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EARTH SCIENCES DIVISION

WELL TEST DATA FROM GEOTHERMAL RESERVOIRS

M.G. Bodvarsson and S.M. Benson

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ABSTRACT

The Geophysics and Reservoir Engineering Group of the Earth Sciences Division of the Lawrence Berkeley Laboratory (LBL) has carried out extensive well testing in geothermal resources throughout the western United States and in northern Mexico since 1975. Considerable amounts of data, information leading to the development of advanced instrumentation, and valuable experience have resulted from the tests. To facilitate the dissemination of well test data and associated information to such interested parties as modelers, developers, and researchers, the present report has been prepared. The report covers in brief each resource tested and each well test conducted by LBL during the eight-year period. The information, collected from published reports and memoranda, includes test particulars, special instrumentation, data interpretation when available, and plots of actual data. Brief geologic and hydrologic descriptions of the geothermal resources are also presented. The format is such that well test descriptions are grouped, in the order performed, into major sections according to resource, each section containing a short resource description followed by individual test details. Additional information regarding instrumentation is provided in Appendix A. Source documentation is provided throughout to facilitate access to further information and raw data. With the aid of this report, a researcher can quickly identify areas of interest and obtain more complete information about specific tests and reservoirs, as well as advances in instrumentation and well testing methods used to evaluate geothermal resources.

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INTRODUCTION

Since 1975 the Geophysics and Reservoir Engineering Group of the Earth Sciences Division of the Lawrence Berkeley Laboratory (LBL) has carried out extensive well testing in geothermal resources throughout the western United States and in northern Mexico (Figure 1). The tests have generally been conducted as part of overall resource evaluation programs and include production, injection, interference, variable-rate, and multiple-well tests. Data from these tests represent a wealth of experience in geothermal well test procedure, instrumentation, and data acquisition. Furthermore, interpretation of the data has yielded many opportunities to observe and record classical reservoir engineering and geohydrologic problems.

Through the years, LBL has received numerous requests from modelers, developers, and researchers for well test data and associated information. Although many of the well tests have been described in various laboratory reports, to date there has been no collective account of the Laboratory's extensive geothermal well test program. The raw data have been retained in computer data bases at LBL. Therefore, to facilitate the dissemination of information on a broader basis, this Geothermal Well Test Catalog has been prepared.

The Catalog was compiled by abstracting information about each resource and well test from pertinent LBL reports and memoranda. Plots of all data acquired in the course of the testing were also prepared. The information was then assembled in an organized format for easy access. The reader is thus given a fully referenced description of each test (i.e., type, duration, instrumentation used, etc.), as well as the actual data. With this information, the reader can easily view the whole spectrum of well testing carried out by LBL in geothermal systems and select and obtain individual reports and test-specific data.

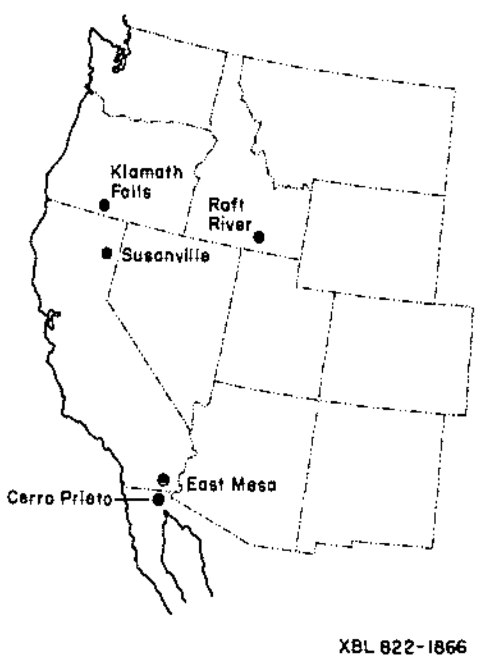


Figure 1. Location map of geothermal resources in which well testing was carried out by LBL.

Reservoir Systems Represented

The geothermal reservoirs tested to date are widely varied both geologically and hydrogeologically, and include:

- Raft River, Idaho - fractured metamorphic and sedimentary units, 140-150°C
- East Mesa, California - sedimentary units, 160-204°C
- Cerro Prieto, Mexico - heterogeneous sedimentary units, 260-330°C
- Susanville, California - shallow, heterogeneous volcanic and sedimentary(?) formations, 35-85°C
- Klamath Falls, Oregon - shallow, heterogeneous volcanic and sedimentary formations, 60-110°C
- Wendel Spring, California - fractured granitic rocks, 120°C

The reservoirs tested include high-temperature (300°C), low-temperature (60°C), single-phase (liquid) and two-phase systems. The range of boundary conditions encountered include systems that are closed, open, confined, semi-confined, fault-charged, and fracture-controlled. Permeabilities ranging from several millidarcies to hundreds of darcies have been calculated from the data. Negative skin values and very high positive skin values have been computed in either naturally fractured or hydraulically fractured wells. Even very clear evidence of a near-wellbore turbulent flow regime has been detected in a fractured, liquid-water hydrothermal system.

Well Tests

The well tests conducted within each resource are varied in type, duration, sophistication and quality, and as such, cover the whole range of the state of the art in geothermal well testing. The test descriptions themselves contain most of the information directly pertinent to the individual test, such as type of test, duration, relative well locations, flow rates, pressure response, instrumentation, and data quality. Brief results of data interpretation are also provided. The calculated hydrologic parameters are also given so that a rough idea of the system parameters is available. More importantly, any special or unique characteristics of geothermal (or hydrologic) systems inferred from the data, such as boundaries, nondarcy flow, earth tides, seismically induced pressure transients, and two-phase wellbore or formation flow are mentioned to alert the reader to potential areas of interest. Further details (well completions, in-depth geology, geophysical data, complete data analysis, etc.) can be obtained from the referenced sources.

Instrumentation

A variety of well test instrumentation ranging from quite simple to highly sophisticated has been used in the LBL tests, including: gas- and fluid-filled capillary tubing, quartz crystal pressure gauges, float-type water-level gauges, wellhead and downhole temperature gauges, and other commercially-available or LBL-designed and fabricated instrumentation. These instruments are noted in the descriptions, and are more fully discussed in Appendix A.

Organization

The organization of the Catalog is such that well test information is grouped into major sections by resource (e.g., East Mesa Geothermal Resource), and then chronologically into short test descriptions within the major section. Each major section is prefaced by a brief description of the hydrothermal resource, as described above. The test descriptions follow in the order the tests were performed. With few exceptions (tests of extremely poor-quality data), all well tests conducted primarily or exclusively by LBL have been included. Table 1 contains a list of well tests covered by the Catalog, in their order of appearance.

Due to chronology, the production, injection, and interference tests are intermingled. Tests are identified by the producing well(s) in the case of production and interference tests, and by the injection well for injection tests. This format has been followed consistently throughout the Catalog, although a few tests may have been identified by different means in the original reports.

The test descriptions are accompanied by plots of the actual data and tables categorizing the pertinent information from each test. Tables of nomenclature and abbreviations provide explanations of terms and symbols used in the text and tables. Appendix A gives details concerning the various instrumentation referred to in the Catalog, and Appendix B contains conversion tables.

Access to Further Information

To obtain a complete set of data or any of the reports referenced in the Catalog, a request should be directed to the Earth Sciences Division, Lawrence Berkeley Laboratory, 1 Cyclotron Road, Berkeley, California 94720. Appropriate reports and/or data can then be forwarded to the requestor. Due to logistical constraints, the data are available only on microfiche or computer printout.

Table 1. Well Tests.

Geothermal Reservoir	Type of Test	Production Well(s)	Observation Well(s)	Injection well(s)	Test Dates	Table Number
Raft River	production	RRGE 2	--	--	9/12/75 - 9/13/75	3
Raft River	interference	RRGE 2	RRGE 1	--	9/30/75 - 10/30/75	4
Raft River	production	RRGE 1	--	--	11/ 4/75 - 11/ 7/75	5
East Mesa	interference	6-2	6-1, 8-1	--	2/13/76 - 2/24/76	7
East Mesa	interference	31-1	38-30	--	4/ 1/76 - 4/12/76	8
East Mesa	interference	6-2, 6-1	6-1, 8-1, 31-1, 44-7, 38-30	--	2/10/77 - 4/13/77	9
East Mesa	interference	38-30	56-30, 31-1, 16-29	18-28	7/14/77 - 7/18/77	10
East Mesa	interference	16-29	56-30, 31-1, 16-30,	18-28	7/26/77 - 7/30/77	11
East Mesa	interference	38-30	56-30, 31-1, 16-30, 78-30	18-28	8/24/77 - 10/ 5/77	12
East Mesa	injection	--	--	5-1	12/ 1/77 - 12/ 6/77	13
East Mesa	production	8-1	--	--	12/16/77 - 12/20/77	14
East Mesa	interference	8-1, 44-7, 6-2	6-1, 48-7	46-7	1/ 6/78 - 3/29/78	15
East Mesa	production	6-2	--	--	4/17/78 - 4/21/78	16
East Mesa	production	6-1	--	--	5/ 2/78 - 5/ 4/78	17
Cerro Prieto	interference	M-50, M-51, M-90, M-91	M-101	--	1/14/78 - 3/30/78	19
Cerro Prieto	interference	M-53	M-104, M-10	--	5/16/78 - 7/24/78	20
Susanville	interference	LDS Church	Naef	--	7/26/78 - 11/29/78	22
Susanville	interference	Davis, S. Pool, LDS Church	Suzy 3, Suzy 4 Naef, LLB #2	--	12/10/78 - 1/ 8/79	23
Susanville	production	WEN-1	--	--	3/ 3/82 - 3/ 8/82	24
Klamath Falls	interference	YMCA #2	YMCA #1, Adamcheck, Glen Head	--	12/ 2/79	26
Klamath Falls	interference	CW-1	Parks, Adamcheck Glen Head	--	10/24/79 - 10/25/79	27
Klamath Falls	interference	CW-1, CW-2	Parks, Olson, Stanke, C.C.	--	9/29/81 - 9/30/81	28
Klamath Falls	interference	CW-2	Parks, Stanke, Olson	Museum	2/ 8/82 - 2/12/82	29

Resource Description

The Raft River geothermal field is located in the Raft River Valley, Idaho (Fig. 2). The resource occurs in a faulted graben filled with sediments of Mio-Pliocene to Pleistocene age, with a total thickness of about 1540 m. The sediments rest on an igneous basement with an intervening zone of metamorphic rocks, about 60 m thick.

The reservoir has a permeability-thickness (kh) ranging from approximately 47,000 to 225,000 md•ft. At the time of the LBL tests, two successful wells had been drilled in the field. The maximum temperature produced from this single-phase (liquid water) geothermal system is approximately 146°C. Conglomerates and fractured metamorphosed rocks are assumed to contribute to the geothermal productivity. Table 2 contains a summary of resource characteristics; the wells listed are those used in the LBL tests.

[abstracted from Witherspoon et al., 1976 and Narasimhan and Witherspoon, 1977]

Well Tests

In September and October 1975, LBL carried out three well tests in the two wells existing at that time, RRGE 1 and RRGE 2. These tests, which consisted of two short-term production tests and one long-term interference test, were conducted to evaluate the permeability and storativity parameters of the reservoir and to determine the reservoir geometry. The three well tests are summarized in this section. All the data have been obtained from the LBL reports indicated, from which more detailed information can be gathered.

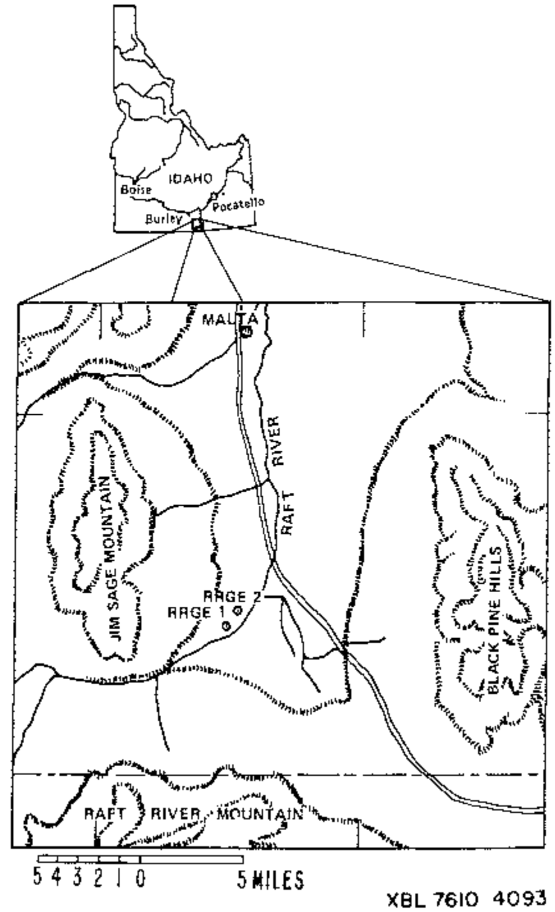


Figure 2. Location map of Raft River geothermal resource and wells.

Table 2. Raft River Geothermal Resource.

Location:	Raft River Valley, Idaho
Reservoir Temperature:	140° - 150°C
Geologic Setting:	Tertiary and Pleistocene sediments to 1524 m depth; Adamellite basement with intervening layer of Paleozoic metamorphic rock (quartzite and schists)
Fluid Characteristics:	Artesian flow; liquid water; wellhead pressures 50-120 psi
Test Wells and Approximate Depths:	RRGE 1 1520 m RRGE 2 1805 m

RRGE 2 Production Test (September 12-13, 1975)

RRGE 2 was flowed at a near-constant artesian rate of 14 l/s for 15 hours, after which the well was shut in and pressure buildup observed for 2.25 hours (Fig. 3 and Table 3). The well was instrumented with a Hewlett Packard quartz crystal pressure gauge set at a depth of 1585 m. The maximum pressure drawdown during production was approximately 37.5 psi. At the time the pressure gauge was removed, the pressure had increased by approximately 24.25 psi. Well test analysis (semilog and type curve) indicated the possible presence of a barrier boundary in the vicinity of RRGE 2.

[abstracted from Narasimhan and Witherspoon, 1977]

Table 3. RRGE 2 Production Test, September 12-13, 1975.

WELL Classification	TEST DESCRIPTION Fluid Flow	Δp (psi)	INSTRUMENTATION (P) Pressure (T) Temperature (Q) Flowrate	ANALYSIS * kh/μ md·ft/cp (m^3/Pa·s)	φch ft/psi (m/Pa)
RRGE 2 production	15 hrs @ 14 l/s	37.5	(P) H.P. downhole (1585 m); bourdon tube at wellhead † (T) thermocouple † (Q) orifice plate and differential pressure gauge	2.6×10^5 (7.8×10^{-8})	2.9×10^{-2} (1.3×10^{-6})
				possible barrier boundary	

* semilog and type curve analysis
† data not available

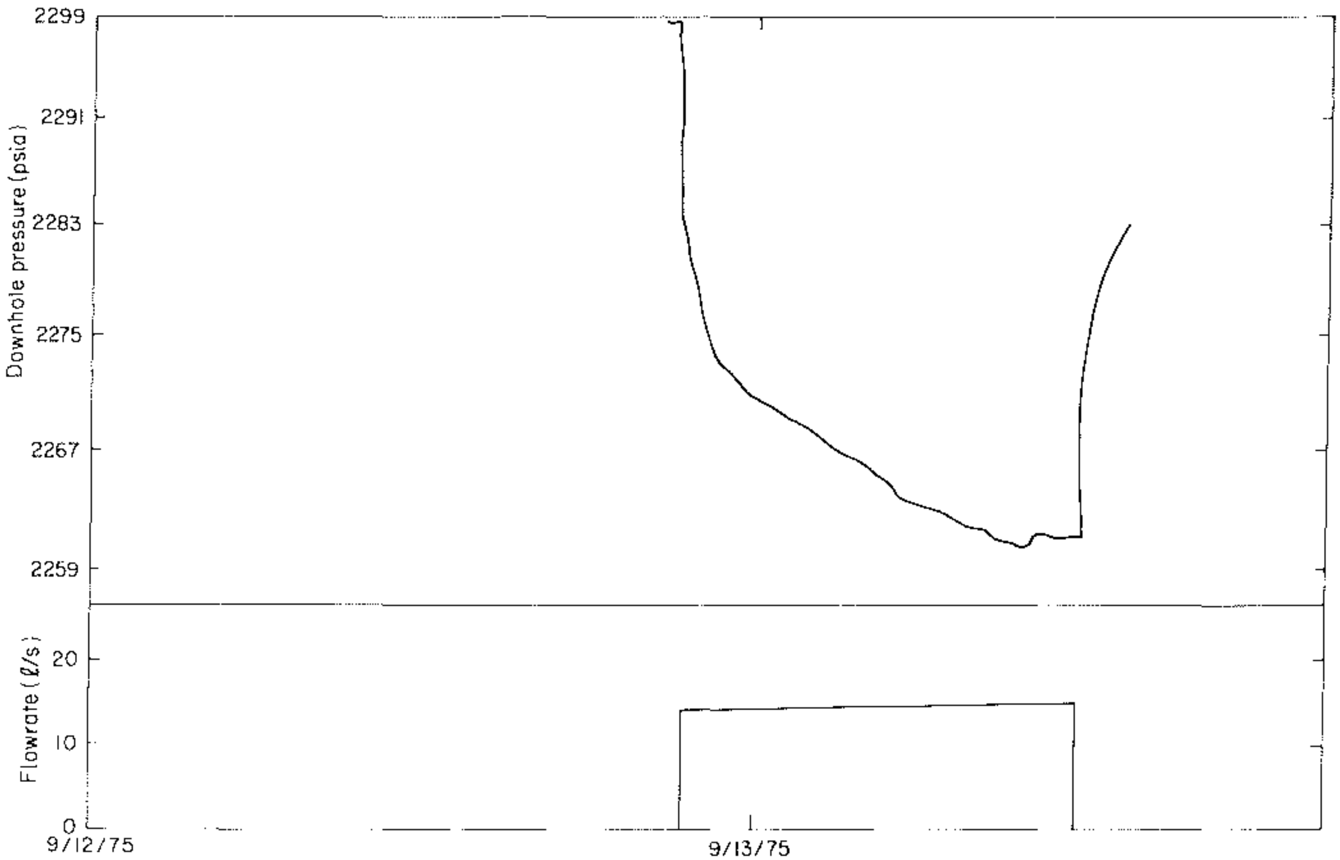


Figure 3. RRGE 2 production data (RRGE 2 production test).

RRGE 2 Interference Test (September 20-October 30, 1975)

RRGE 2 was flowed at a near-constant artesian rate of 25 l/s for a period of 615.5 hours while interference effects were monitored in RRGE 1, 1220 m away (Fig. 4 and Table 4). Pressures were monitored in RRGE 1 both at the wellhead and downhole for data comparison. The downhole tool, a Hewlett Packard quartz crystal gauge, recorded a maximum pressure drawdown of 3.6 psi due to production from RRGE 2. A similar, but less expensive, Paroscientific surface gauge was used at the wellhead of RRGE 1.

The Hewlett Packard gauge was available for only the first 16 days of the test. In addition, the instrument failed five times due to cablehead leakage. Each time, the instrument was removed, repaired, and relowered, resulting in an absolute pressure change of approximately 1.0 psi. The surface gauge was used throughout the test, but continuous recording equipment was not installed until September 30, resulting in sparse data for the first 10 days. Data from both instruments show the effects of earth tides (amplitudes ± 0.1 psi). Analysis of the data by semilog and type curve techniques indicated that the pressure response was possibly affected by the presence of a barrier boundary.

[abstracted from Witherspoon et al., 1976 and Narasimhan and Witherspoon, 1977]

Table 4. RRGE 2 Interference Test, September 20 - October 30, 1975.

WELL	TEST DESCRIPTION			INSTRUMENTATION	ANALYSIS *	
Classification	Fluid Flow	ΔP (psi)	Distance to Production Well(s) (m)	(P) Pressure (T) Temperature (Q) Flowrate	kh/μ md·ft/cp (m^3/Pa·s)	φch ft/psi (m/Pa)
RRGE 2 production	25 days @ 25 l/s					
RRGE 1 observation		3.6 ¶	1220	(P) H.P. downhole (300 m); Paros. at wellhead (T) thermocouple †	1.2×10^6 (3.8×10^{-7}) possible barrier boundary	1.2×10^{-3} (5.2×10^{-8})

* semilog and type curve analysis
¶ earth tides apparent (±0.1 psi)
† data not available

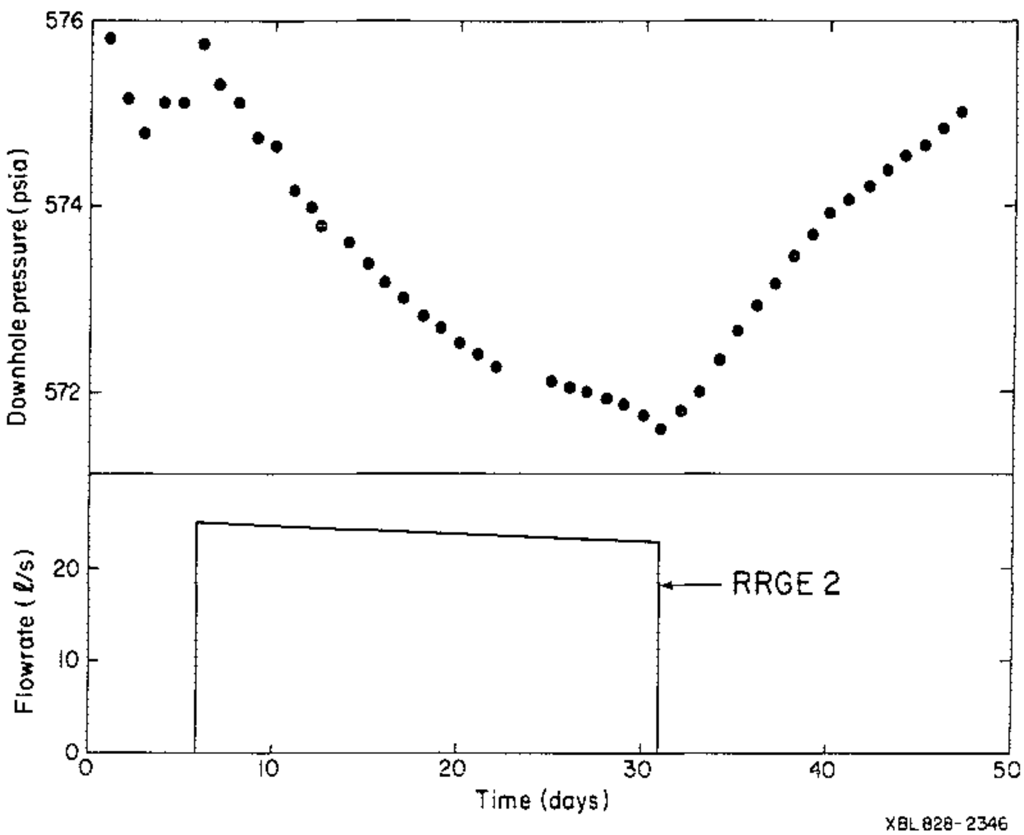


Figure 4. RRGE 1 interference data (RRGE 2 production test).

