,708)	615.5	RRGE 1	4,000	(1) 1,000 (2) at surface	575.0 150.0	3.6					
East Mesa, California	1	EM 6-2	90 (3,084)	273	EM 6-1	1,480	1,100	553.8	0.7	EM 8-1	2,320	1,500	709.60	0
	2	EM 31-1	130 (4,450)	237	RG 38-30	1,250	1,500	726.18	4.6					

effect of earth tides. One needs to consider only the pressure data corresponding to those instants of time at which the computed change in gravity is zero. The dashed line in Fig. 3 has been drawn in this fashion.

In contrast to the Idaho experience, the raw data collected at East Mesa have been characterized by considerable noise (Fig. 4). The noise level in the data showed a total variability of about 0.5 psi. The source of the noise is not yet clearly understood. The Salton Trough, of which East Mesa forms a part, is seismically active and this activity could be a possible cause of the noise. At the same time, it is also possible that the noise may be generated by the instrument-cable system. It was essential to extract the mean trend from the noisy data before attempting an interpretation of reservoir performance. A nonlinear regression technique was used for this

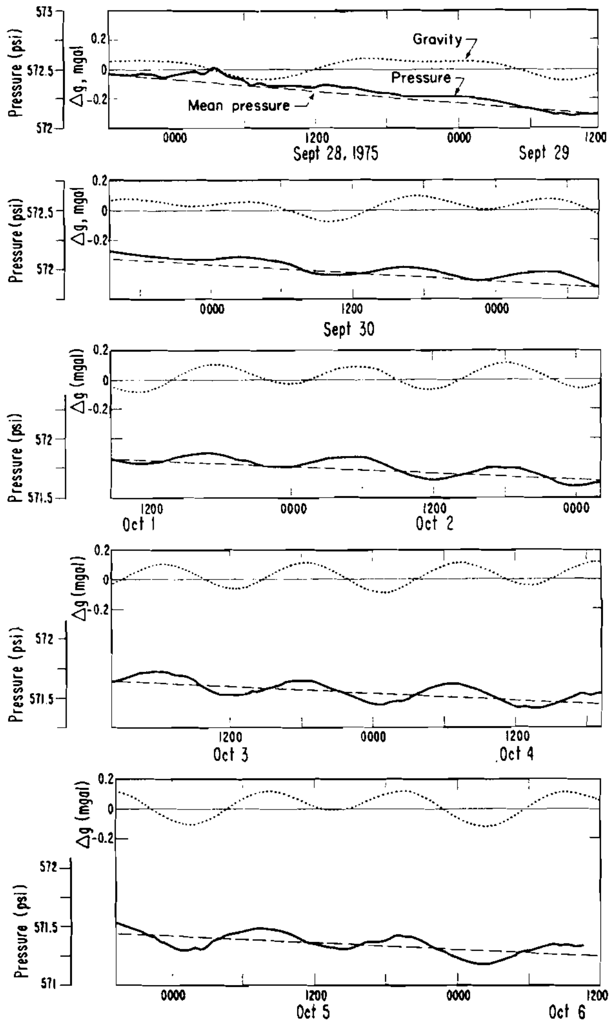

Fig. 3—Correlation between variation in the earth's gravitational field and water pressure in Well RRGE 1 during the interference test.

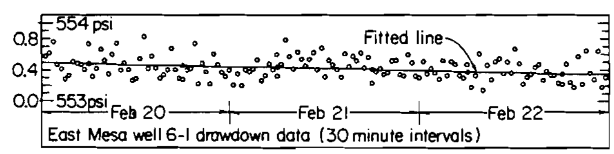

Fig. 4—Comparison of the pressure data recorded in Well EM 6-1 during the first interference test with the fitted line used for analysis.