RRGE 1 Production Test (November 4-7, 1975)

RRGE 1 was produced at an average artesian rate of 1.7 l/s for 30 hours while downhole pressures were measured with a Hewlett Packard gauge set in the well at a depth of 1430 m (Fig. 5 and Table 5). Data were recorded for 18 hours prior to production, during production, and for 19 hours after RRGE 1 was shut in. A maximum drawdown of approximately 1.1 psi was recorded. Semilog and type curve techniques were used for data analysis. Diurnal earth tide effects were observed (amplitudes ± 0.1 psi) in the data.

[abstracted from Narasimhan and Witherspoon, 1977]

Table 5. RRGE 1 Production Test, November 4-7, 1975

WELL Classification	TEST DESCRIPTION Fluid Flow	ΔP (psi)	INSTRUMENTATION (P) Pressure (T) Temperature (Q) Flowrate	ANALYSIS * kh/μ md·ft/cp (m^3/Pa·s)	ϕch ft/psi (m/Pa)
RRGE 1 production	30 hrs @ 1.7 l/s	1.1 ¶	(P) H.P. downhole (1430 m); bourdon tube at wellhead † (T) thermocouple †	5.8×10^5 (1.7×10^{-7})	2.5×10^{-2} (1.1×10^{-7})

* semilog and type curve analysis
† data not available
¶ earth tides apparent (±0.1 psi)

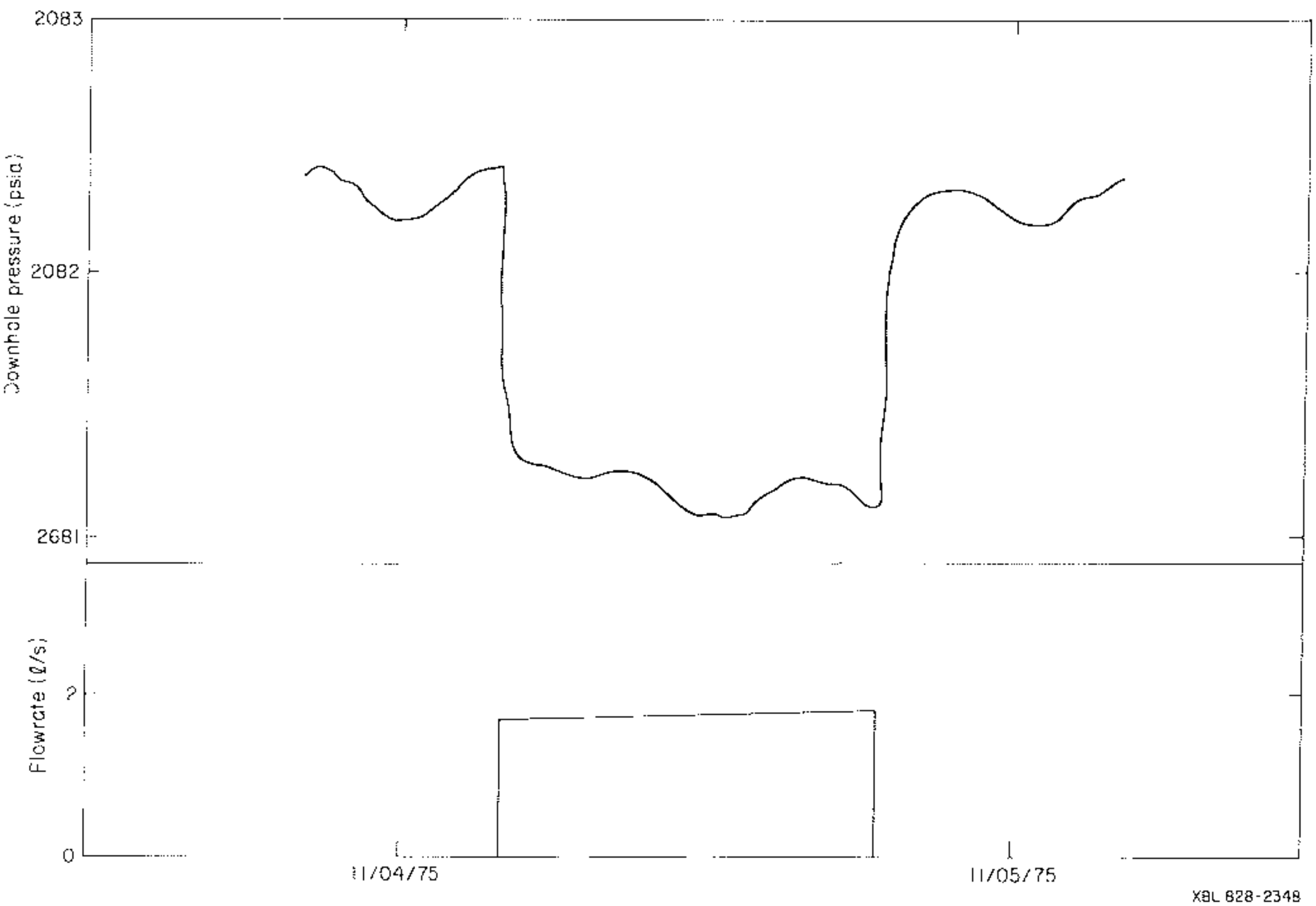


Figure 5. RRGE 1 production data (RRGE 1 production test).

Resource Description

The East Mesa Geothermal Resource is located in the Imperial Valley of southern California (Fig. 6). The reservoir rocks are essentially flat-lying, poorly consolidated, late Pliocene to late Pleistocene deltaic sandstones, siltstones and clays. The reservoir is believed to extend from approximately 1500 m below sea level to about 3300 m, at which depth crystalline basement rocks are encountered. The reservoir is capped by a 610 m clay sequence, so that little surface evidence of geothermal activity is seen.

Structurally, the reservoir sediments, being within the Salton Trough area, are considerably faulted. To date, at least three faults, varying in trend from NNW-SSE to WNW-ESE, have been identified.

The reservoir itself is moderately permeable and somewhat heterogeneous. The average reservoir transmissivity (kh/μ) is approximately 130,000 md'ft/cp. Values are slightly higher in the northern portion of the field. Field temperatures at depth range from 160° to 204°C, with the hottest temperatures being in the south-central portions. At a depth of 2130 m, the 150°C temperature contour extends over an area of approximately 12 square miles. The reservoir contains single-phase liquid water.

At the time of the LBL tests, 15 wells had been drilled by the U. S. Bureau of Reclamation and private companies (Fig. 7). All wells have artesian flow and shut-in wellhead pressures of 50-120 psi. Well depths vary from 943 m to 2770 m. Tests conducted so far indicate the presence of a pronounced flow barrier trending NNE and the possible presence of two discontinuous barriers in the northern portion. A poorly-defined constant potential boundary is indicated in the central portion. See Table 6 for a summary of resource characteristics; the wells listed are those used in the LBL tests.

[abstracted from Witherspoon et al., 1976 and Narasimhan et al., 1977]

Well Tests

Since 1976, LBL has conducted numerous production, injection and interference tests at the East Mesa geothermal resource, using all available wells. From analysis of interference test data, it has been possible to locate hydraulic boundaries, infer reservoir recharge, and obtain estimates of reservoir parameters: transmissivity (kh/μ), and storativity (ϕch). These tests have been documented in several LBL reports from which the following information has been abstracted and from which more detailed information can be obtained.

Table 6. East Mesa, California, Geothermal Resource.

Location:	Imperial Valley, southern California							
Reservoir Temperature (°C):	160° - 204°C							
Geologic Setting:	Poorly consolidated, late Pliocene to late Pleistocene deltaic sandstones, siltstones and clays with a total thickness of 3050 m, overlying crystalline basement rock and underlying a 600 m clay cap							
Fluid Characteristics:	Artesian flow; liquid water; wellhead pressures 50-120 psi							
Test Wells and Approximate Depths:	WPRS *	6-1	2447 m	Magma † 44-7	2240 m	Republic ¶	38-30	2770 m
		6-2	1830 m	48-7	2300 m		56-30	2292 m
		5-1	1829 m	46-7	943 m		16-29	2437 m
		8-1	1891 m				16-30	2438 m
		31-1	1899 m				18-28	2438 m
							78-30	2268 m

* U. S. Water and Power Resources Service, formerly U. S. Bureau of Reclamation
† Magma Power Co.
¶ Republic Geothermal, Inc.

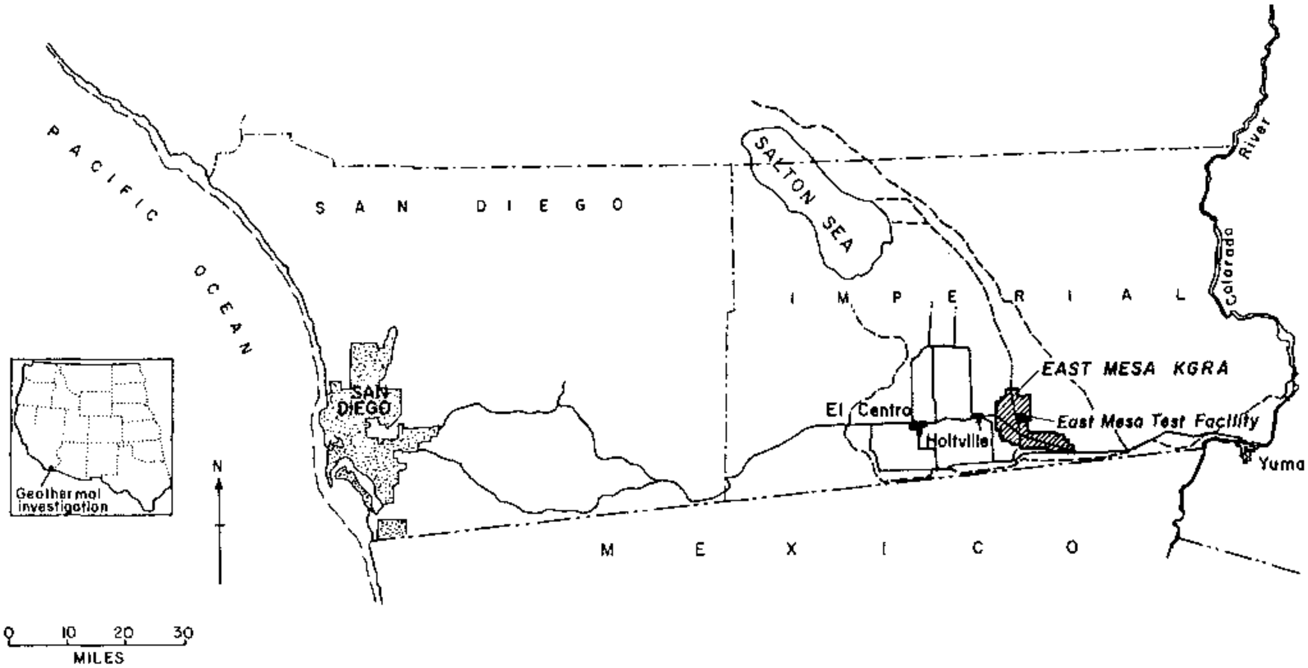
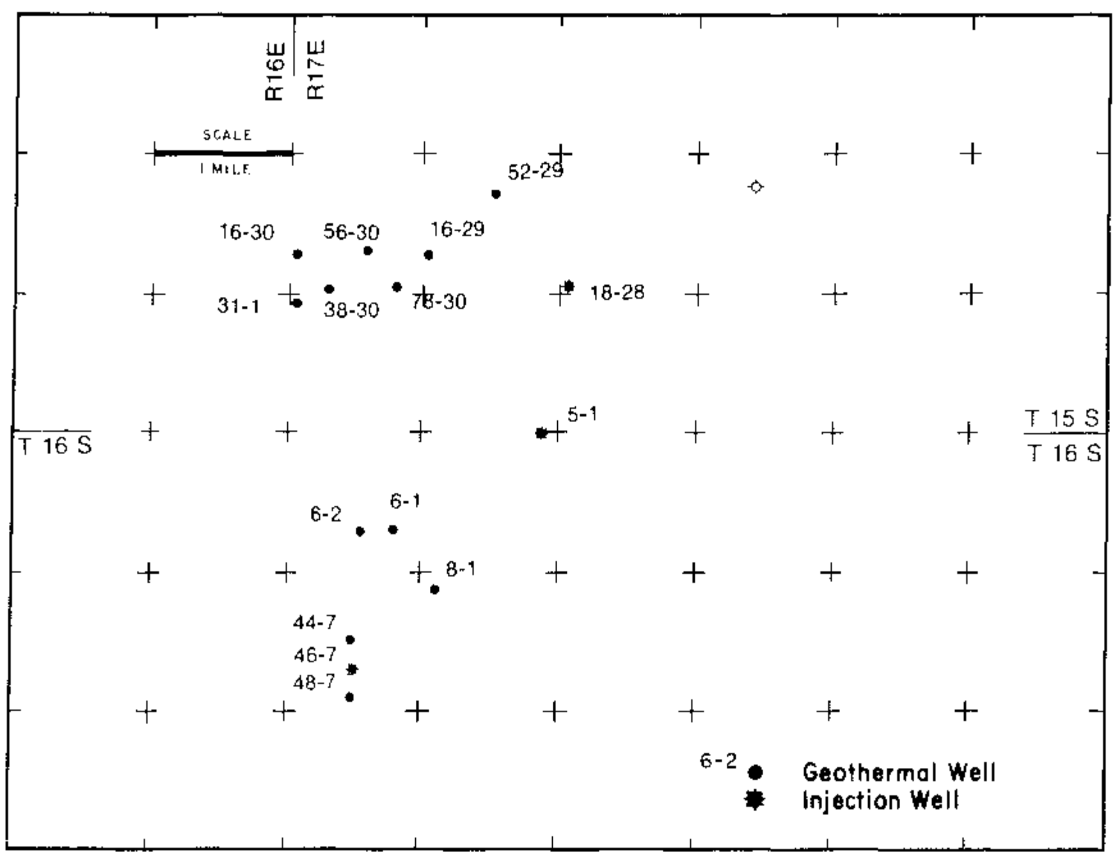


Figure 6. Location map, East Mesa geothermal resource.

XBL 783-475



XBL 815-3016

Figure 7. Well location map, East Mesa geothermal resource.

Well 6-2 Interference Test (February 13-24, 1976)

Well 6-2 was flowed for 11 days at a near-constant artesian rate of 5.6 l/s while interference effects were measured in wells 6-1 and 8-1, located 460 m and 1100 m away, respectively (Figs. 8 and 9 and Table 7). In well 6-1, downhole pressure and temperature were measured for one day prior to production, during production, and for 6 days after well 6-2 was shut in. In well 8-1, pressure and temperature measurements were taken for 5 days prior to and during well 6-2 production. Hewlett Packard pressure gauges and Gearhart Owen temperature probes were used in both wells, at depths of 335 m (well 6-1) and 460 m (well 8-1).

Flowrates in the production well were measured with an orifice plate and a differential pressure gauge. Total flow was calculated using the liquid flowrate and the fraction of total flow converted to steam at the recorded wellhead temperatures and pressures. No downhole pressure transient data were recorded in this well.

A maximum pressure drop of 0.7 psi was recorded in well 6-1, but no measurable drawdown was observed in well 8-1, suggesting a lack of communication between wells 6-2 and 8-1. Type-curve analysis of the data from well 6-1 indicated the possible presence of a constant potential boundary (open fault?) near well 6-1.

There was considerable noise in the data from both wells. A 3.0 psi pressure anomaly recorded in well 8-1 prior to the test corresponded with a small seismic event recorded by the Bureau of Reclamation.

[abstracted from Witherspoon et al., 1976 and Narasimhan et al., 1977a]

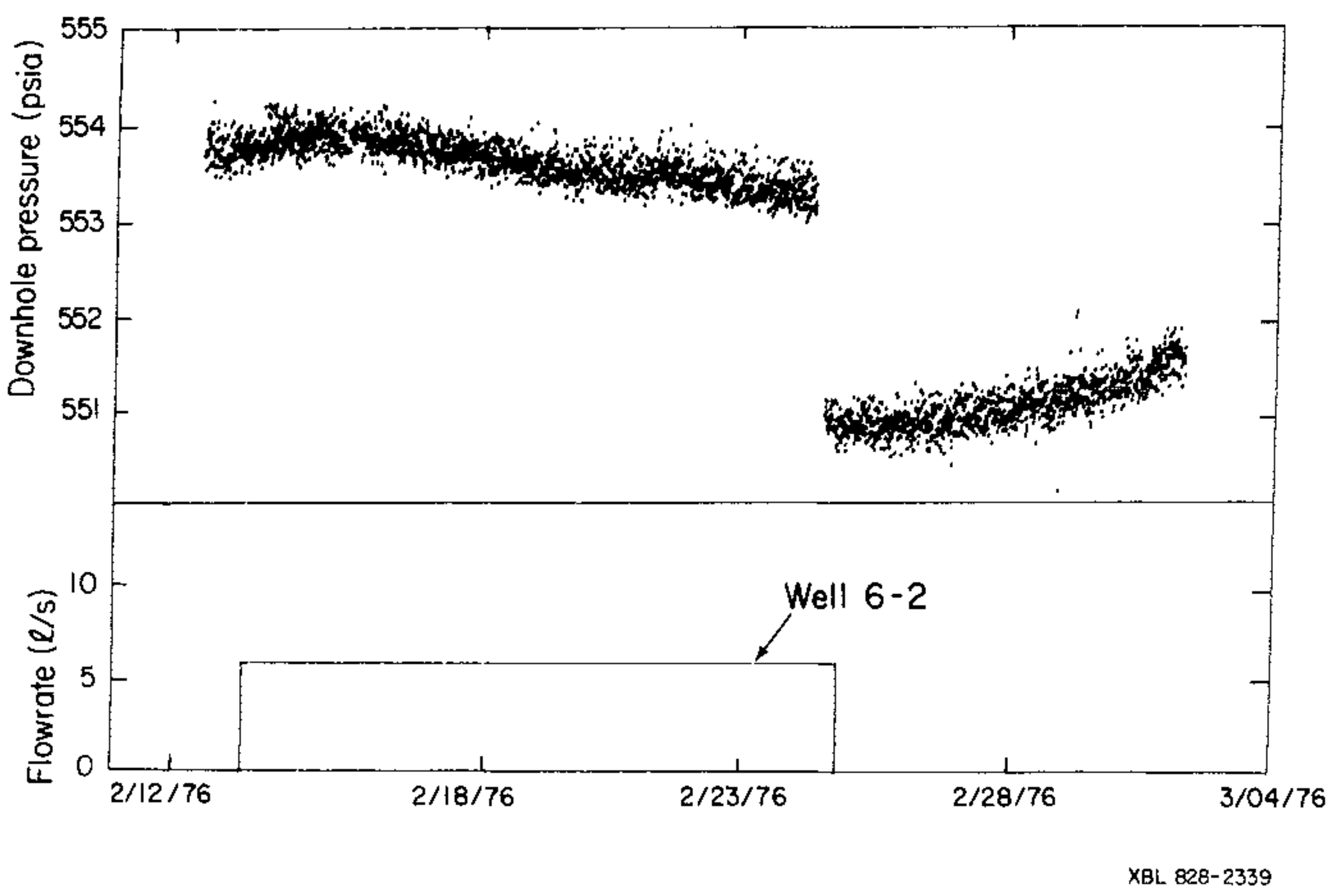


Figure 8. 6-1 interference data (6-2 interference test).

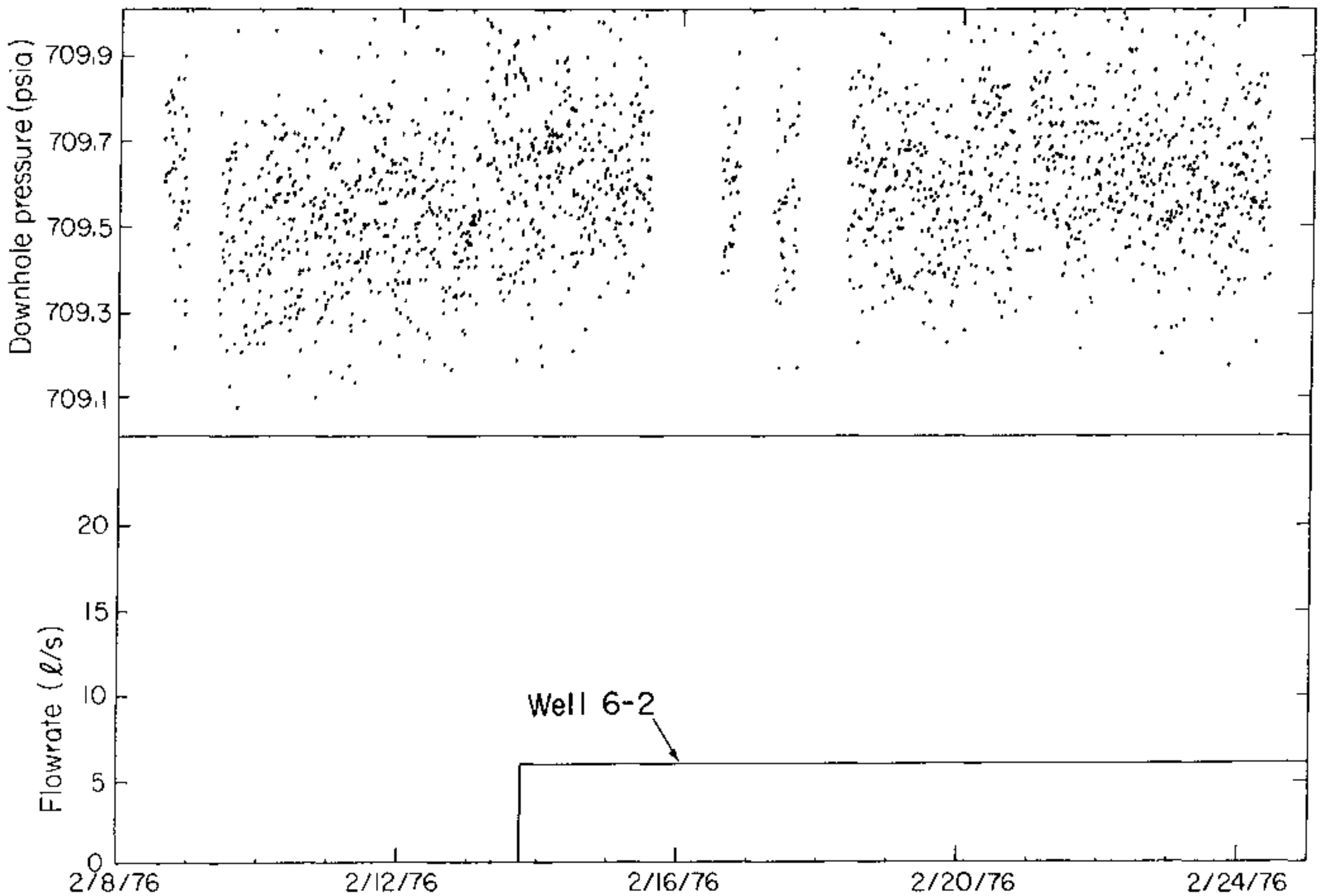


Figure 9. 8-1 interference data (6-2 interference test).

Table 7. Well 6-2 Interference Test, February 13-24, 1976.

WELL	TEST DESCRIPTION			INSTRUMENTATION	ANALYSIS *	
Classification	Fluid Flow	ΔP (psi)	Distance to Production Well(s) (m)	(P) Pressure (T) Temperature (Q) Flowrate	kh/μ md·ft/cp (m^3/Pa·s)	φch ft/psi (m/Pa)
6-2 production	11 days @ 5.7 l/s			(P) bourdon tube at wellhead (T) thermocouple at wellhead (Q) weir box		
6-1 observation		0.7	460	(P) H.P. downhole (335 m) (T) G.O. downhole (335 m)	6.2×10^4 (1.9×10^{-8}) possible constant potential boundary	5.7×10^{-3} (2.5×10^{-7})
8-1 observation		0	1100	(P) H.P. downhole (460 m) (T) G.O. downhole (460 m)	extremely noisy data	

* type curve analysis

Well 31-1 Interference Test (April 1-12, 1976)

Well 31-1 was flowed for 10 days at a steady artesian flow rate of 8.2 l/s while interference effects were observed in well 38-30, located 380 m away (Fig. 10 and Table 8). A Hewlett Packard pressure gauge, set at a depth of 460 m in well 38-30, measured 10 days of interference data and 4 days of recovery data. A maximum pressure drawdown of approximately 4.5 psi was recorded.

In well 31-1, flowrate was measured with a weir box, and downhole temperature was also recorded. The interference data were extremely noisy. Type curve analysis of the data indicated the possible presence of a barrier boundary near well 38-30.

[abstracted from Witherspoon et al., 1976 and Narasimhan et al., 1977a]

Table 8. Well 31-1 Interference Test, April 1-12, 1976.

WELL	TEST DESCRIPTION			INSTRUMENTATION	ANALYSIS *	
Classification	Fluid Flow	ΔP (psi)	Distance to Production Well(s) (m)	(P) Pressure (T) Temperature (Q) Flowrate	kh/μ md·ft/cp (m^3/Pa·s)	φch ft/psi (m/Pa)
31-1 production	10 days @ 8.2 l/s			(T) thermocouple at wellhead † (Q) weir box		
38-30 observation		4.5	380	(P) H.P. downhole (460 m)	1.4×10^5 (4.1×10^{-8})	2.1×10^{-3} (9.3×10^{-8})
					possible barrier boundary	

* type curve analysis
† data not available

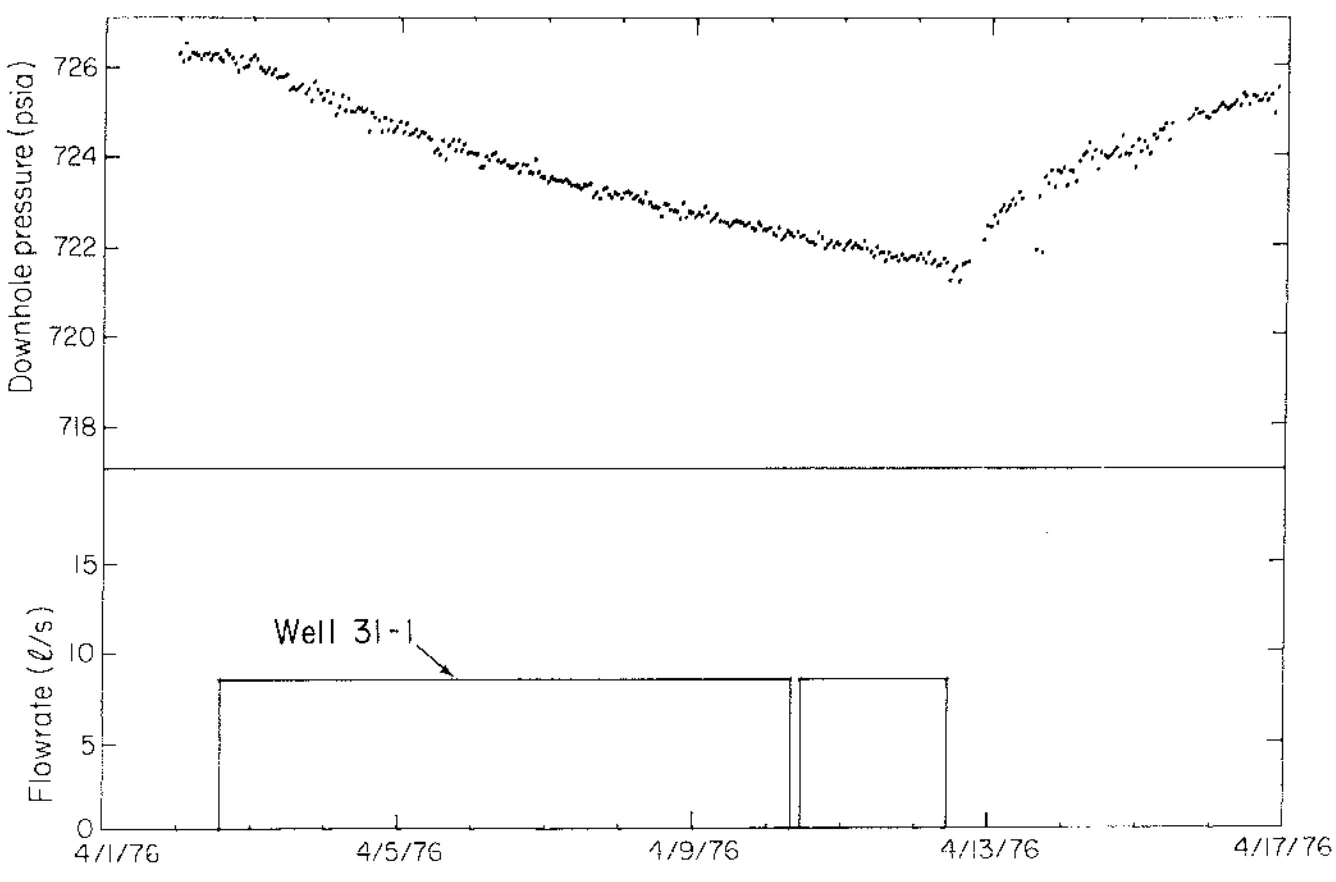


Figure 10. 38-30 interference data (31-1 interference test).

Wells 6-2/6-1 Interference Test, February 10 - April 13, 1977

Well 6-2 was initially produced for a 12-day period at a variable artesian flowrate of 2.5 - 7.0 l/s while wellhead pressures were monitored at wells 6-1, 8-1 and 31-1, located 450, 1120, and 2700 m away, respectively (Figs. 11-13 and Table 9). On day 13 of the test, well 6-1 was opened while well 6-2 production continued uninterrupted. The flowrate in well 6-2 stabilized at 3.0 l/s and at 4.0 l/s in well 6-1. Wells 8-1, 31-1, 44-7, and 38-30 were monitored for interference effects (Figs. 12-15). Well 8-1 was observed for only 4 weeks, while wells 31-1, 44-7, and 38-30 were observed for the entire 9-week period of production.

Flowrates were measured with an orifice plate in well 6-2, and a weir box in well 6-1. Downhole pressure in well 6-2 was measured using 1525 m of nitrogen gas-filled tubing (0.066 cm I.D.) connected to a Sperry Sun pressure transmission system at the surface. However, the effect of ambient temperature changes on the gas in the capillary tubing obscured any real pressure transients. Paroscientific pressure transducers were installed at the wellhead in all observation wells.

Total pressure drawdown was approximately 0.7 psi in well 6-1, 0.2 psi in well 31-1, and 0.4 - 0.7 psi in well 44-7. No apparent drawdown was observed in wells 8-1 and 38-30, suggesting a lack of communication between these wells and wells 6-1 and 6-2. However, the drawdown in 8-1 may have been obscured by the excessive scatter in the data. Earth tide effects (amplitude ± 0.1 psi) were observed in the data from wells 31-1 and 44-7.

Analysis of data collected from well 6-1 was difficult due to the uncertainty of establishing initial reservoir pressures. This uncertainty was due to the fact that well 6-1 was flowed briefly a few days before the test and was still cooling down when the test was started.

[abstracted from Howard et al., 1978b and Narasimhan et al., 1978]

Table 9. 6-2/6-1 Interference Test, February 10 - April 13, 1977.

WELL	TEST DESCRIPTION			INSTRUMENTATION	ANALYSIS *	
Classification	Fluid Flow	ΔP (psi)	Distance to Production Well(s) (m)	(P) Pressure (T) Temperature (Q) Flowrate	kh/μ md·ft/cp (m^3/Pa·s)	φch ft/psi (m/Pa)
6-2	12 days @ 2.5-7 l/s; 7 wks @ 3 l/s			(P) S.S. with 1525 m of 0.066-cm I.D. nitrogen gas tubing (T) thermocouple † (Q) orifice plate and weir box		
6-1 production	7 wks @ 4 l/s			(Q) weir box		
6-1 observation		0.7	450	(P) Paros. at wellhead	1.1×10^{5} (3.3×10^{-8})	6.0×10^{-3} (2.6×10^{-7})
8-1 observation		0	1120 (to 6-2) 710 (to 6-1)	(P) H.P. downhole		
31-1 observation		0.2	2700 (to 6-2) 2900 (to 6-1)	(P) Paros. at wellhead	1.5×10^{5} (4.4×10^{-8}) constant potential boundary	2.0×10^{-3} (8.8×10^{-3})
44-7 observation		0.7	900 (to 6-2) 970 (to 6-1)	(P) Paros. at wellhead	1.3×10^{-5} (3.8×10^{-8})	6.0×10^{-4} (2.6×10^{-8})
38-30 observation		0	2900 (to 6-2) 3000 (to 6-1)	(P) Paros. at wellhead		

* computer-assisted analysis
† data not available

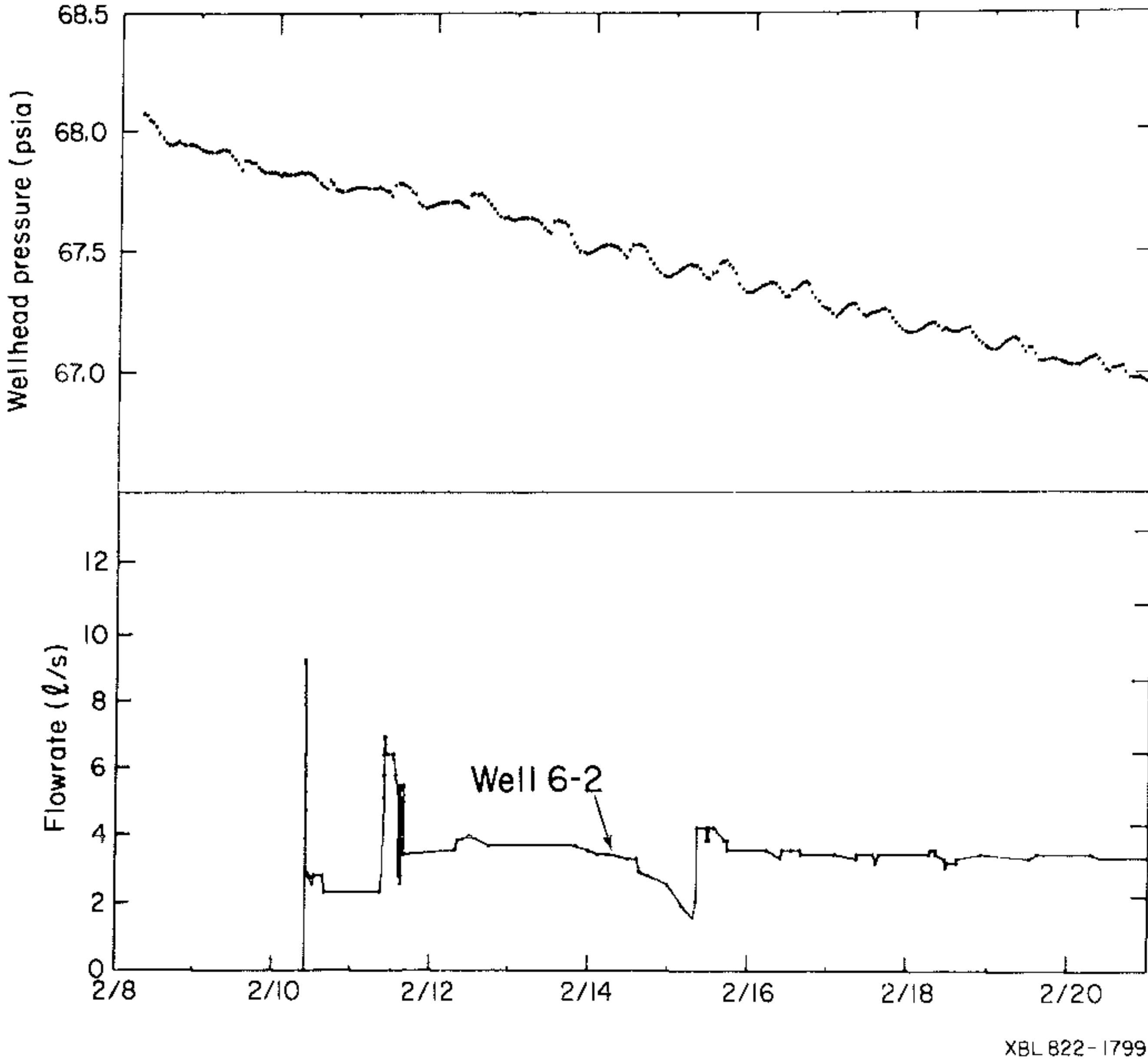


Figure 11. 6-1 interference data (6-2/6-1 interference test).

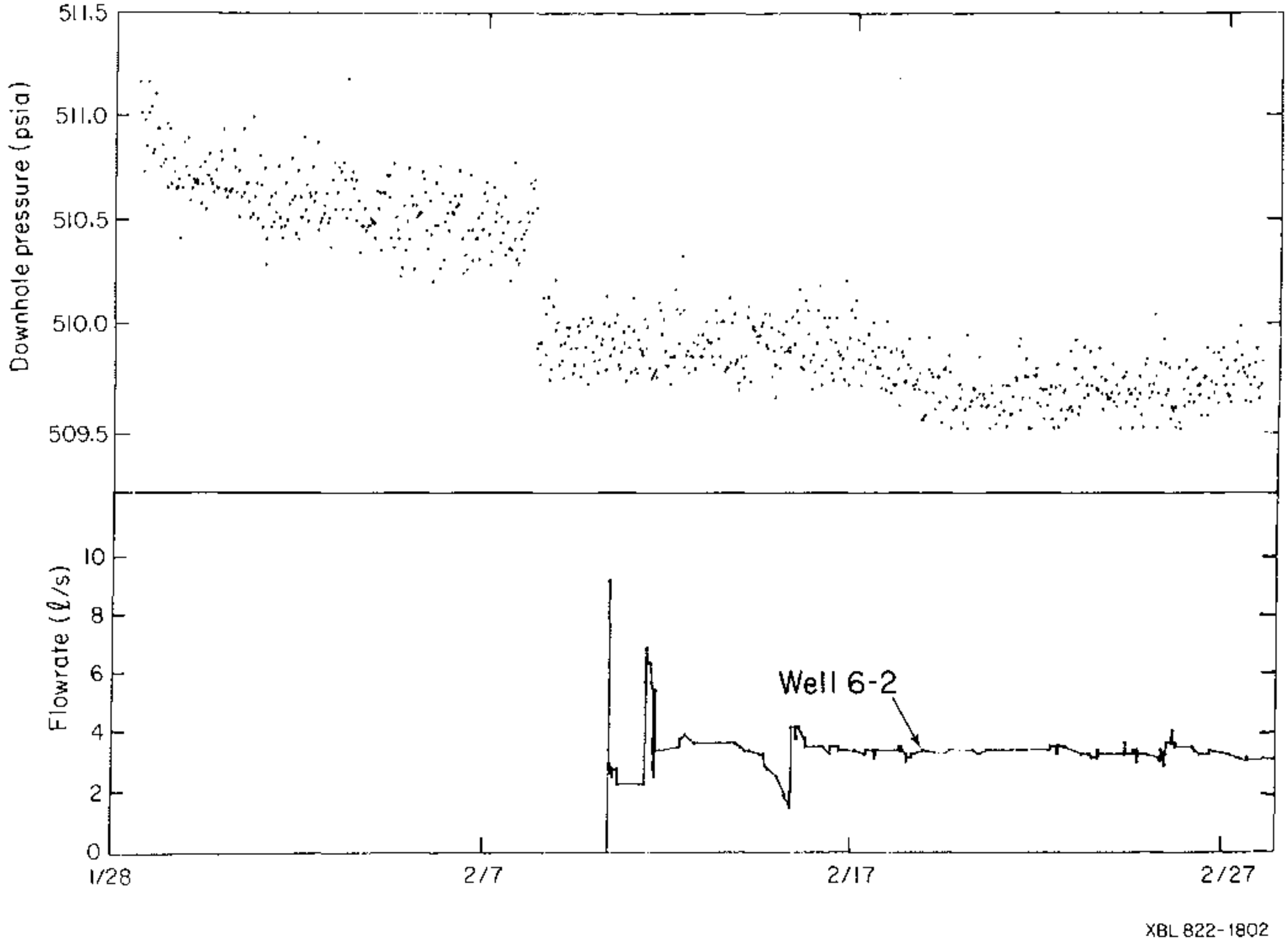


Figure 12. 8-1 interference data (6-2/6-1 interference test).

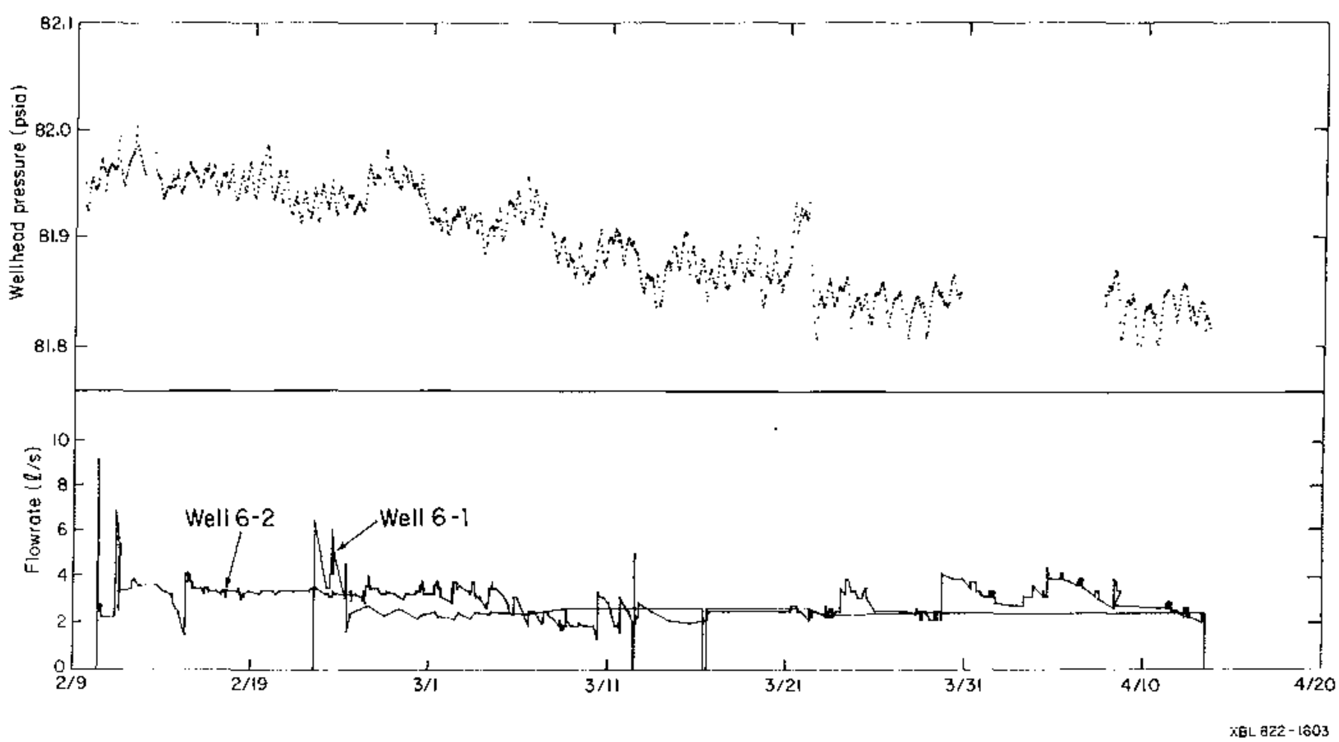


Figure 13. 31-1 interference data (6-2/6-1 interference test).

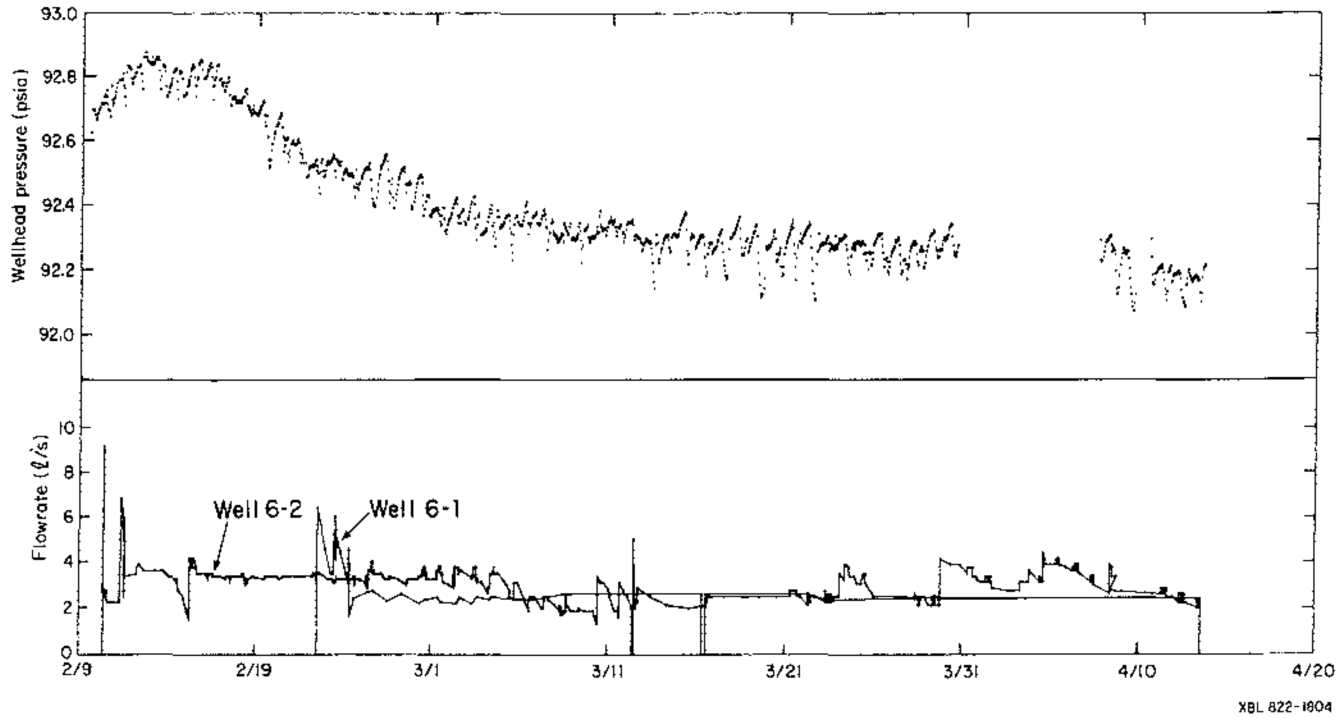


Figure 14. 44-7 interference data (6-2/6-1 interference test).