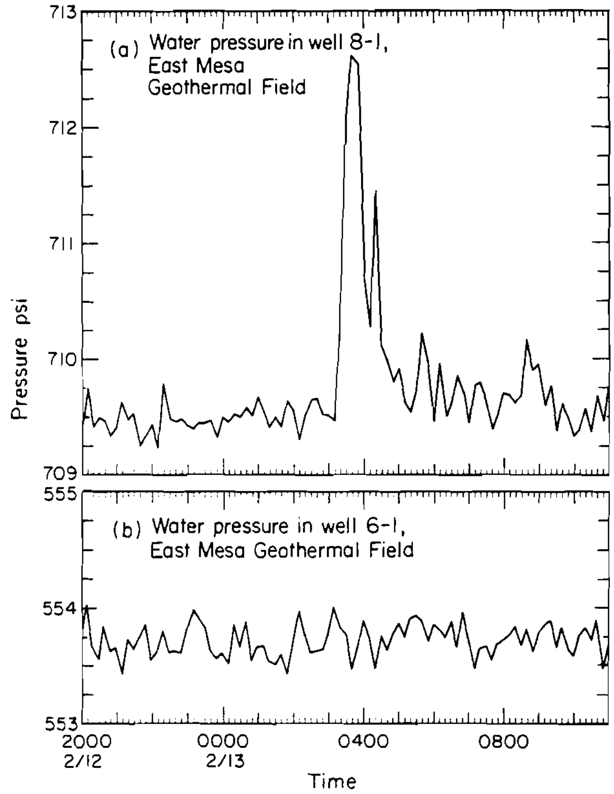

Fig. 5—Comparison of water pressure fluctuations in Well EM 8-1 with Well EM 6-1 recorded before the start of the first interference test.

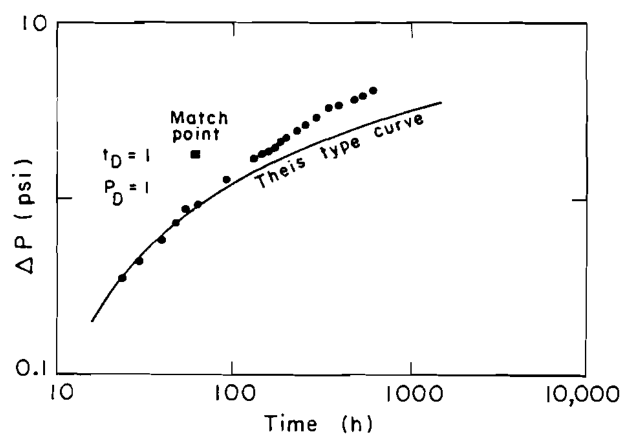

Fig. 6—Interference test, Well RRGE 1: Log-log plot of time vs drawdown.

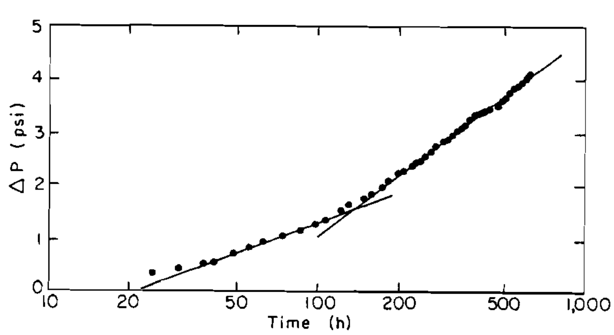

Fig. 7—Interference test, Well RRGE 1: Semilog plot of time vs drawdown.

purpose. The line connecting the solid dots in Fig. 4 is a segment of the regression line calculated with this method.

Although the over-all noise present in the East Mesa may not be caused by microseisms, there is evidence that the reservoir is indeed seismically active and that this activity does affect water pressures in wells. Fig. 5 presents the pressure history observed in shut-in Wells EM 6-1 and EM 8-1 during the morning of Feb. 13, 1976. Beginning at 3:10 a.m., the fluid pressure in Well EM 8-1 rose rapidly, reaching a peak of about 3 psi above the mean at 3:47 a.m. After this, the pressure dissipated gradually with the occurrence of a few minor peaks. Fortunately, the Bureau of Reclamation also maintains a microseismic network at the East Mesa site. Examination of the seismographic records pertaining to the period in Fig. 5 showed that from 3:12 until 3:47 a.m. some 14 minor seismic events occurred in the area. The epicenters apparently were located 2 to 4 miles east and northeast of Well EM 8-1. These events were picked up by a geophone located 1 mile southeast of Well EM 8-1. Another geophone, located 1½ miles north of Well EM 6-1, picked up the same events shortly afterward. The signals appeared to have attenuated significantly before reaching that geophone. Note that Well EM 6-1 (Fig. 5) does not show any of the pressure peaks sensed by Well EM 8-1. This difference in the seismic response of these two East Mesa wells is not yet fully understood, but it may have significant implications in understanding the structure of the geothermal reservoir at East Mesa.