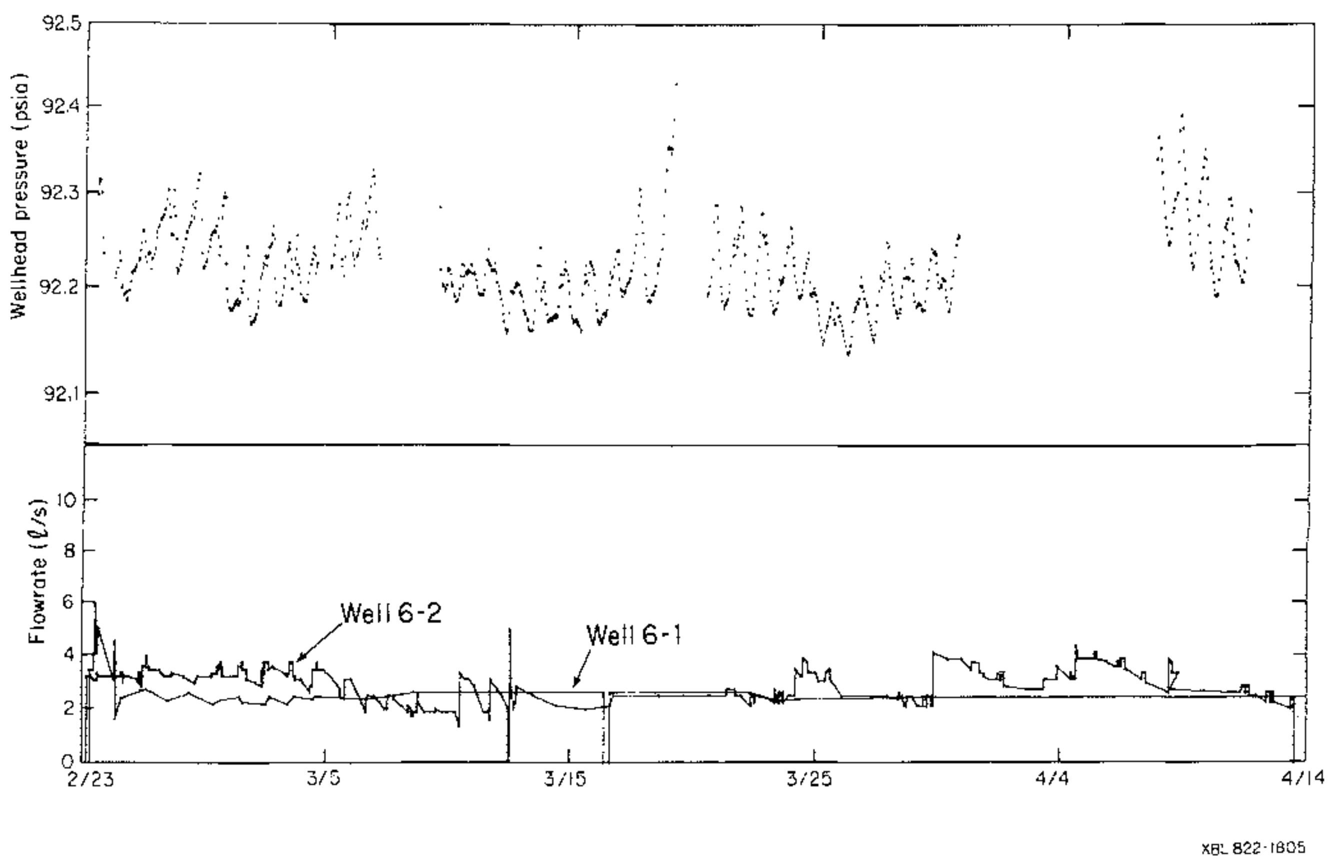


Figure 15. 38-30 interference data (5-1/6-1 interference test).

Well 38-30 Interference Test (July 14-18, 1977)

Well 38-30 was produced for 4 days at a variable artesian flowrate consisting of 7 step-rate changes while wells 56-30, 31-1 and 16-29 were monitored for interference effects (Figs. 16-19 and Table 10). These wells are located 580 m, 380 m and 1280 m, respectively, from the production well. Downhole pressures were monitored in the production well using 1860 m of nitrogen gas-filled tubing (0.14 cm I.D.) connected to a Sperry Sun pressure transmission system at the surface (Fig. 16). Wellhead pressures were monitored in the observation wells for 13 days prior to the test, during the test, and for 8 days afterwards.

A maximum pressure drawdown of about 150 psi was recorded in the production well. Due to temperature effects on the gas in the tubing, initial pressures were obscured. Pronounced drawdowns were measured in all three observation wells: 14.0 psi in well 31-1, 22.0 psi in well 56-30, and 1.3 psi in well 16-29. Analytic results indicate a Productivity Index ($Q/\Delta P$) for well 38-30 of approximately 4.6×10^{-8} $m^3/s/Pa$. Computer-assisted analysis of data from wells 56-30 and 31-1 indicates the presence of a barrier boundary. Earth tide effects (amplitude ± 0.1 psi) were apparent in the observation wells.

Throughout the test, produced fluids were injected into well 18-28 (2870 m from the production well) at a highly variable rate (Fig. 20). Downhole pressures in the injection well were monitored for 13 days prior to injection and during injection. The total pressure increase in this well was approximately 350 psi. The inability to maintain a constant injection rate made analysis of the data difficult.

[abstracted from Narasimhan et al., 1977b; Howard et al., 1978b,c; McEdwards and Benson, 1978; McEdwards et al., 1978; and Narasimhan et al., 1978]

Table 10. Well 38-30 Interference Test, July 14-18, 1977.

WELL Classification	TEST DESCRIPTION Fluid Flow	ΔP (psi)	Distance to Production Well(s) (m)	INSTRUMENTATION (P) Pressure (T) Temperature (Q) Flowrate	ANALYSIS * kh/μ md·ft/cp (m^3/Pa·s)	ϕch ft/psi (m/Pa)
38-30 production	4 days stepwise variable @ 16-32-47-57-32-16 l/s	150		(P) S.S. with 1860 m of nitrogen gas-filled 0.14-cm I.D. tubing (Q) orifice plates (steam and water)	1.3×10^5 (4.0×10^{-8}) P.I. = 4.6×10^{-8} $m^3/s\cdot Pa$	
18-28 injection	highly variable	350	2870	(P) H.P. downhole (1530 m) (T) G.O. downhole (1530 m) (Q) orifice plate		
56-30 observation		23	580	(P) Paros. at wellhead	1.4×10^5 (4.4×10^{-8}) barrier boundary indicated	4.3×10^{-4} (1.9×10^{-8})
31-1 observation		12	380	(P) Paros. at wellhead	1.9×10^5 (5.8×10^{-8}) barrier boundary indicated	2.0×10^{-3} (8.8×10^{-8})
16-29		1.5	1280	(P) Paros. at wellhead	1.2×10^5 (3.5×10^{-8})	4.0×10^{-3} (1.7×10^{-7})

* computer-assisted analysis

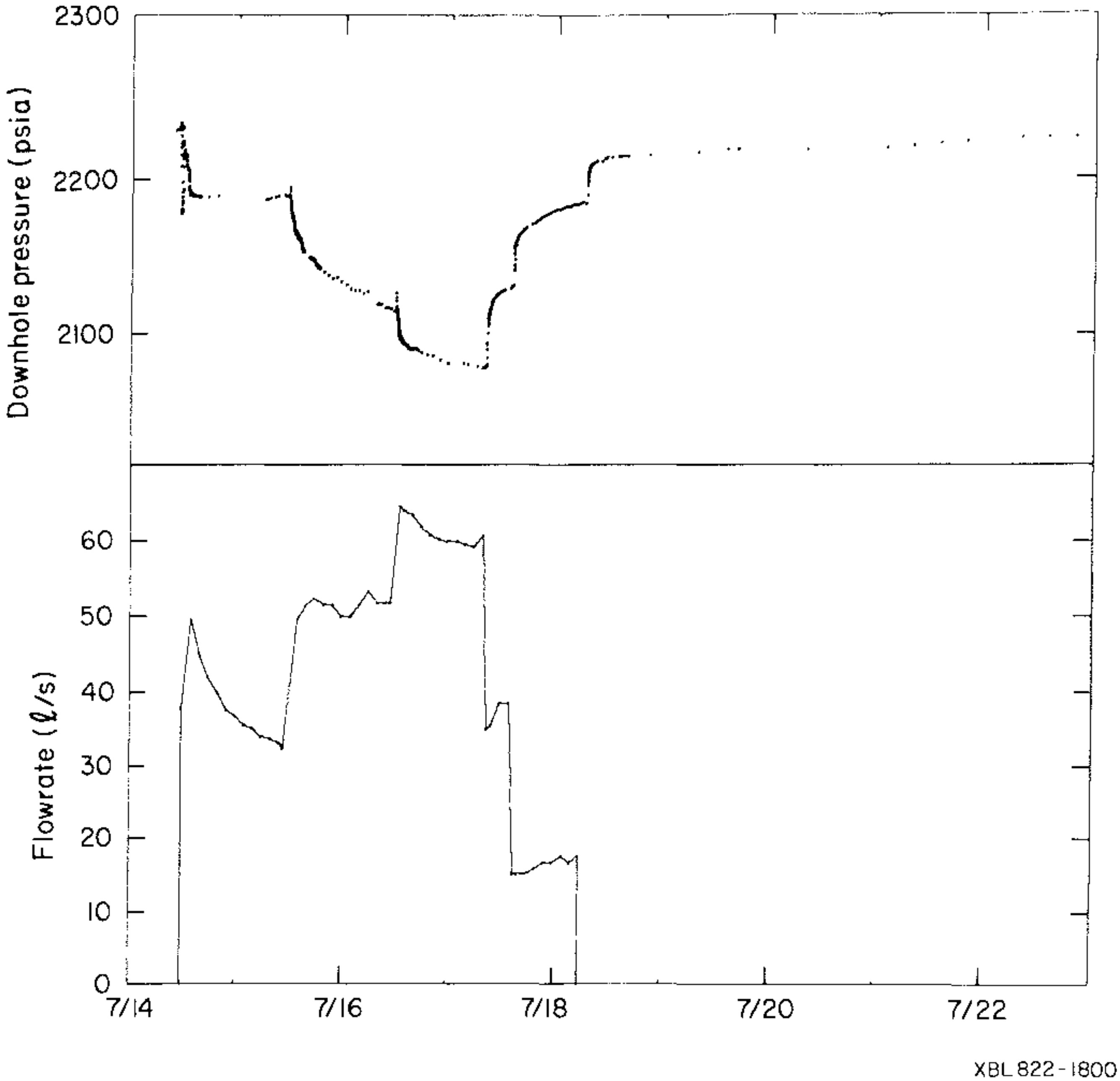


Figure 16. 38-30 interference data (38-30 interference test).

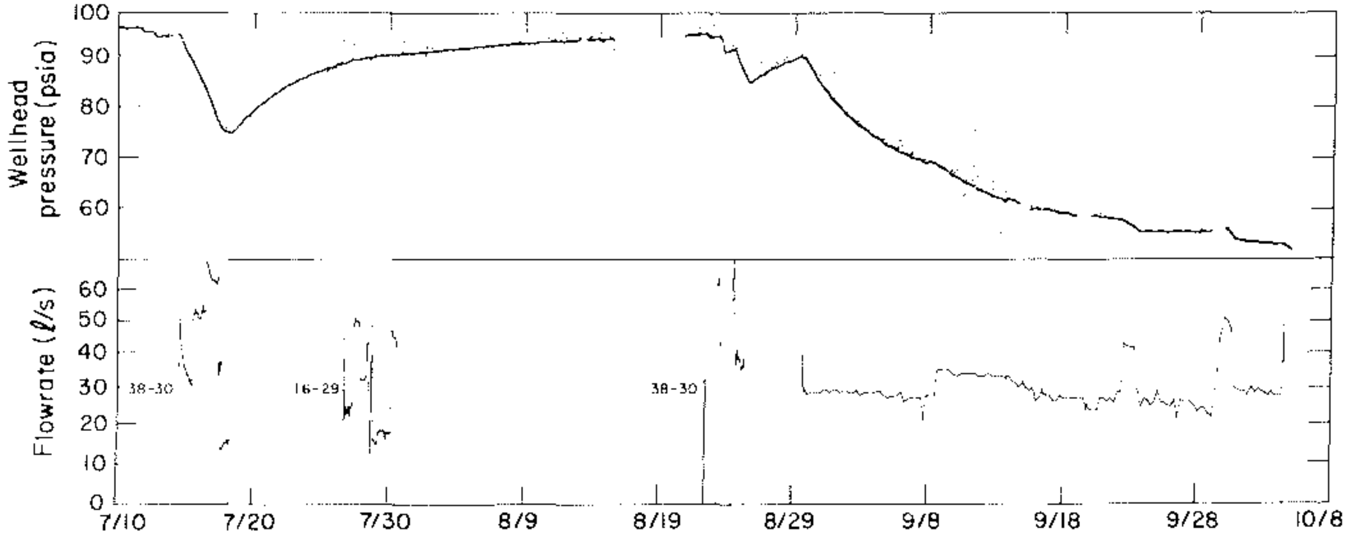
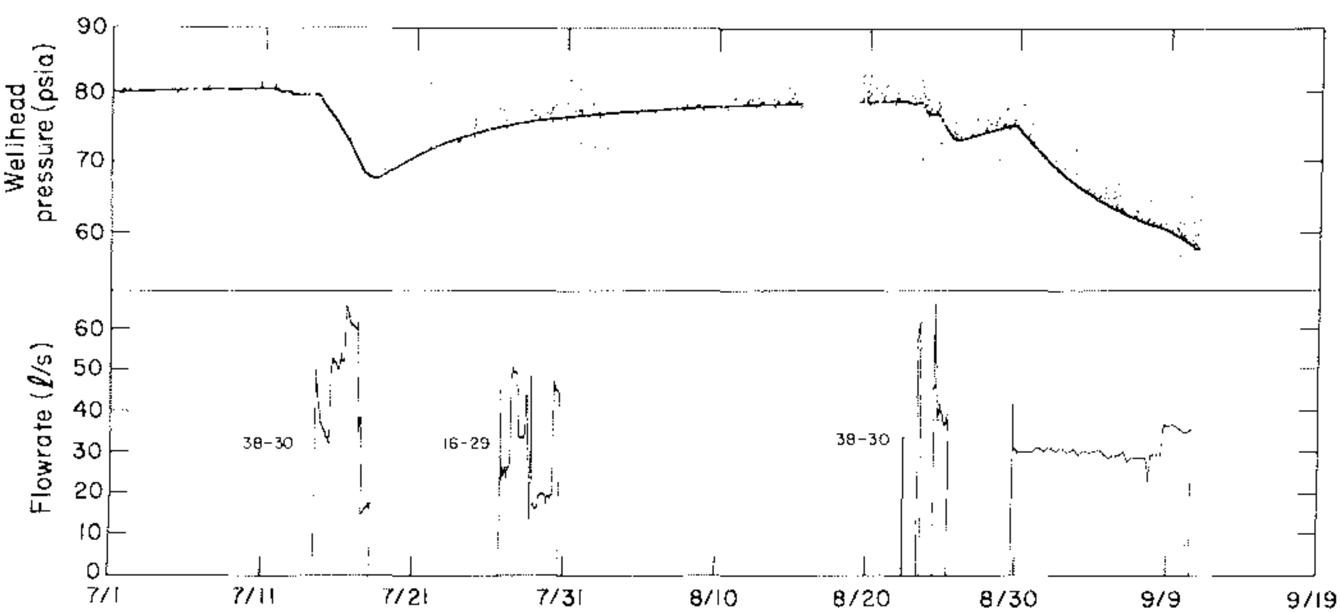


Figure 17. 56-30 interference data (38-30, 16-29, and 38-30 interference tests). XBL 793-7389A



XBL 793-7385

Figure 18. 31-1 interference data (38-30, 16-19, and 38-30 interference tests).

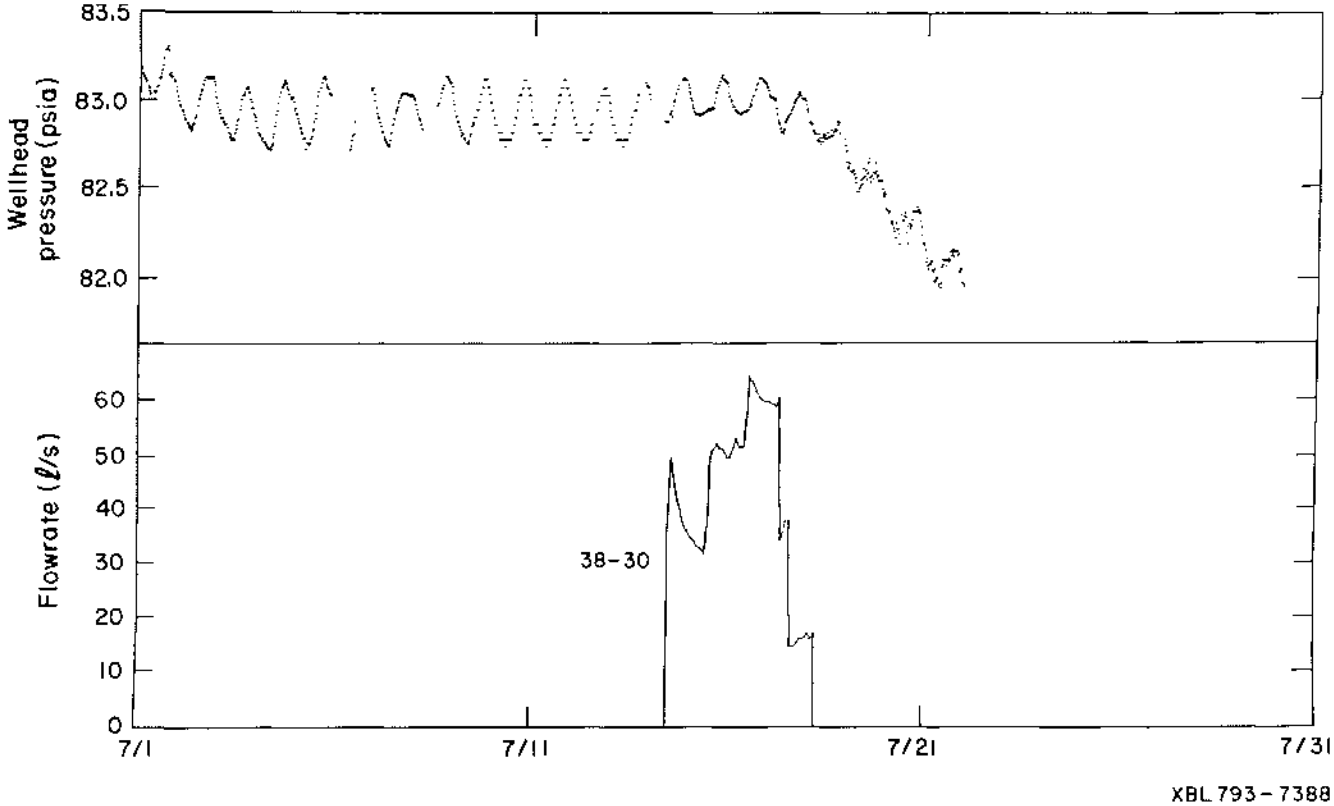


Figure 19. 16-19 interference data (38-30 interference test).

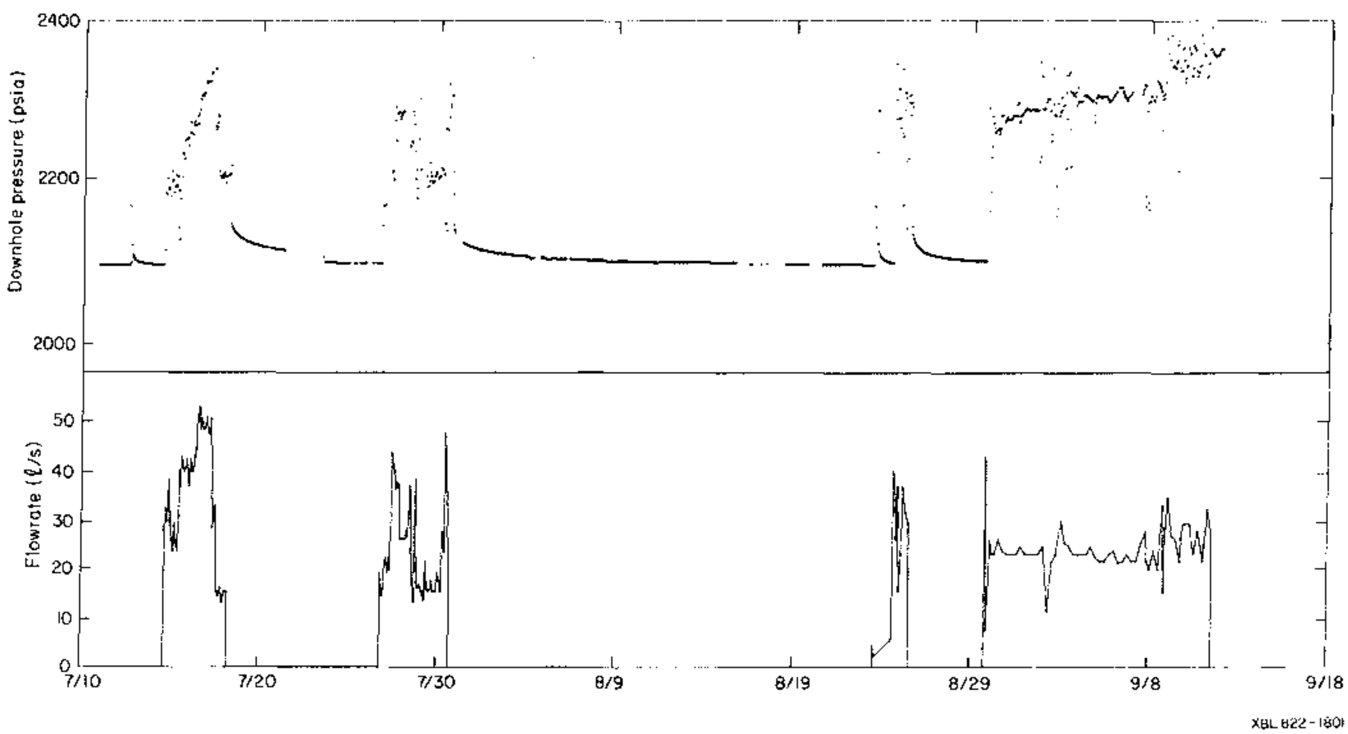


Figure 20. 18-28 interference data (38-30, 16-29, and 38-30 interference tests).

16-29 Interference Test (July 26-30, 1977)

Well 16-29 was produced for four days at a highly variable artesian flowrate of 12.6 - 44 l/s while interference effects were monitored in wells 56-30, 31-1 and 16-30 (Figs. 17, 18, 21, and Table 11). These wells are located 800 m, 1330 m, and 1610 m, respectively, from the production well. No pressure response due to well 16-29 production was observed in any of the three wells.

Downhole pressures from well 16-29 were measured for only a limited period of time prior to and after production. During production, an influx of cold water into the well from the top 150 m was observed. Analysis of the buildup data from the production well led to a reservoir transmissivity (kH) estimate of 32,000 md·ft in the vicinity of wells 16-29.

During this test well 18-28, located 1700 m from the production well, was injected at a highly variable rate (Fig. 20). Downhole pressures during injection were measured with a Hewlett Packard gauge. The inability to maintain a constant injection rate made the analysis of the data somewhat difficult.

[abstracted from Narasimhan et al., 1977; Howard et al., 1978b; McEdwards and Benson, 1978; McEdwards et al., 1978; and Narasimhan et al., 1978]

Table 11. Well 16-29 Interference Test, July 26-30, 1977.

WELL	TEST DESCRIPTION			INSTRUMENTATION	ANALYSIS *	
Classification	Fluid Flow	ΔP (psi)	Distance to Production Well(s) (m)	(P) Pressure (T) Temperature (Q) Flowrate	kh/μ md·ft/cp (m^3/Pa·s)	φch ft/psi (m/Pa)
16-29 production	4 days variable @ 13-44 l/s			(Q) orifice plates (steam and water)		
18-28 injection	4 days highly variable		1700	(P) H.P. downhole (1520 m) (T) G.O. downhole (1520 m) (Q) orifice plate	7.3×10^4 (2.2×10^{-8})	
56-30 observation		0	800	(P) Paros. at wellhead		
31-1 observation		0	1330	(P) Paros. at wellhead		
16-29 observation		0	1610	(P) Paros. at wellhead		

* semilog analysis

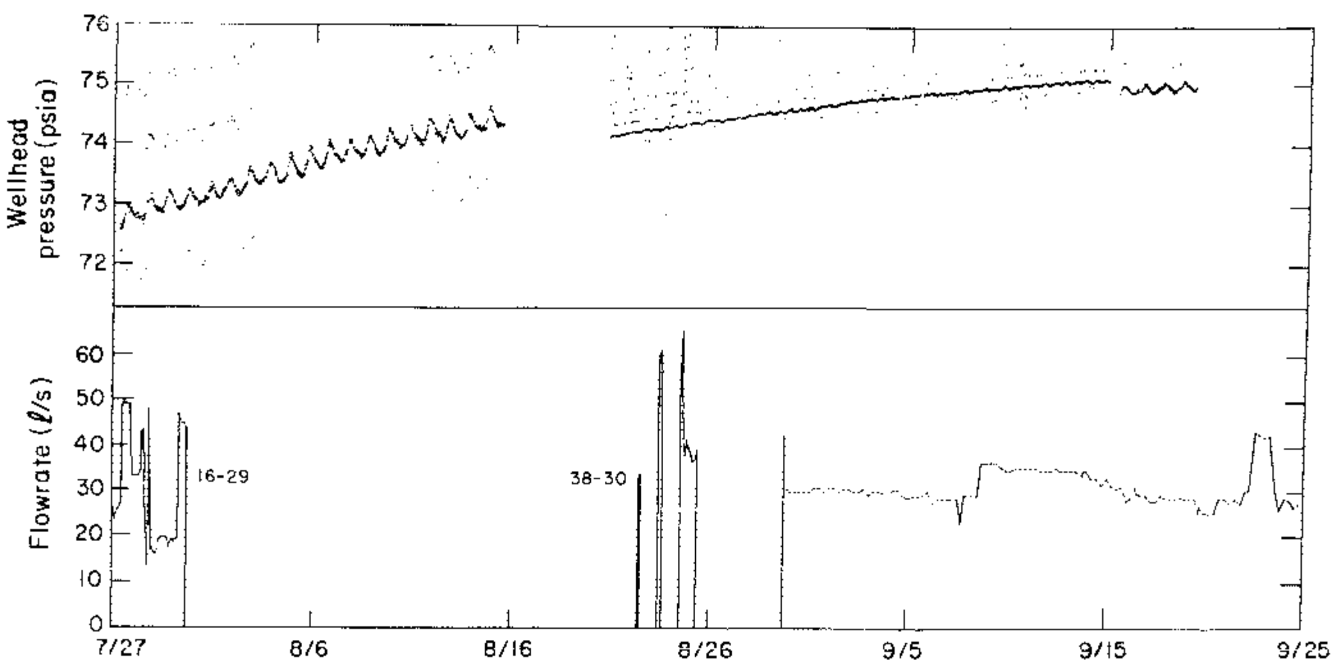


Figure 21. 16-30 interference data (16-29 and 38-30 interference tests). XBL 793-7387

Well 38-30 Interference Test (August 24-October 5, 1977)

Well 38-30 was pumped at a rate of approximately 25 l/s for 40 days while wells 56-30, 31-1, 16-30 and 78-30 were observed for interference effects (Figs. 17, 18, 21, 22 and Table 12). These wells are located approximately 580 m, 380 m, 580 m, and 800 m, respectively, from the production well. A Peerless shaft-driven pump was set at a depth of 125 m in the production well. Wellhead pressures were measured in the observation wells using Paroscientific gauges. In addition to measurements taken during production, 24 days of background data were obtained in wells 56-30, 31-1, and 16-30, and 11 days of recovery data in wells 56-30, 16-30, and 78-30. The pressure gauge was removed from well 31-1 before the end of the test. The 400-psia pressure gauge on well 16-30 was replaced with a 900-psia gauge during the test. A 12.0 psi draw down was recorded in well 78-30, however, it is not certain that the drawdown was caused by the production of well 38-30.

Analysis of data (computer-assisted) from wells 56-30 and 31-1 indicates the presence of a barrier boundary in the reservoir. Well 16-30 showed no pressure decline due to well 38-30 production. Analysis of data from well 78-30 suggests the presence of a partial barrier between well 78-30 and well 38-30.

As in the previous two tests, the produced fluid was injected into well 18-28 at a highly variable rate, slightly less than the production flow rate (Fig. 20). Downhole pressure in the injection well was monitored with a Hewlett Packard gauge for 24 days prior to the test but during only the first 21 days of injection. The difficulty of maintaining a constant injection rate made analysis of data from this well difficult.

[abstracted from Narasimhan et al., 1977; Howard et al., 1978b,c; McEdwards and Benson, 1978; McEdwards et al., 1978; and Narasimhan et al., 1978]

Table 12. Well 38-30 Interference Test, August 24 - October 5, 1977.

WELL Classification	TEST DESCRIPTION Fluid Flow	ΔP (psi)	Distance to Production Well(s) (m)	INSTRUMENTATION (P) Pressure (T) Temperature (Q) Flowrate	ANALYSIS * kh/μ md·ft/cp (m^3/Pa·s)	φch ft/psi (m/Pa)
38-30 production	40 days @ 25 l/s	15		(Q) orifice plate (steam and water)		
18-28 injection	40 days highly variable	350	2870	(P) H.P. downhole (1524 m) (T) G.O. downhole (1524 m) (Q) orifice plate	7.6×10^4 (2.3×10^{-8})	
56-30 observation		45	580	(P) Paros. at wellhead	1.3×10^5 (3.9×10^{-8}) barrier boundary indicated	6.4×10^{-4} (2.8×10^{-8})
31-1 observation		25	380	(P) Paros. at wellhead	1.7×10^5 (5.3×10^{-8}) barrier boundary indicated	2.4×10^{-3} (7.1×10^{-7})
16-30 observation		0	580	(P) Paros. at wellhead †		
78-30		12	800	(P) Paros. at wellhead	5.8×10^4 (1.7×10^{-8})	6.7×10^{-3} (2.9×10^{-7})

* computer-assisted analysis
† pressure gauge changed from 400 psia gauge to 900 psia gauge

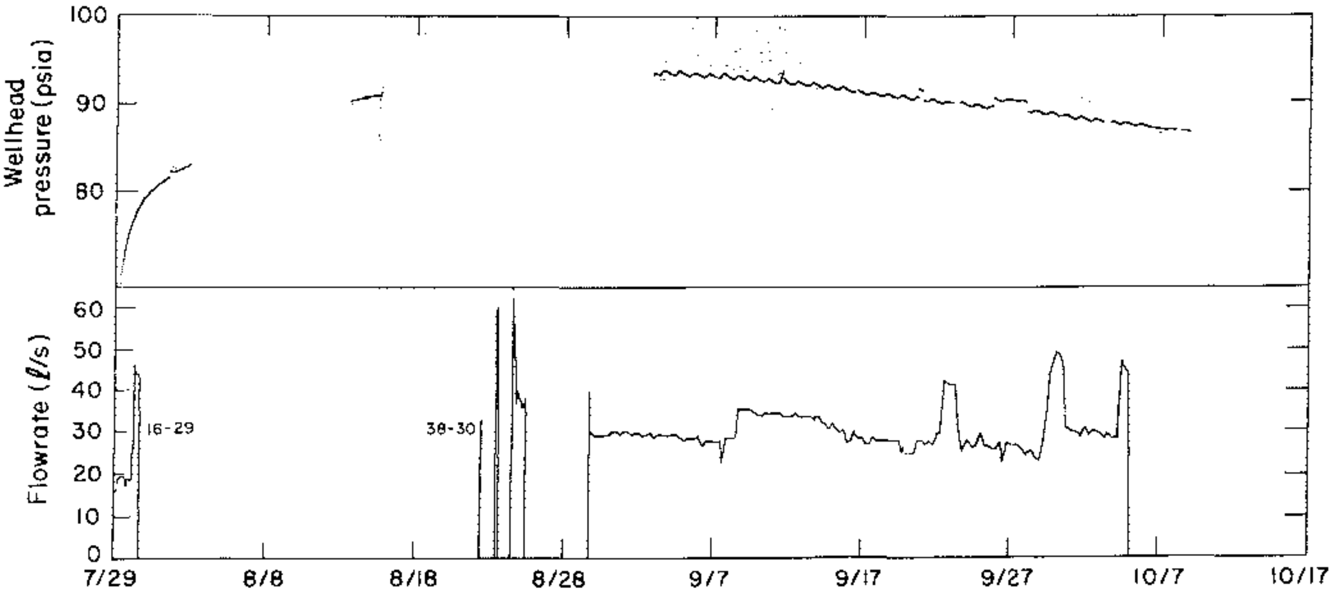


Figure 22. 78-30 interference data (16-29 and 38-30 interference tests). XBL 793-7386

Well 5-1 Injection Test (December 1-6, 1977)

Brine (20°C) from nearby well 6-2 was injected into well 5-1 for 5 days at five stepwise variable flowrates, each step lasting about one day (Fig. 23 and Table 13). Two positive displacement injection pumps (constant capacities 9.5 and 14.0 l/s) were used singly and together to achieve the variable flowrates. Downhole pressures were monitored using 1280 m of silicon oil-filled, 0.14 cm I.D., steel tubing connected to a Paroscientific pressure transducer at the surface. Note that the pressures measured with silicon oil-filled tubing reflect the difference in density between the oil and the wellbore brine. Therefore, this type of pressure measurement is useful only for determining downhole pressure changes, not the absolute downhole pressure.

Early downhole pressure response was obscured by thermal effects on the capillary tubing in the wellbore. The average Injectivity Index ($Q/\Delta P$) for this well is approximately 7.7 x 10^{-9} $m^3/s \cdot Pa$.

[abstracted from McEdwards and Benson, 1978 and McEdwards et al., 1978]

Table 13. Well 5-1 Injection Test, December 1-6, 1977.

WELL Classification	TEST DESCRIPTION Fluid Flow	ΔP (psi)	INSTRUMENTATION (P) Pressure (T) Temperature (Q) Flowrate	ANALYSIS * kh/μ md·ft/cp (m^3/Pa·s)	ϕch ft/psi (m/Pa)
5-1 injection	5 days stepwise variable @ 9-5-14-23-14-9.5 l/s	450	(P) Paros. with 1240 m of silicon oil-filled stainless steel tubing (Q) orifice plate	4.3 x 10^4 (1.3 x 10^{-8})	

* semilog analysis

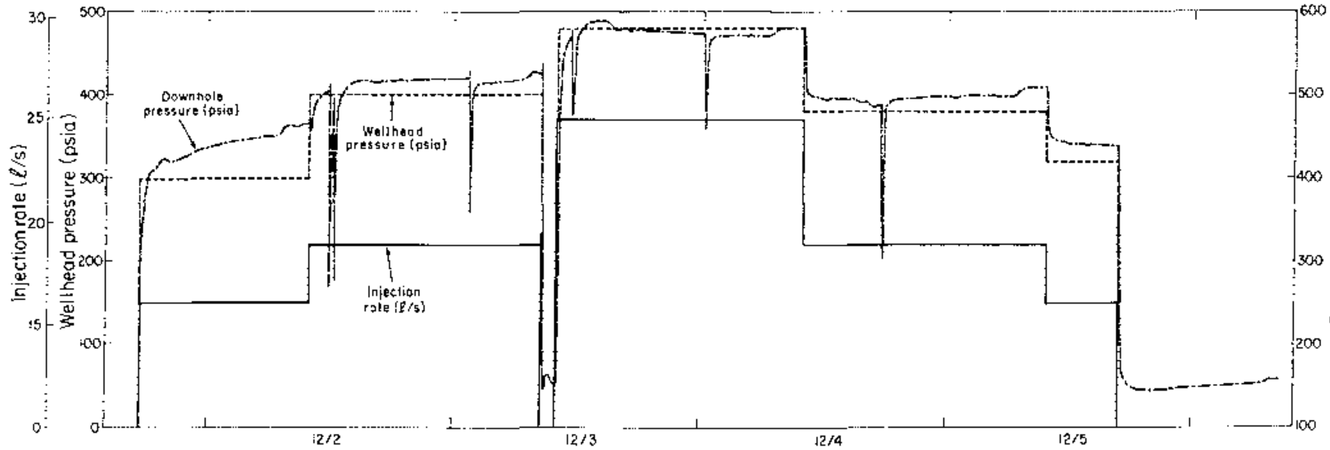


Figure 23. 5-1 injection data (S-1 injection test).

Well 8-1 Production Test (December 16-20, 1977)

Well 8-1 was produced for 5 days at a stepwise variable artesian flow rate consisting of 11 steps between 0 and 20 l/s (Fig. 24 and Table 14). Downhole pressures were measured using 1280 m of silicon oil-filled tubing (0.14 cm I.D.) connected at the surface to a Paroscientific pressure gauge. (Pressure measurements only indicate relative downhole pressures, not absolute downhole pressures).

One day of background data and 5 days of injection data were recorded. There was no initial pressure reading due to thermal effects on the tubing. The maximum drawdown recorded was 150 psi. Flashing in the wellbore was evidenced by scale buildup. The Productivity Index ($Q/\Delta P$) for this well is 2.2×10^{-8} $m^3/s \cdot Pa$.

[abstracted from Howard et al., 1978a and McEdwards et al., 1978]

Table 14. Well 8-1 Production Test, December 16-20, 1977.

WELL Classification	TEST DESCRIPTION Fluid Flow	ΔP (psi)	INSTRUMENTATION (P) Pressure (T) Temperature (Q) Flowrate	ANALYSIS* kh/μ md·ft/cp (m^3/Pa·s)	ANALYSIS* $\phi c h r_e^2$ † ft^3/psi (m^3/Pa)
8-1 production	5 days stepwise variable between 0 and 20 l/s	150	(P) Paros. with 1280 m of silicon oil-filled 0.14-cm I.D. tubing (Q) atmospheric flash tank and weir box	6.0×10^4 (1.8×10^{-3})	0.02 (9.4×10^{-8})

* semilog analysis † r_e = effective wellbore radius

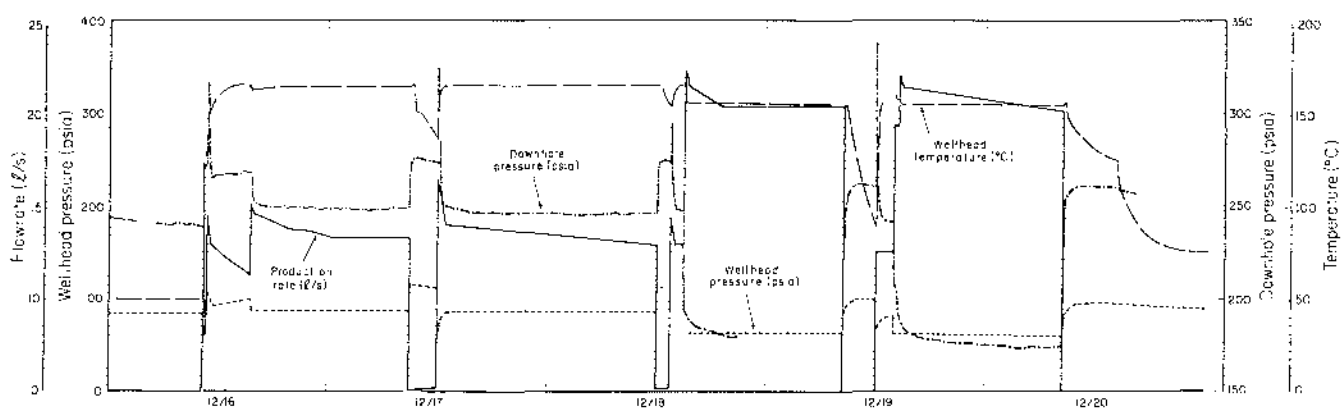


Figure 24. 8-1 production data (8-1 production test).

Wells 8-1/44-7 Interference Test
(January 6 - March 29, 1978)

This test involved four production wells (8-1, 44-7, 6-2, and 46-7) and two observation wells (6-1 and 48-7) (Figs. 25 and 26 and Table 15). See Figure 7 and Table 15 for well locations and distances between wells. Well 8-1 was produced for 33 days at a flowrate of approximately 15 l/s. Well 6-2 was opened at the same time for about 100 days of production at a rate of approximately 3 l/s. Well 44-7 was opened a month later and produced at a highly variable rate of 0 - 50 l/s for 41 days. Fluid produced from well 44-7 was injected into well 46-7, a shallow (930 m) injection well, concurrent to production.

Only a small (2.5 psi) drawdown was observed at well 6-1, which, combined with the absence of any buildup when wells 8-1 and 44-7 were shut in, indicates a lack of communication between well 6-1 and both wells 44-7 and 8-1. The analysis is further complicated by the fact that wells 6-1 and 6-2 are completed in different depth intervals, making partial penetration effects important.

It is not clear whether there is communication between wells 8-1 and 48-7. Wells 48-7 and 6-2 are too far apart for well 48-7 to show a pressure response to the small rate at which well 6-2 produced. The 17-psi pressure drop at well 48-7 clearly indicates communication between well 44-7 and 48-7. Computer-assisted analysis indicates a reservoir kh/μ of 2.5×10^5 md·ft/cp and a storativity of 1×10^{-3} ft/psi. The effect of injection into the shallow well, 46-7, upon 48-7 is uncertain.

[abstracted from Howard et al., 1978b and McEdwards et al., 1978]

Table 15. Wells 8-1/44-7 Interference Test, January 6 - March 29, 1978.

WELL Classification	TEST DESCRIPTION Fluid Flow	Δp (psi)	Distance to Production Well(s) (m)	INSTRUMENTATION (P) Pressure (T) Temperature (Q) Flowrate	ANALYSIS * kh/μ md·ft/cp (m^3/Pa·s)	ϕch ft/psi (m/Pa)
8-1 production	33 days variable @ 14-8-17 l/s			(Q) atmospheric flashtank and weir box		
44-7 production	41 days highly variable between 0 and 50 l/s			(Q) orifice plate		
6-2 production	~ 100 days @ 3 l/s			(Q) atmospheric flashtank and weir box		
46-7 injection	41 days highly variable between 0 and 50 l/s					
6-1 observation		2.5	710 (to 8-1) 970 (to 44-7) 450 (to 6-2)	(P) Paros. at wellhead	1.4×10^6 † (4.2×10^{-8})	2.0×10^{-3} † (9.0×10^{-8})
48-7 observation		17	1600 (to 8-1) 800 (to 44-7) 1900 (to 6-2)	(P) Paros. at wellhead	2.5×10^5 (7.5×10^{-7})	1.0×10^{-3} (5.0×10^{-8})

* computer-assisted analysis
† this analysis includes only interference effects due to production of well 6-2

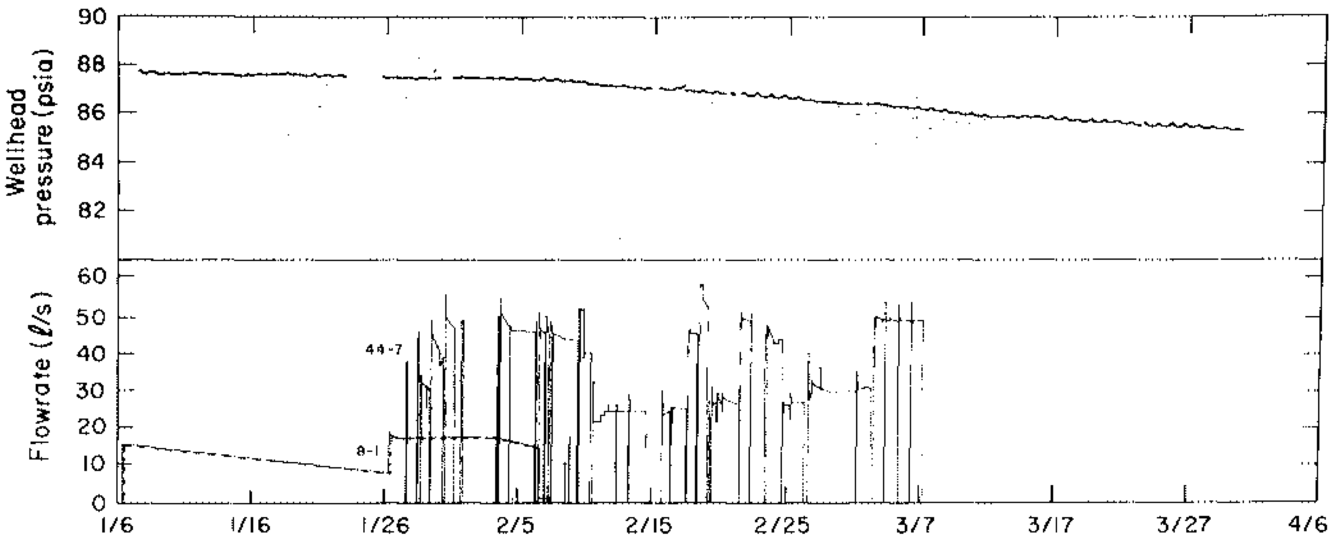


Figure 25. 6-1 interference data (8-1/44-7 interference test). XBL 793-7390

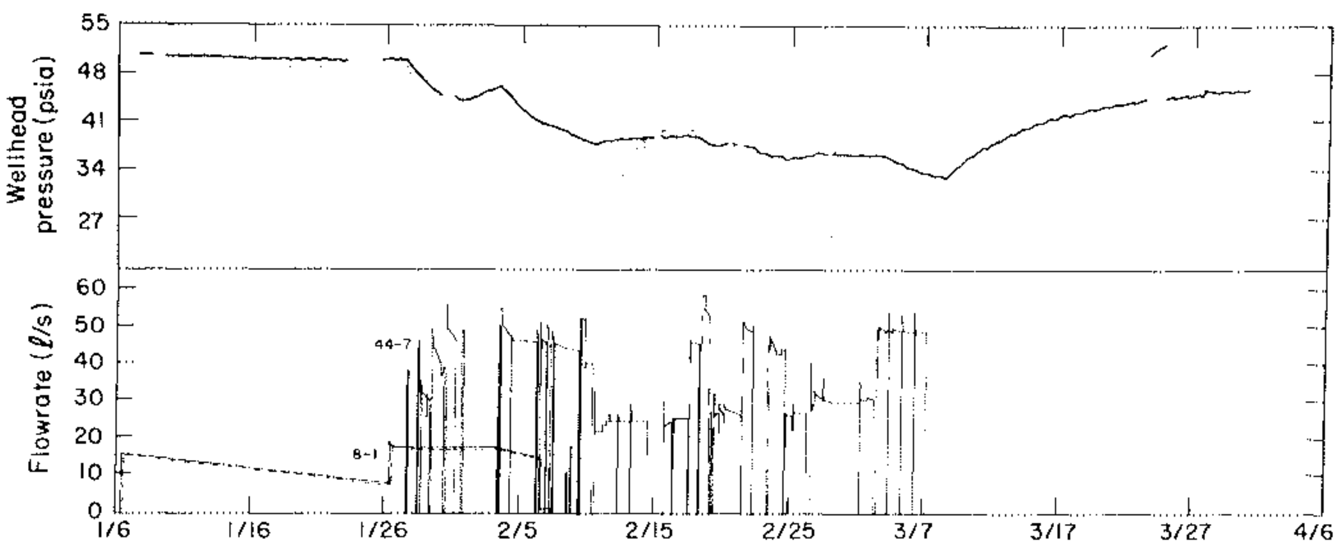


Figure 26. 48-7 interference data (8-1/44-7 interference test). XBL 793-7389

Well 6-2 Production Test (April 17-21, 1978)

Well 6-2 was flowed for 5 days at a variable artesian flowrate of 6 to 22 l/s (Fig. 27 and Table 16). Pressures in the well were measured for 2 days prior to the test and for one day after the well was shut in. Downhole pressures were measured with 1525 m of nitrogen gas-filled tubing (0.14 cm I.D.) connected to a Sperry Sun pressure monitor at the surface. The maximum pressure drawdown recorded was approximately 50 psi. The measured downhole pressure data were strongly influenced by the effect of thermal transients on the capillary tubing in the wellbore. Flashing occurred in the well as evidenced by the deposition of carbonate scale on the capillary tubing to a depth of approximately 120 m. Scale deposited during previous flow periods has narrowed the interior diameter of the casing at the base of the wellhead to 1.2 cm in diameter. The computed Productivity Index ($Q/\Delta P$) for this well is 3.1×10^{-8} $m^3/s \cdot Pa$.