Interpretation

The flow rates associated with the three tests conducted were chosen to prevent flashing of hot water in the well. Thus, the reservoir-well system was filled with a single fluid and the conventional well-testing techniques used in petroleum engineering and hydrogeology were employed for interpretation. Although both drawdown and buildup data were analyzed, major emphasis was placed on the interpretation of the drawdown data insofar as the observation well data was concerned. The drawdown data were analyzed by matching the data with type curves and by using the asymptotic solution. These techniques determined the parameters kh and ϕch and permitted inferences regarding the presence of boundaries.

Interference Test, Raft River Valley Field, Idaho

A log-log plot of drawdown vs time is presented in Fig. 6 and a semilog plot of the same data is given in Fig. 7. The data points correspond to instants of zero gravitational effect and thus avoid the perturbations caused by earth tides. The log-log plot yielded a kh of 228,000 md-ft and a ϕch of 1.19×10^{-3} ft/psi, while the semilog plot yielded a kh of 228,000 md-ft and a ϕch of 9.38×10^{-4} ft/psi. Figs. 6 and 7 clearly show the effects of the presence of a barrier boundary. The distance from the observation well to the image well was computed at about 12,000 ft. With only two wells available for testing, it is not possible to locate the exact position of the barrier boundary.

Although we are not concerned here with the details of the production well tests, it is of interest to present briefly the pressure-buildup data obtained from Well RRGE 2 after a short-term production test during which the well was produced for 15 hours at a rate of 225 gal/min (7,700 B/D) and then shut in. The total drawdown at the end of 15 hours was 37.5 psi.

The buildup observed in this well is presented in Fig. 8. Note that because of the sophistication of the available instrumentation, buildup data could be collected beginning 2 seconds after shut-in. Qualitatively, the most interesting feature of Fig. 8 is neither a unit slope nor a half-slope in the observed data in the first 10 seconds of observation. Thus, we were not able to detect wellbore storage. Apparently the reservoir is not dominated by a fracture near the well.

Interference Test 1, East Mesa, California

During this interference test, Well EM 6-2 was produced and Wells EM 6-1 and EM 8-1 acted as observation wells (Table 3). However, only Well EM 6-1 showed noticeable pressure declines as a direct consequence of the production at Well EM 6-2. Well EM 8-1 did not show any pressure drop at all. Interpretation of the pressure drawdown observed in Well EM 6-1 is presented in Fig. 9. The data used in the interpretation correspond to the mean values obtained with the nonlinear regression fit. Because of the high noise level inherent in the data, it was not possible to remove earth-tide perturbations as was done in the Raft River data. Instead, a nonlinear regression technique was used and the interpretative data correspond to the mean values obtained by the regression technique. Type-curve matching of the early drawdown data suggests a kh of 11,200 md-ft and a ϕch of 5.7×10^{-3} ft/psi. The observed data depart from the type curve after about 100 hours, suggesting the possible presence of a leaky boundary some distance from Well EM 6-1. Calculations indicate that such a boundary may exist about 200 to 1,700 ft from Well EM 6-1. As can be seen from Fig. 2, the reservoir is faulted considerably near Wells EM 6-2, EM 6-1, and EM 8-1. There are indications that faults may be intersecting each other in this part of the reservoir. It seems possible that the leaky boundary suggested by Fig. 9 may be indicative of an intersecting fault system.

At the same time, it also should be pointed out that it is difficult to interpret the data in Fig. 9 with certainty. An examination of Table 2 shows that Well EM 6-2 produces from the interval 4,800 to 6,000 ft, while the producing interval extends from 6,200 to 8,000 ft. There is a 200-ft break between the bottom of Well EM 6-2 and the top of Well EM 6-1, although both may be tapping the same production zone. Therefore, it is not immediately clear whether the observed departure from the type curve in Fig. 9 can be attributed to a leaky boundary or to the different depth intervals that are open in the two wells.