[abstracted from Howard et al., 1978a and McEdwards et al., 1978]

Table 16. Well 6-2 Production Test, April 17-21, 1978.

WELL Classification	TEST DESCRIPTION Fluid Flow	Δp (psi)	INSTRUMENTATION (P) Pressure (T) Temperature (Q) Flowrate	ANALYSIS * kh/μ md·ft/cp (m^3/Pa·s)	$\phi c h r_e^2$ † ft^3/psi (m^3/Pa)
6-2 production	5 days stepwise variable between 6 and 22 l/s	50	(P) S.S. with 1525 m of nitrogen gas-filled 0.14-cm I.D. tubing; Paros. at wellhead (Q) atmospheric flashtank and weir box	7.3×10^4 (2.2×10^{-8})	1.1×10^{-1} (4.3×10^{-7})

* semilog and type curve analysis
† r_e = effective wellbore radius

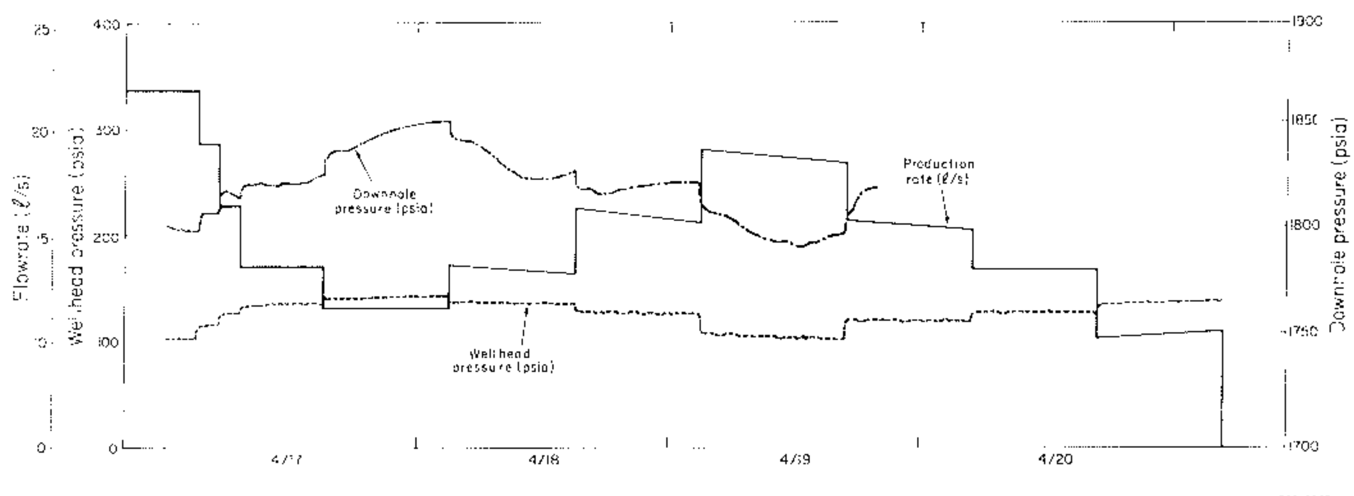


Figure 27. 6-2 production data (6-2 production test).

Well 6-1 Production Test (May 1-4, 1978)

Well 6-1 was produced for 3 days at stepwise variable artesian flowrates of 8, 11, 16, 11, 9 and 6 l/s (Fig. 28 and Table 17). Pressures in the well were observed for 2 days prior to production, during production, and for one day after the well was shut in. Downhole pressures were measured using 1525 m of silicon oil-filled, 0.14 cm I.D. tubing connected at the surface to a 900-psia Paroscientific gauge. (Pressure measurements reflect downhole pressure changes, not absolute downhole pressures.) The maximum pressure drawdown recorded was approximately 200 psi. Thermal effects on the oil-filled tubing in the wellbore obscured early pressure transients.

The Productivity Index (Q/ΔP) for this well is 7.6×10^{-9} m^3/Pa·s. Flashing occurred in the wellbore as evidenced by deposition of calcium carbonate scale on the top 270 m of capillary tubing.

[abstracted from Howard et al., 1978a and McEdwards et al., 1978]

Table 17. Well 6-1 Production Test, May 2-4, 1978.

WELL Classification	TEST DESCRIPTION Fluid Flow	ΔP (psi)	INSTRUMENTATION (P) Pressure (T) Temperature (Q) Flowrate	ANALYSIS * kh/μ md·ft/cp (m^3/Pa·s)	$\phi c h r_e^2$ † ft^3/psi (m^3/Pa)
6-1 production	3 days stepwise variable @ 8-11-16-11-9-6 l/s	200	(P) Paros. with 1525 m silicon oil-filled 0.14-cm I.D. tubing; Paros. at wellhead (T) thermocouple (Q) atmospheric flashtank and weir box	1.4×10^4 (4.2×10^{-9})	0.10 (4.5×10^{-7})

* semilog analysis
† r_e = effective wellbore radius

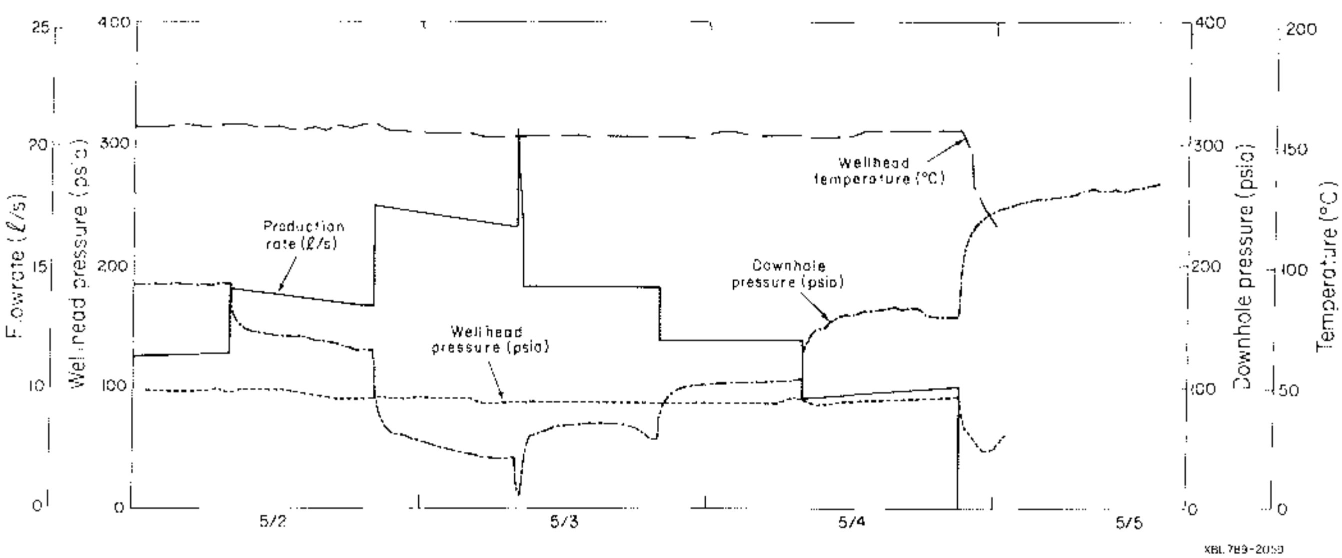


Figure 28. 6-1 production data (6-1 production test).

CERRO PRIETO GEOTHERMAL RESOURCE
BAJA CALIFORNIA, MEXICO

Resource Description

The Cerro Prieto geothermal resource is located near Mexicali, in Baja California, Mexico (Fig. 29). The producing field is situated in the alluvial plain of the Mexicali Valley, which is part of the seismically active Salton Trough/Gulf of California rift basin system. The field is made up of a thick sequence of essentially deltaic deposits that are discordant upon a granite and metasedimentary basement. Several major strike-slip faults have been identified within the resource.

Lithologic studies indicate that several major producing intervals lie at depths of 500 to 1900 m. The resource is a liquid-dominated system which shows boiling near the producing wells. Fluid temperatures in the resource range from 260° to 350°C. It is thought that secondary matrix porosity and permeability may play important roles in the hydrology of the reservoir.

To date (1982), approximately 100 deep wells have been drilled into the reservoir (Fig. 30). Roughly 33 of these wells, ranging in depth from 1000 m to 2500 m, supply a steam-water mixture to the geothermal power plant, operational since April 1973. The artesian production rate of the water-steam mixture from the wells is now close to 4300 tonnes/hr. See Table 18 for a summary of resource characteristics. The wells listed are those used in the LBL tests.

[abstracted from Barmejo M. et al., 1978; Domínguez A. et al., 1981; Puente C. and de la Peña, 1978; Schroeder et al., 1978; and Lyons and van de Kamp, 1980]

Well Tests

The following well tests were performed by LBL during the period January through July 1978. The tests were undertaken as part of a joint effort of LBL and Comisión Federal de Electricidad de México (CFE) to conduct a comprehensive investigation of the entire Cerro Prieto geothermal field. All information has been abstracted from the indicated LBL report, prepared by the principal investigators, from which further information can be obtained.

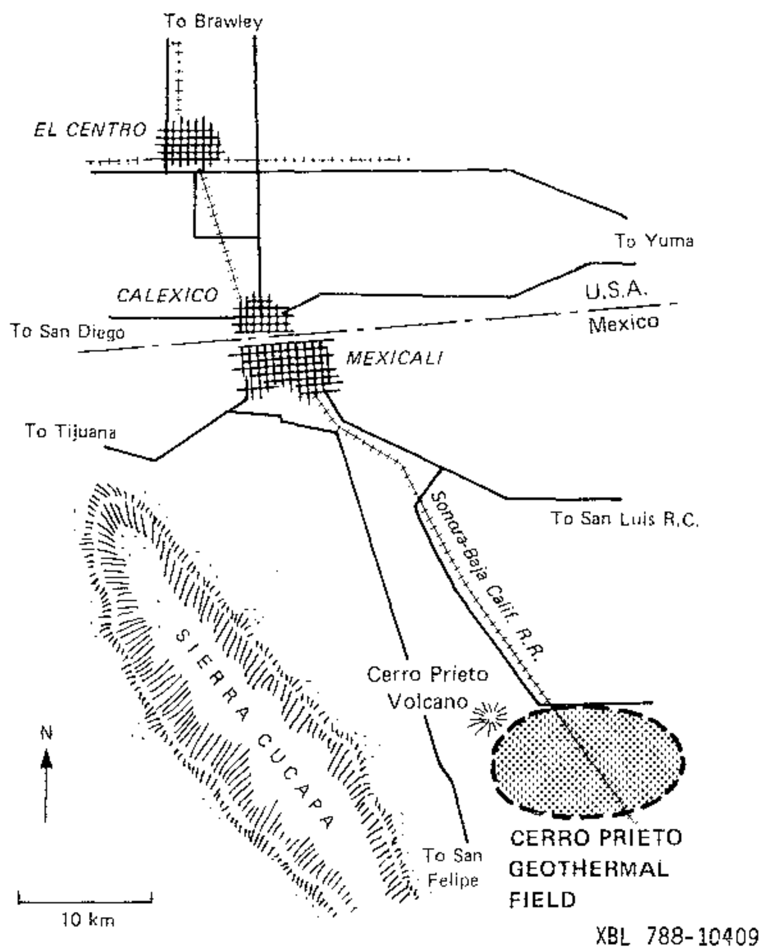


Figure 29. Location map, Cerro Prieto geothermal resource.

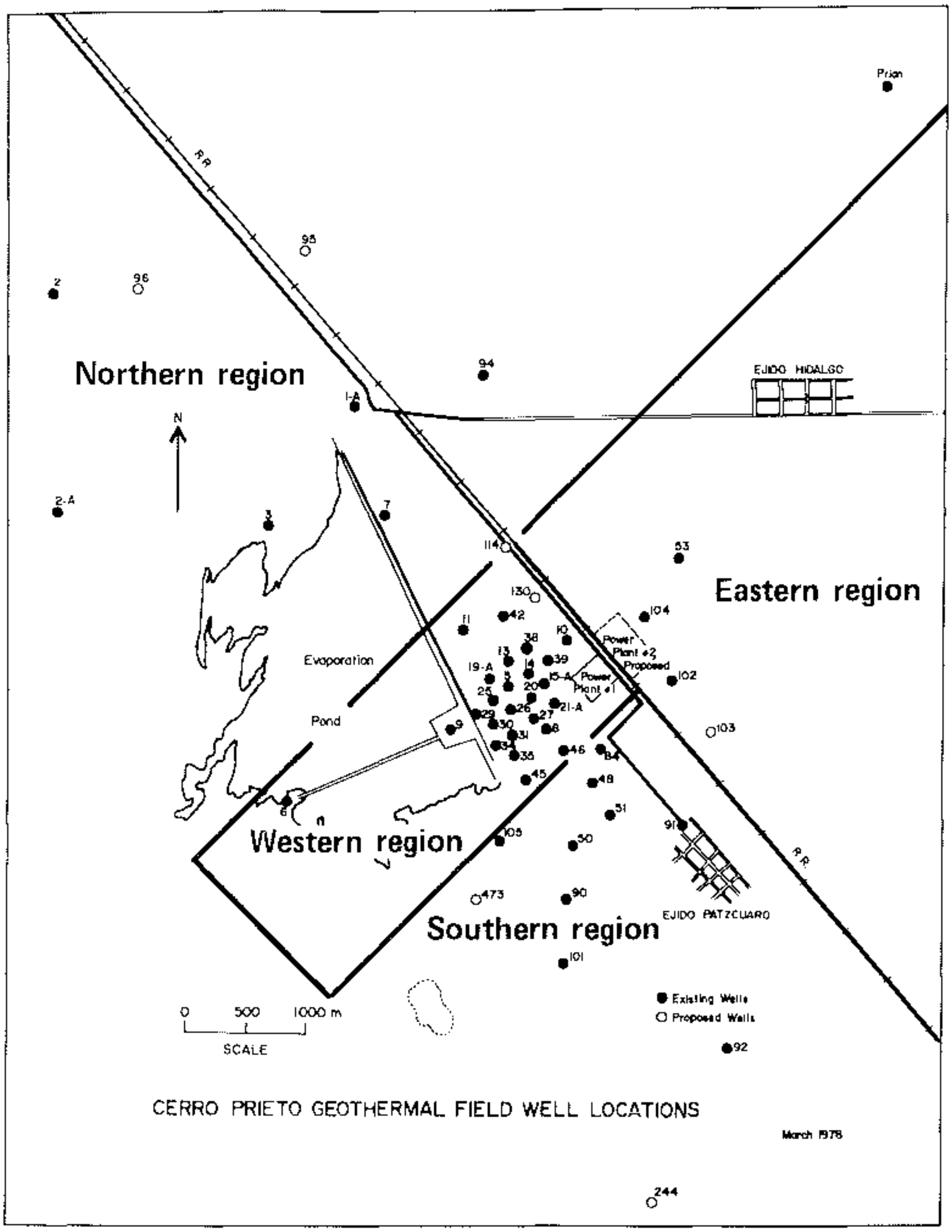


Figure 30. Well location map, Cerro Prieto geothermal resource.

Table 18. Cerro Prieto geothermal resource, Baja California, Mexico.

Location:	Mexicali Valley, Baja California, Mexico			
Reservoir Temperature:	200° - 330°C			
Geologic Setting:	Thick sequence of essentially deltaic sedimentary deposits discordant upon granite and metasedimentary basement; located in faulted, seismically active Salton Trough area			
Fluid Characteristics:	Artesian flow; two-phase liquid-dominated system			
Test Wells and Approximate Depths:	M-10	1448 m	M-90	1386 m
	M-50	1256 m	M-91	2300 m
	M-51	1600 m	M-101	1396 m
	M-53	1997 m	M-104	1728 m

Wells M-50/M-51/M-90/M-91 Interference Test, January 14-March 30, 1978

The first interference test utilized four production wells: M-50, M-51, M-90 and M-91. Well M-101 was monitored for interference effects (Fig. 31 and Table 19). These wells are located approximately 1.5 km from the main producing field (Fig. 30). The producing interval of well M-91 is somewhat deeper than those of the other three wells.

The producing wells were flowed at variable flowrates with overlapping intervals of 4 days to 2 weeks. A total of 30 days of drawdown and 15 days of recovery were observed. Pressure changes were measured in well M-101 using 304 m of nitrogen-filled, 0.14 cm I.D. stainless steel tubing connected to a Paroscientific Digiquartz pressure transducer at the surface.

Since there were multiple producing wells, a least squares matching routine was used in which multiple producing wells and variable flow rates can be accounted for. An excellent match of the observed and calculated data was obtained, resulting in a calculated transmissivity of 1.5 x 10^6 md·ft/cp and a storativity of 2.3 x 10^{-2} ft/psi.

[abstracted from Schroeder et al., 1978]

Table 19. M-50/M-51/M-90/M-91 Interference Test, January 14 - March 30, 1978.

WELL Classification	TEST DESCRIPTION Fluid Flow	ΔP (psi)	Distance to Production Well(s) (m)	INSTRUMENTATION (P) Pressure (T) Temperature (Q) Flowrate	ANALYSIS * kh/μ md·ft/cp (m^3/Pa·s)	φch ft/psi (m/Pa)
M-50 production	4 days (2/23-2/27) stepwise variable @ 1.4-19-53-61-42-1.3 kg/s			(Q) James method and weir box		
M-51 production	14 days (2/7-2/21) stepwise variable @ 1.6-42-66-80-66-75-80-30-36-33-1.6 kg/s			(Q) James method and weir box		
M-90 production	16 days (2/16-3/1) stepwise variable @ 1.6-15-28-35-41-53-58-39-5.5 kg/s			(Q) James method and weir box		
M-91 production	12 days (1/29-2/9) stepwise variable @ 47-50-55-72-80-85-86-60-2.2 kg/s			(Q) James method and weir box		
M-101 observation		5.0	960 (to M-50) 1285 (to M-51) 530 (to M-90) 1480 (to M-91)	(P) Paros. with 304 m of nitrogen gas-filled 0.14-cm I.D. tubing	1.5 x 10^6 (4.5 x 10^{-7})	2.3 x 10^{-2} (1.1 x 10^{-6})

* computer-assisted analysis

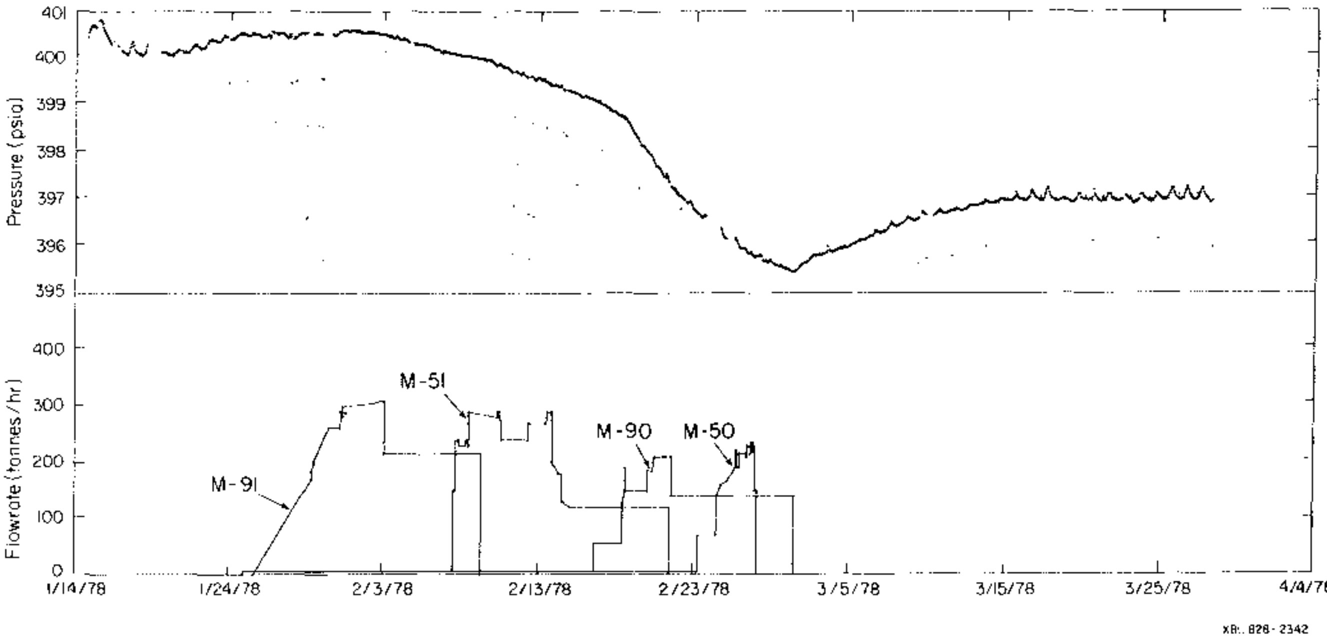


Figure 31. M-101 interference data (M-50/M-51/M-90/M-91 interference test).