Interference Test 2, East Mesa, California

During this test, Well EM 31-1 was produced (Table 3) and Republic Geothermal's Well RG 38-30 was used as an observation well. The interpretation of the drawdown data is presented in Fig. 10. Type-curve matching of the early drawdown data has indicated a kh of 29,500 md-ft,

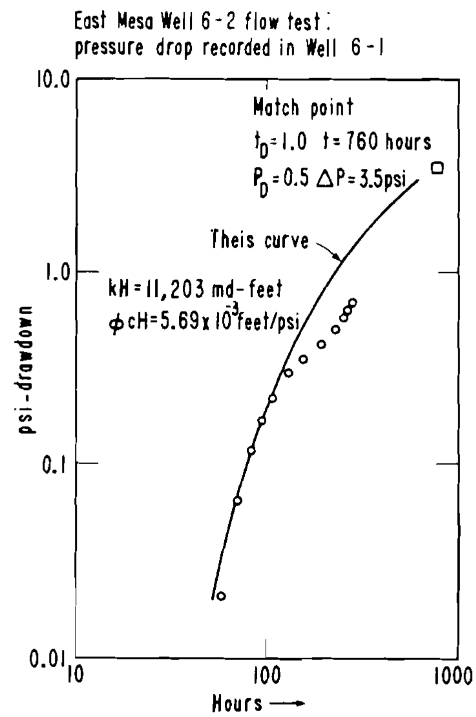

Fig. 9—Interference test, Well 6-1: Log-log plot of time vs drawdown.

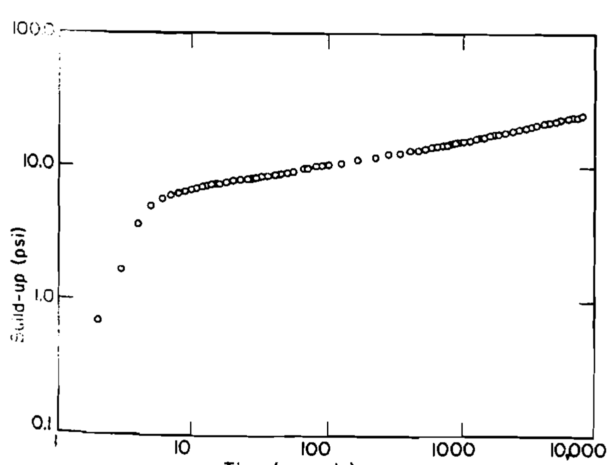

Fig. 8—Short-term production test, Well RRGE 2: Log-log plot of buildup vs time.

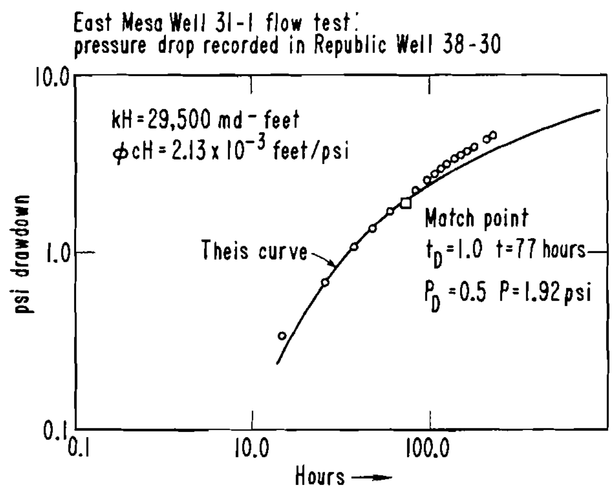

Fig. 10—Interference test, Well RG 38-30: Log-log plot of time vs drawdown.

which is nearly three times the value obtained for the region between Well EM 6-2 and Well EM 6-1. The ϕch value is about 2.1 × 10^{-3} ft/psi. Unlike Test 1 at East Mesa, Test 2 indicates the presence of a barrier boundary that exists about 1,100 to 2,400 ft from Well RG 38-30.

Conclusions

The experience gained in testing geothermal reservoirs in Idaho and California has shown that the availability of sophisticated pressure-measuring devices has greatly increased our ability to conduct sensitive pumping tests. We can now measure very weak pulses over a long period of time, even in the presence of extraneous noises and masking effects, and can, therefore, apply to geothermal reservoirs well-testing techniques that have been developed successfully over a long period of time.

Theoretical studies, such as that of Bredehoeft,[6] suggest that depending on their elastic properties, different reservoirs may respond differently to earth tides. By studying the coherence between earth-tide and fluid-pressure changes, it may be possible to estimate the gross elastic properties of the reservoir. Also, differing responses of different wells in a given field to known seismic events may give clues about reservoir geometry. By passively monitoring reservoir pressure over prolonged periods of time, one can arrive at over-all long-range estimates of reservoir parameters and geometry.

Nomenclature

c = compressibility, psi^{-1}
h = reservoir thickness, ft
k = permeability, md
ϕ = porosity

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