Well M-53 Interference Test, May 16 - July 24, 1978

This test involved the observation of wells M-10 and M-104 while M-53 was developed to supply steam to the existing power plant (Figs. 32 and 33 and Table 20). Pressure measurements were recorded in the observation wells for 15 days prior to production of well M-53. Both wells experienced pressure increases when none should have occurred. Pressures in well M-104 continued to rise nearly two weeks after well M-53 was opened for flow. A 5.3-Richter-magnitude earthquake was recorded on May 5, 1978 and the abnormal pressure behavior has been attributed to this event. Due to the seismic effects, pressure transient analysis of the interference data was considered impossible.

[abstracted from Schroeder et al., 1978]

Table 20. M-53 Interference Test, May 16 - July 24, 1978.

WELL Classification	TEST DESCRIPTION Fluid Flow	ΔP (psi)	Distance to Production Well(s) (m)	INSTRUMENTATION (P) Pressure (T) Temperature (Q) Flowrate	ANALYSIS * kh/μ md·ft/cp (m^3/Pa·s)	ϕch ft/psi (m/Pa)
M-53 production	70 days variable between 0 and 40 kg/s			(Q) James method and weir box		
M-104 observation	~ 3 months		550	(P) Paros. with 540 m of nitrogen gas-filled 0.14-cm I.D. tubing	*	
M-10 observation	~ 3 months		1200	(P) Paros. with 540 m of nitrogen gas-filled 0.14-cm I.D. tubing	*	

* due to seismic effects, analysis of data not possible

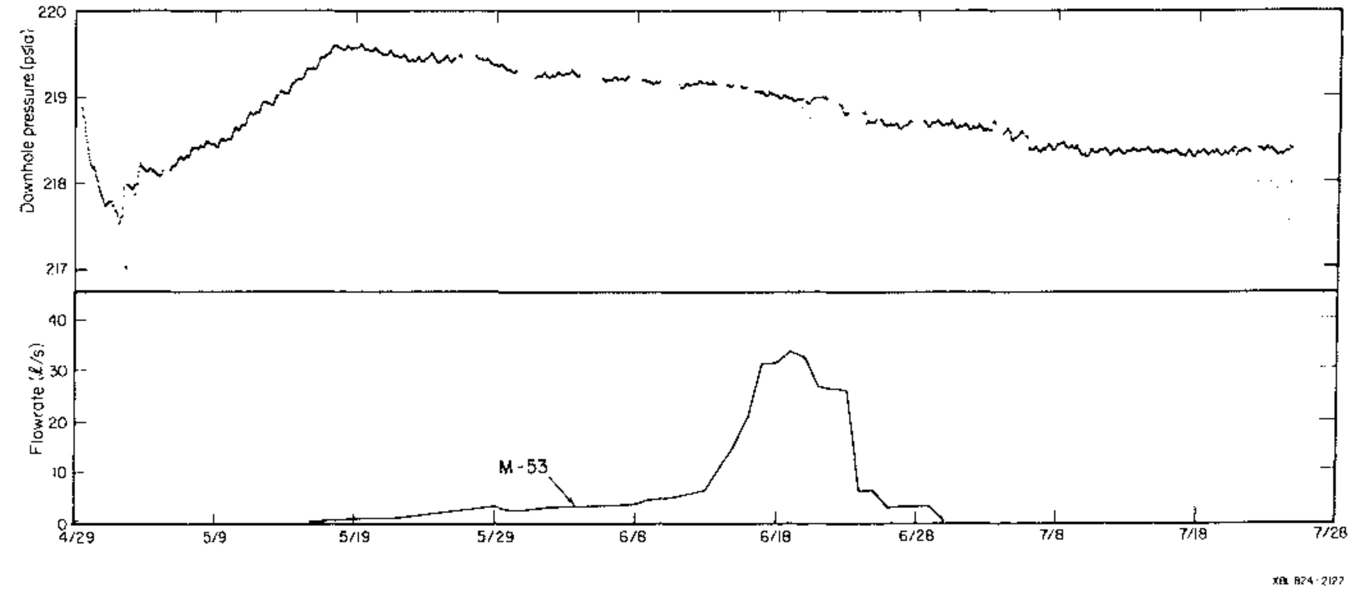


Figure 32. M-10 interference data (M-53 interference test).

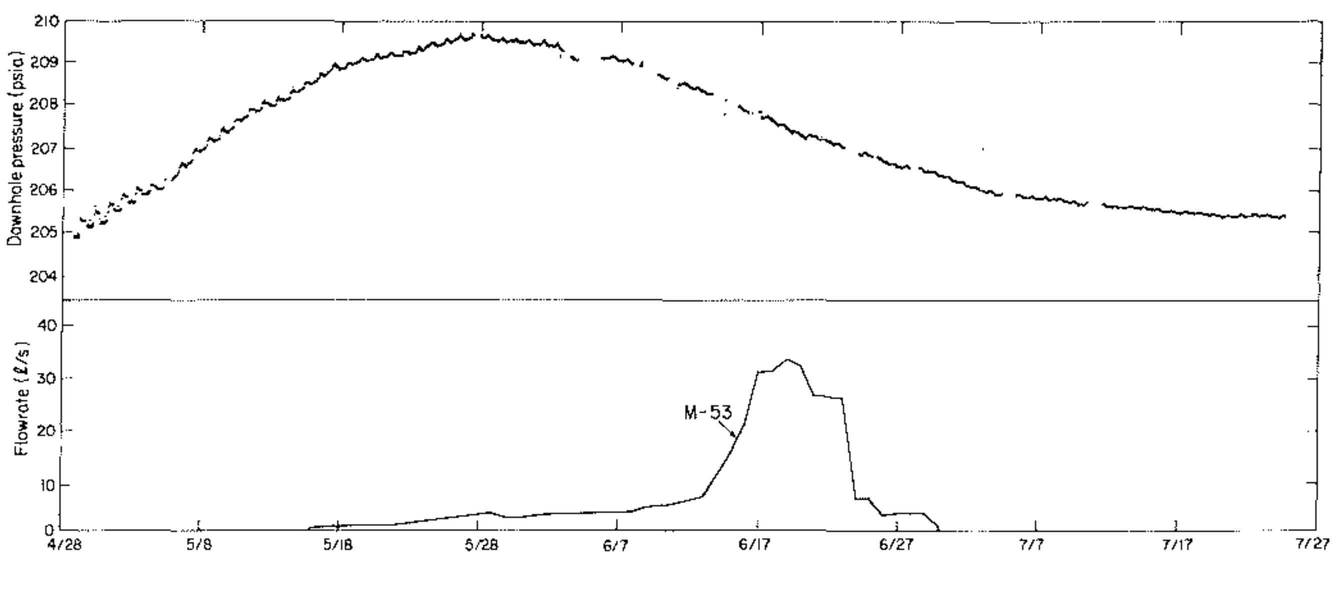


Figure 33. M-104 interference data (M-53 interference test).

Resource Description

The Susanville geothermal resource is located in northeast California, at the intersection of three major physiographic provinces: the Modoc Plateau, the Sierra Nevada, and the Basin and Range (Fig. 34). The 17 Susanville wells and heat flow holes drilled to date (1982) penetrate Holocene alluvium and Pleistocene Lahontan sediments, interbedded with Plio-Pleistocene basalts and andesites.

Interpretation of data from well logs, well tests and geophysical surveys indicates the presence of a fault-related reservoir of high permeability, low porosity, shallow depth (200 m), limited thickness and limited lateral extent. Most likely, both sedimentary and fractured basaltic units contribute to well production. Maximum temperatures in the wells range from 35° to 85°C. Well depths range from 127 m to 636 m. See Figure 35 for well locations, and Table 21 for a summary of resource characteristics. The wells listed are those used in the LBL tests.

A well in a second geothermal site (Wendel Hot Springs, in the Wendel-Amedee area), located approximately 20 miles southeast of Susanville, was also tested (Fig. 34). The well, approximately 2600 m deep, penetrates the granitic basement rock underlying the shallow geothermal anomaly of Susanville.

[abstracted from Benson et al., 1980a and Benson, 1982a]

Well Tests

Two interference tests were conducted at the Susanville geothermal field between July 1978 and January 1979. A third test, the WEN-1 production test, was conducted in March 1982 in the Wendel-Amedee area. The tests are described below. All information has been abstracted from a report prepared by the principle investigators. More complete information can be obtained from this source, as indicated in the individual sections.

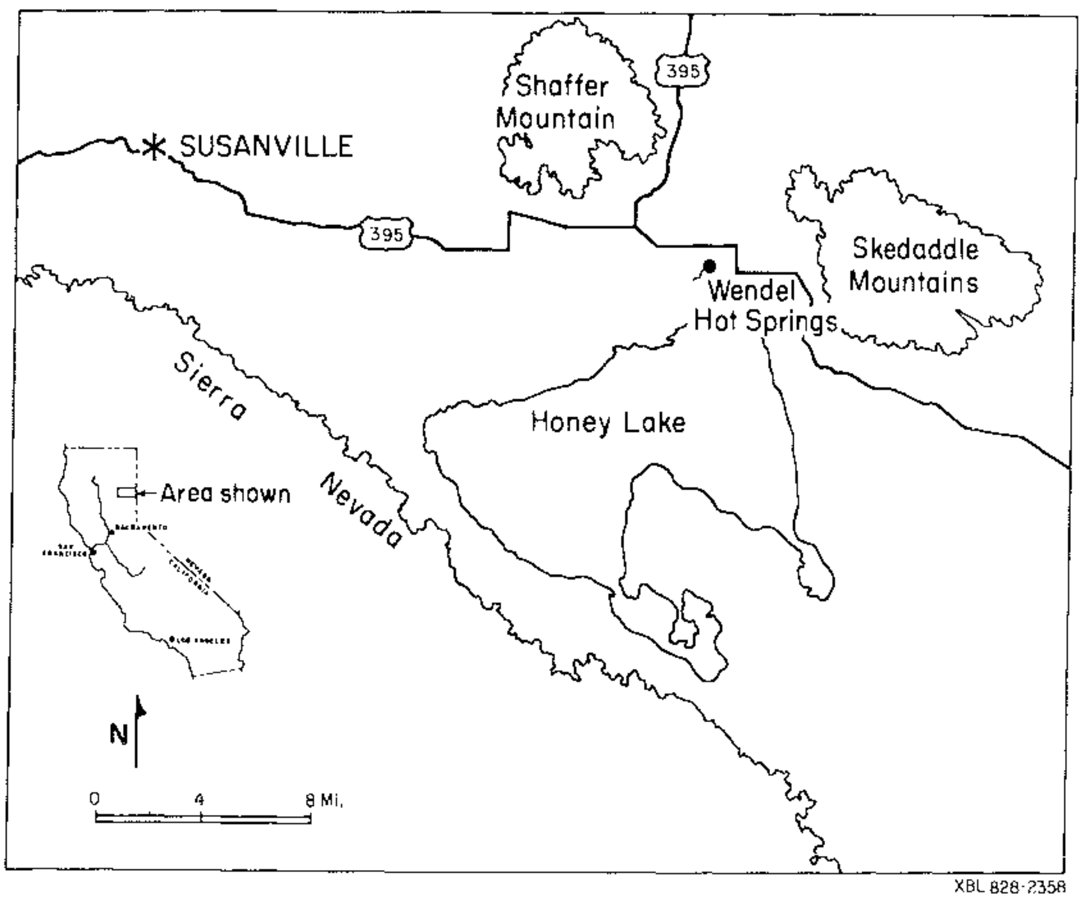
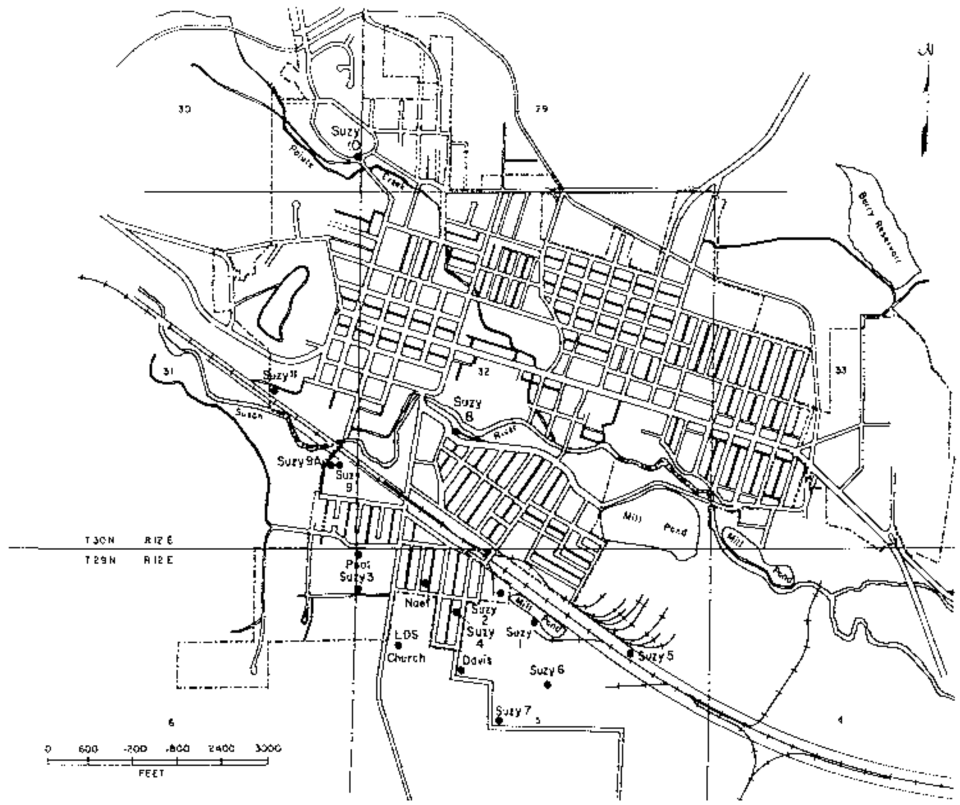


Figure 34. Location map, Susanville geothermal resource and Wendel-Amedee Hot Springs.



XBL 801 6767

Figure 35. Well location map, Susanville geothermal resource.

Table 21. Susanville geothermal resource, California.

Location:	Susanville, California
Reservoir Temperature:	35° - 85°C
Geologic Setting:	Holocene alluvium and Pleistocene Lahontan sediments, interbedded with Plio-Pleistocene basalts and andesites
Fluid Characteristics:	Non-artesian; liquid water
Test Wells and Approximate Depths:	

Suzy 1	271 m	Naef	127 m	Suzy 8	161 m
Suzy 2	512 m	Davis	192 m	Suzy 9	136 m
Suzy 3	636 m	LBL#2	152 m	Suzy 9a	249 m
Suzy 4	234 m	Swimming Pool	335 m	Suzy 10	197 m
Suzy 5	225 m	LDS Church	175 m	Suzy 11	243 m
Suzy 6	190 m	Suzy 7	224 m	WEN-1	1779 m

LDS Church Well Interference Test (July 26-November 29, 1978)

The LDS Church well is pumped intermittently year-round. Beginning in July 1928, interference effects from the Church well production were monitored in the Naef well, approximately 950 m away (Fig. 36 and Table 22). The production rate of the Church well, which has no flow measurement device, was measured using a stopwatch and a bucket. The drawdowns observed in Figure 36 result from the LDS Church well production.

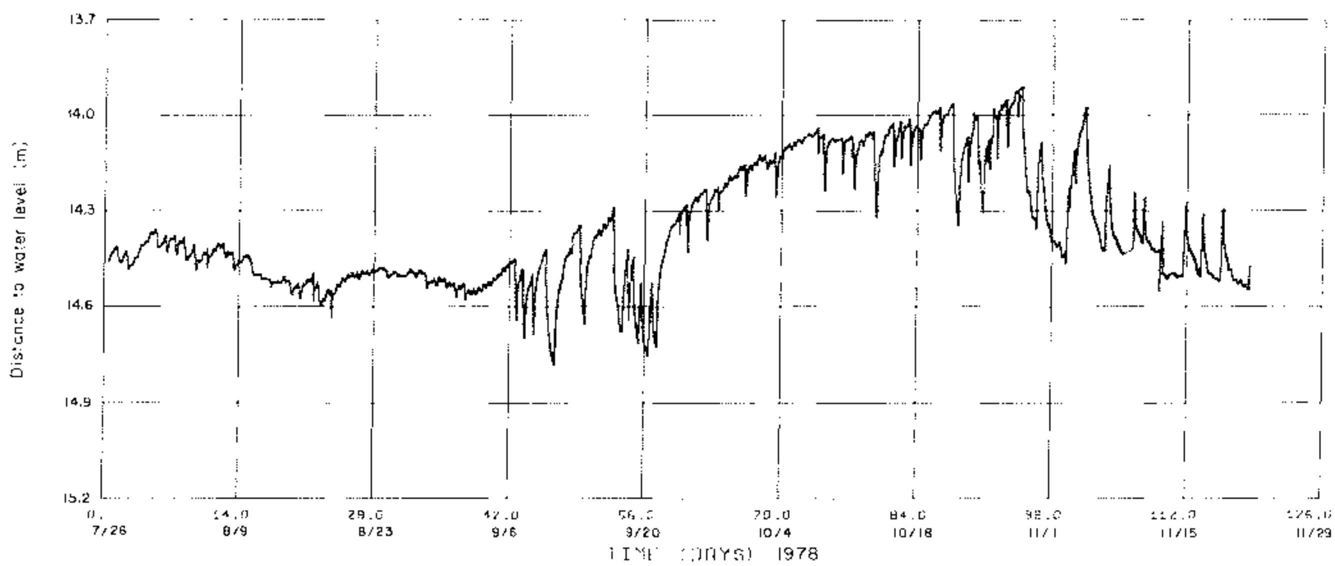
Interference effects were monitored in the Naef well using a Leupold-Stevens Type A continuously recording water level device. The water level recorder was left on the Naef well for a period of 4 months, during which time many drawdown and recovery episodes were recorded. A maximum pressure drawdown of approximately 0.7 psi was recorded during the test. The analysis indicated the possible presence of a barrier boundary in the vicinity of the Naef well.

[abstracted from Benson et al., 1980a]

Table 22. LDS Church Well Interference Test, July 26 - November 29, 1978.

WELL	TEST DESCRIPTION			INSTRUMENTATION	ANALYSIS *	
Classification	Fluid Flow	ΔP (psi)	Distance to Production Well(s) (m)	(P) Pressure (T) Temperature (Q) Flowrate	kh/μ md·ft/cp (m^3/Pa·s)	ϕch ft/psi (m/Pa)
LDS Church Well production	intermittent year-round @ ~ 6 l/s			(Q) stopwatch and container		
Naef Well observation		0.7	315	(P) L.-S. water level recorder †	3.6×10^6 (1.1×10^{-6}) possible barrier boundary	2.3×10^{-4} (1.0×10^{-8})

* computer-assisted analysis
† in non-artesian wells, pressure changes are recorded by measuring changes in water level in the wells



XBL 795-7492

Figure 36. Naef well interference data (Church well interference test).

Davis Well Interference Test
(December 10, 1978 - January 8, 1979)

In December 1978, the Davis Well was flowed for 9 days at an approximate flow rate of 16 l/s, while interference effects were monitored in the Davis well and seven other wells: Suzy 1, 2, 3, 4, and 5, Naef, and Lassen Lumber and Box #2 (Figs. 37 -41 and Table 23). The LSD Church well was flowed intermittently throughout the test at approximately 5.7 l/s. See Figure 35 and Table 23 for well locations and distances to the production well(s).

Reservoir pressures were monitored in the wells for approximately one week before the Davis well was flowed, during production, and for 18 days after the well was shut in. On the 19th day (1/6/79) the Swimming Pool well was opened for 3 days of production at a flowrate of approximately 17 l/s. It is thought that this well produces from a different zone. Interference effects were monitored in all the observation wells with the instruments summarized in Table 23. Maximum drawdowns recorded in the observation wells were: 1.5 psi (Suzy 3), 2.0 psi (Suzy 4), 1.7 psi (Naef), and 0.5 psi (LLB#2). Due to excessive background noise, the data from Suzy 1, 3, and 5 were unsuitable for analysis. Data from wells Suzy 4 and LLB#2 were unsuitable for standard analysis due to unexplained pressure behavior in the wells.

[abstracted from Benson et al., 1980a]

Table 23. Davis Well Interference Test, December 10, 1978 - January 8, 1979.

WELL Classification	TEST DESCRIPTION Fluid Flow	ΔP (psi)	Distance to Production Well(s) (m)	INSTRUMENTATION (P) Pressure (T) Temperature (Q) Flowrate	ANALYSIS * kh/μ md·ft/cp (m^3/Pa·s)	ch ft/psi (m/Pa)
Davis production	9 days @ 16 l/s			(P) Paros. with 15 m of nitrogen gas-filled 0.32-cm I.D. tubing (T) RTD (Q) orifice plate and pitot tube	7.3×10^5 (2.2×10^{-7})	
Swim. Pool production	3 days @ 17 l/s			(Q) pump curves		
LDS Church production	29 days @ 5.7 l/s intermittent			(Q) stopwatch and container		
Suzy 3 observation		1.5	592 (to Davis) 150 (to Swim.P) 325 (to Church)	(P) Paros. with nitrogen gas-filled 0.96-cm I.D tubing to 76-m depth		
Suzy 4 observation		2.0	260 (to Davis) 465 (to Swim.P) 313 (to Church)	(P) Paros. downhole (152 m)		
Naef observation		1.7	380 (to Davis) 430 (to Swim.P) 315 (to Church)	(P) L.-S. water- level recorder †	2.3×10^6 (6.9×10^{-7}) possible barrier boundary	7.2×10^{-4} (3.2×10^{-8})
LLB #2 observation		0.5	818 (to Davis) 1530 (to Swim.P) 1160 (to Church)	(P) H.P. downhole (130 m) (T) G.O. downhole (130 m)		

* semilog (Davis well) and computer-assisted (Naef well) analysis
† in nonartesian wells, pressure changes are recorded by measuring changes in water level in the wells

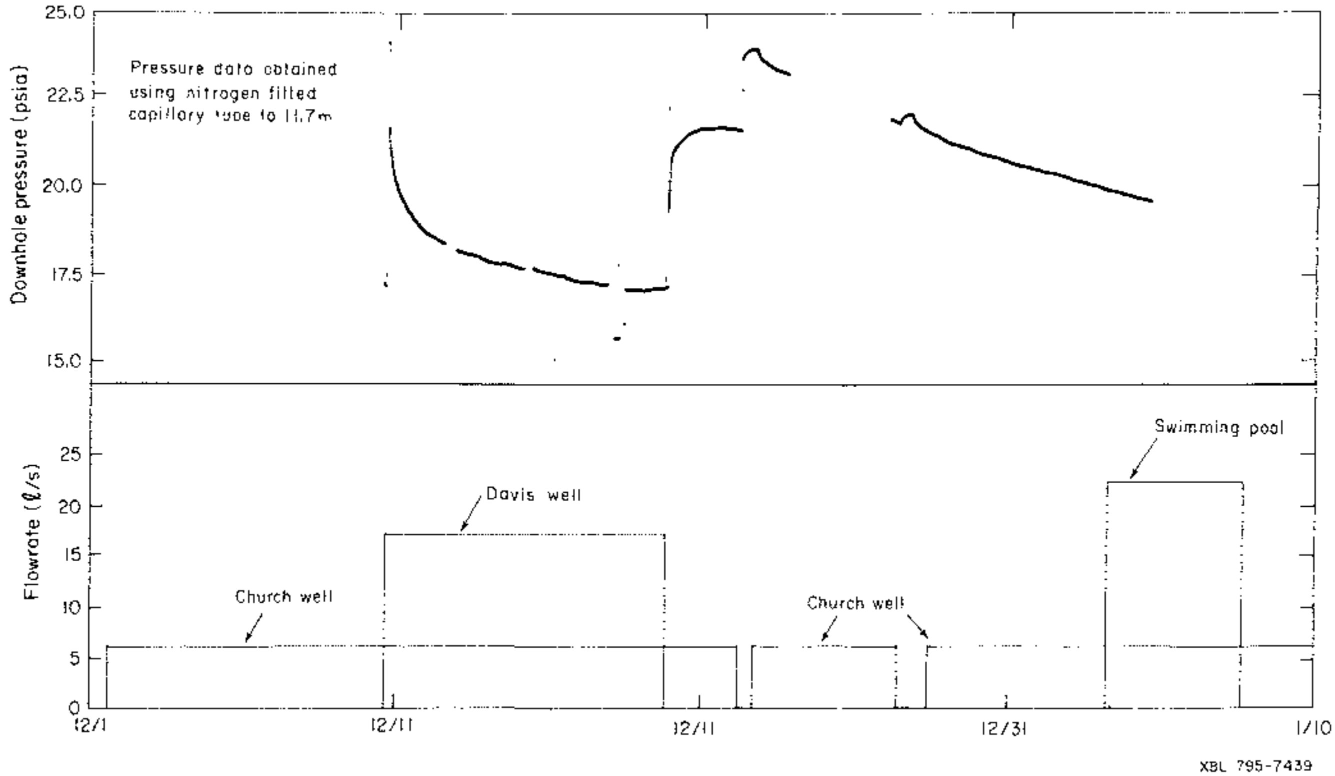


Figure 37. Davis well production data (Davis well interference test).

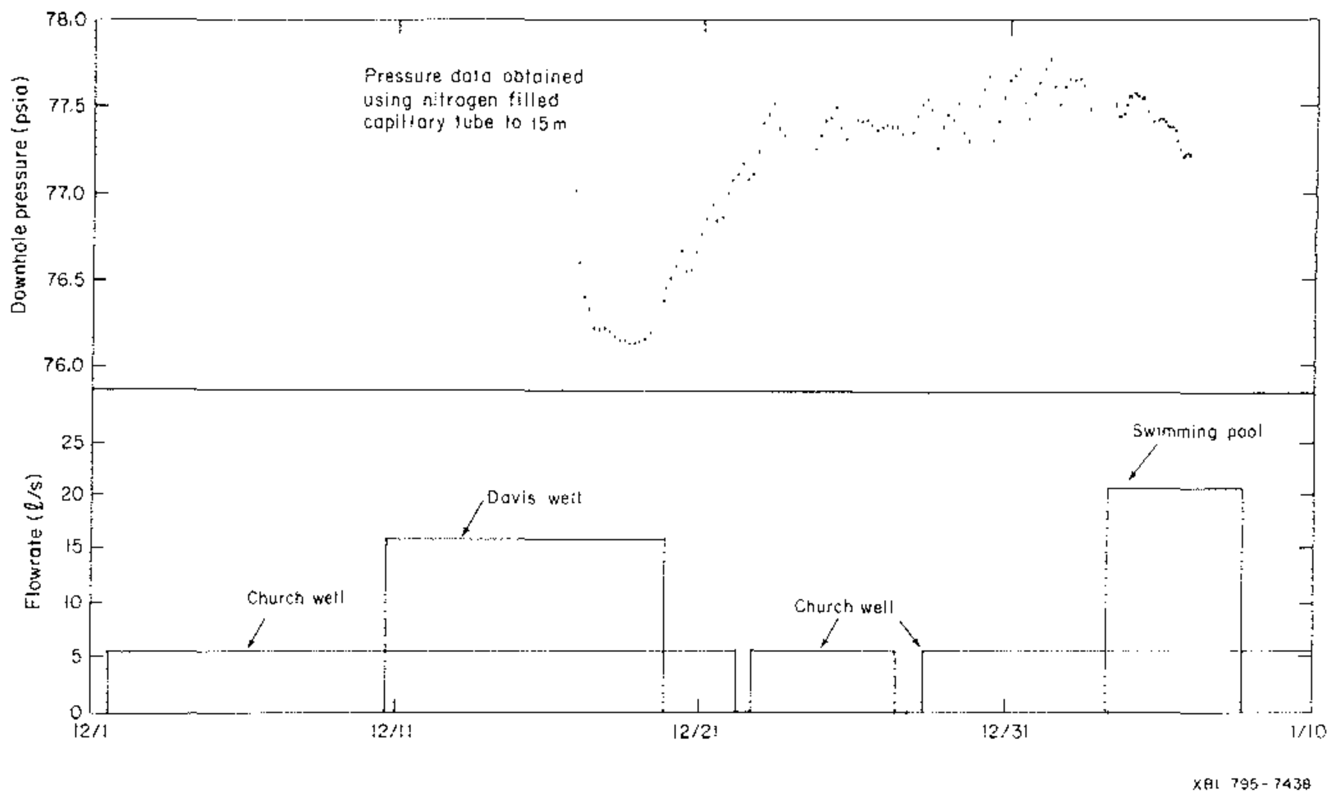


Figure 38. Suzy 3 interference data (Davis well interference test).

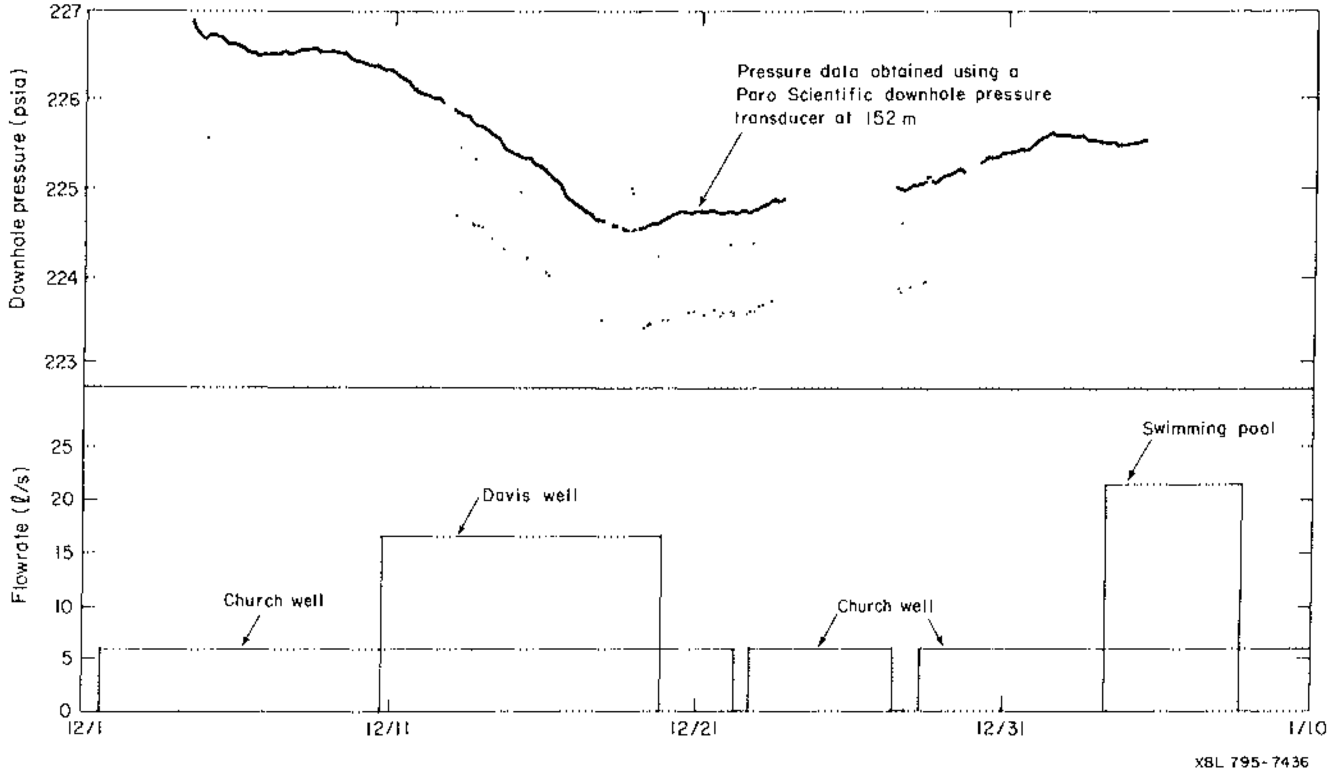


Figure 39. Suzy 4 interference data (Davis well interference test).

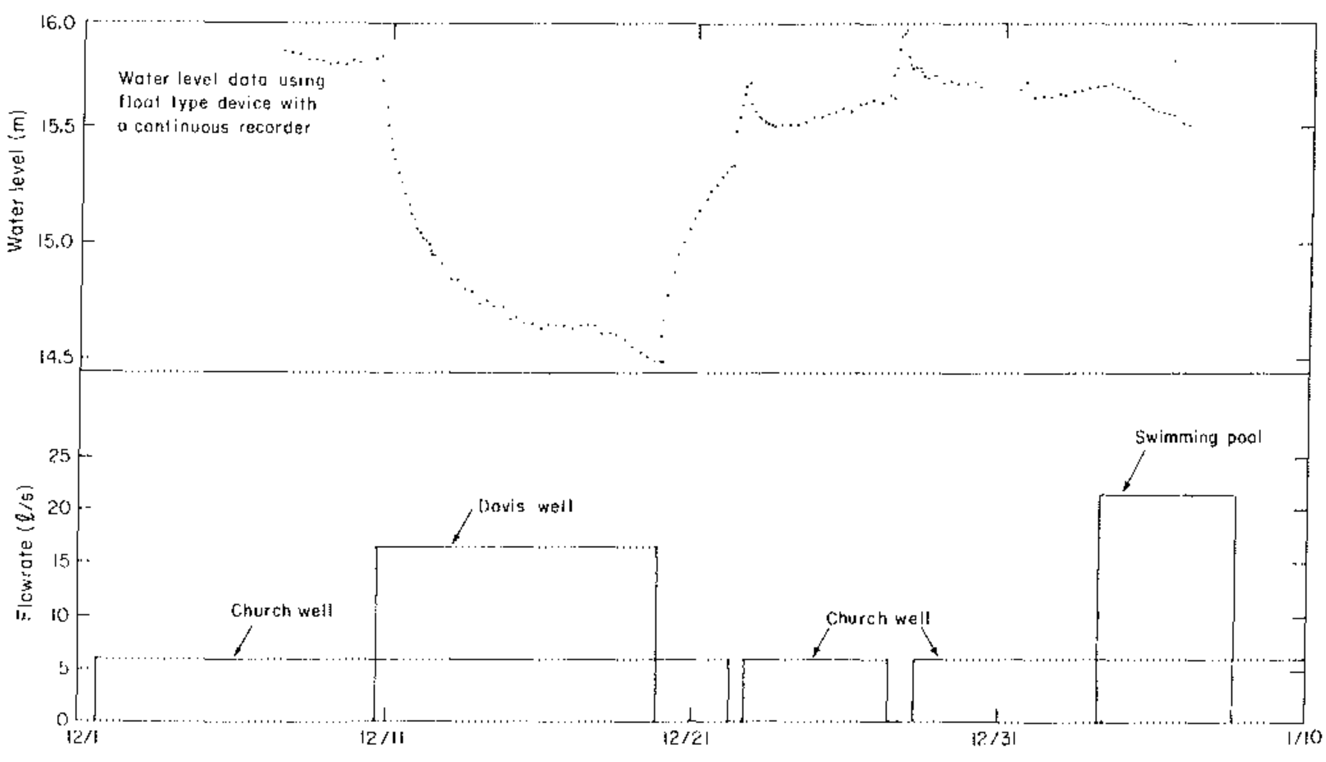


Figure 40. Naef well interference data (Davis well interference test).

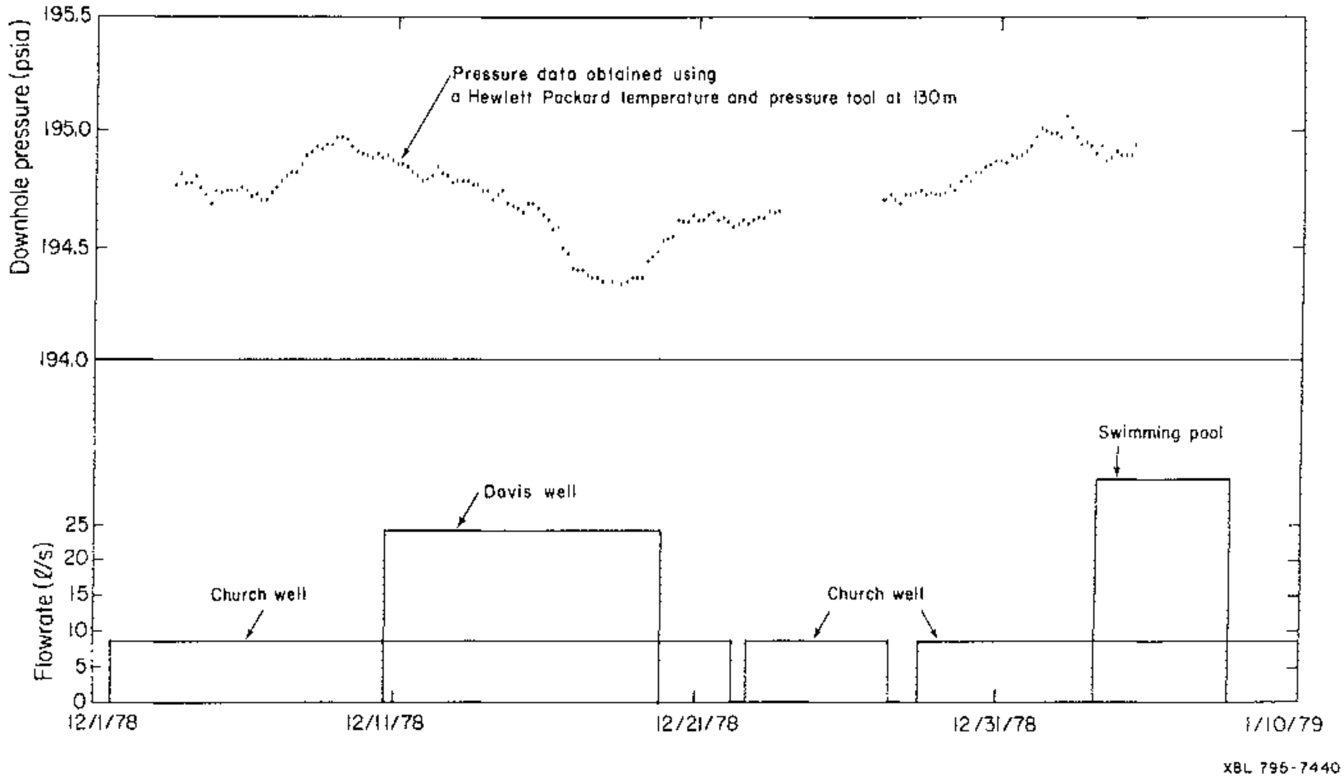


Figure 41. LLB #2 interference data (Davis well interference test).

WEN-1 Production Test (March 3-7, 1982)

Well WEN-1 was produced for five days at stepwise variable (artesian) flowrates of 13, 27, 42, and 39 l/s (see Fig. 42 and Table 24). The first three rates were held constant for 12 hours each, and the third rate for 75 hours. Pressure and temperature measurements were recorded at the wellhead and downhole for the duration of the test and for approximately 12 hours after the well was shut in. Downhole pressure data were obtained with a Hewlett Packard quartz crystal gauge, and wellhead pressure was measured with a Paroscientific gauge. Downhole and wellhead temperatures were measured with a Gearhart-Owen temperature gauge, and a thermocouple, respectively. Flow rates were measured with an orifice plate and differential pressure gauge.

Semilog analysis of drawdown data indicates a reservoir transmissivity of approximately 3.3 x 10^6 md·ft/cp (9.9 x 10^{-7} m^3/Pa·s). The Productivity Index ($Q/\Delta P$) for this well varied with each change in flow rate, indicating non-Darcy flow in the reservoir.

[abstracted from Benson, 1982a]

Table 24. WEN-1 Production Test, March 1-8, 1982.

WELL Classification	TEST DESCRIPTION Fluid Flow	ΔP (psi)	INSTRUMENTATION (P) Pressure (T) Temperature (Q) Flowrate	ANALYSIS * kh/μ md·ft/cp (m^3/Pa·s)	ϕch ft/psi (m/Pa)
WEN-1 production	5 days stepwise variable @ 13, 27, 42, 39 l/s	31.5	(P) H.P. downhole Paros at wellhead (T) G.O. downhole thermocouple at wellhead (Q) orifice plate	3.3 x 10^6 (9.9 x 10^{-7}) P.I. = 4.5 x 10^{-7}, 2.7 x 10^{-7} 2.0 x 10^{-7}, 2.1 x 10^{-7} m^3/s·Pa †	

* semilog analysis
† appears to be non-Darcy flow in reservoir

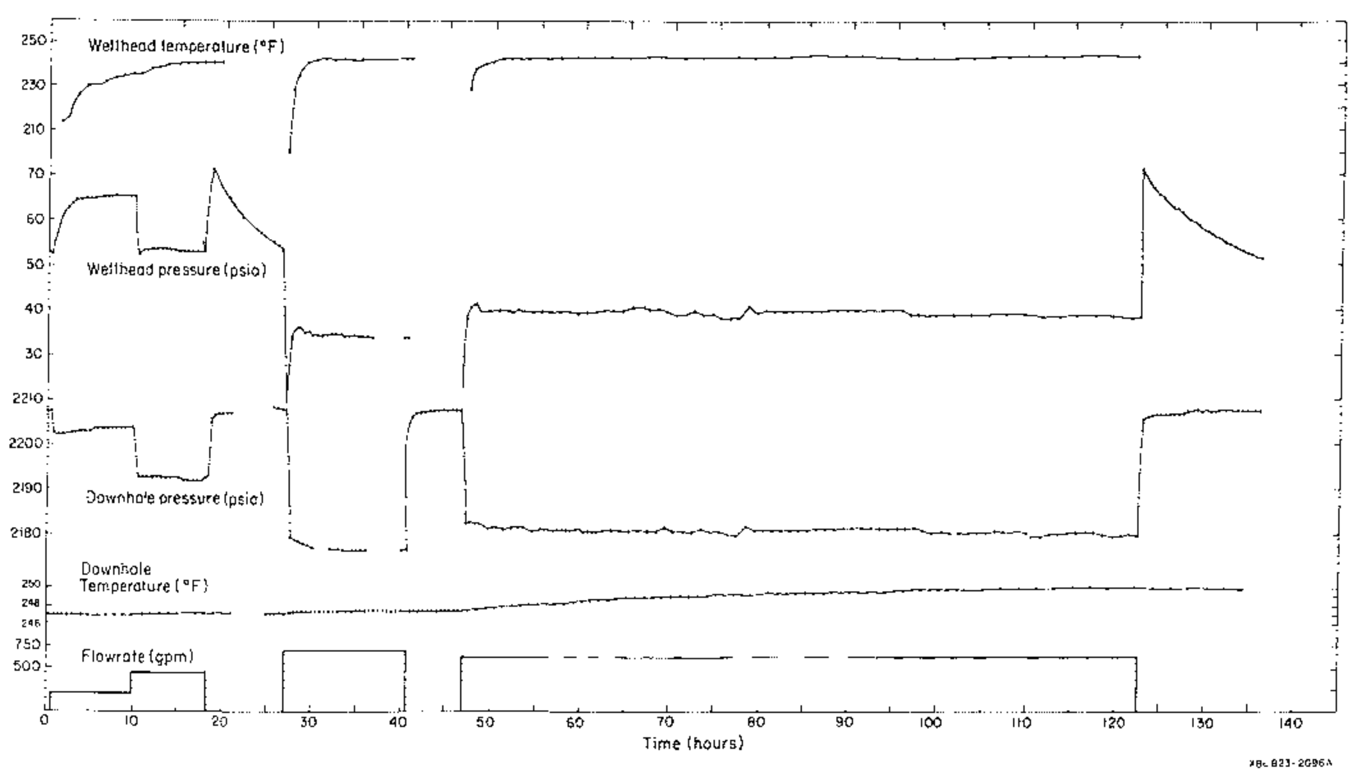


Figure 42. WEN-1 production data (WEN-1 production test).

Resource Description

The Klamath Falls geothermal resource, located in south-central Oregon, is situated in a horst and graben structure of the Basin and Range Province (Fig. 43). The subsurface lithology consists of alternating layers of basalt flows, lake sediments, volcanic ash, and tuff. The stratigraphy is complex, with considerable faulting, fracturing and thermal alteration.

A shallow geothermal anomaly (< 200 m depth) hydrologically described as a highly permeable, fractured network interspersed with distinct rock units, produces 60° - 110°C fluids. Roughly 400 wells penetrate the formation, producing geothermal energy for heating homes, swimming pools, and businesses. Figure 44 shows only those wells tested by LBL. See Table 25 for a summary of resource characteristics and wells used in the LBL tests.

[abstracted from Benson et al., 1980b and O'Brien and Benson, 1981]

Well Tests

In order to assess the potential and nature of the Klamath Falls geothermal resource, LBL conducted several interference tests in the resource from late 1979 through early 1982. These tests are described below. All information has been abstracted from LBL reports, as indicated.

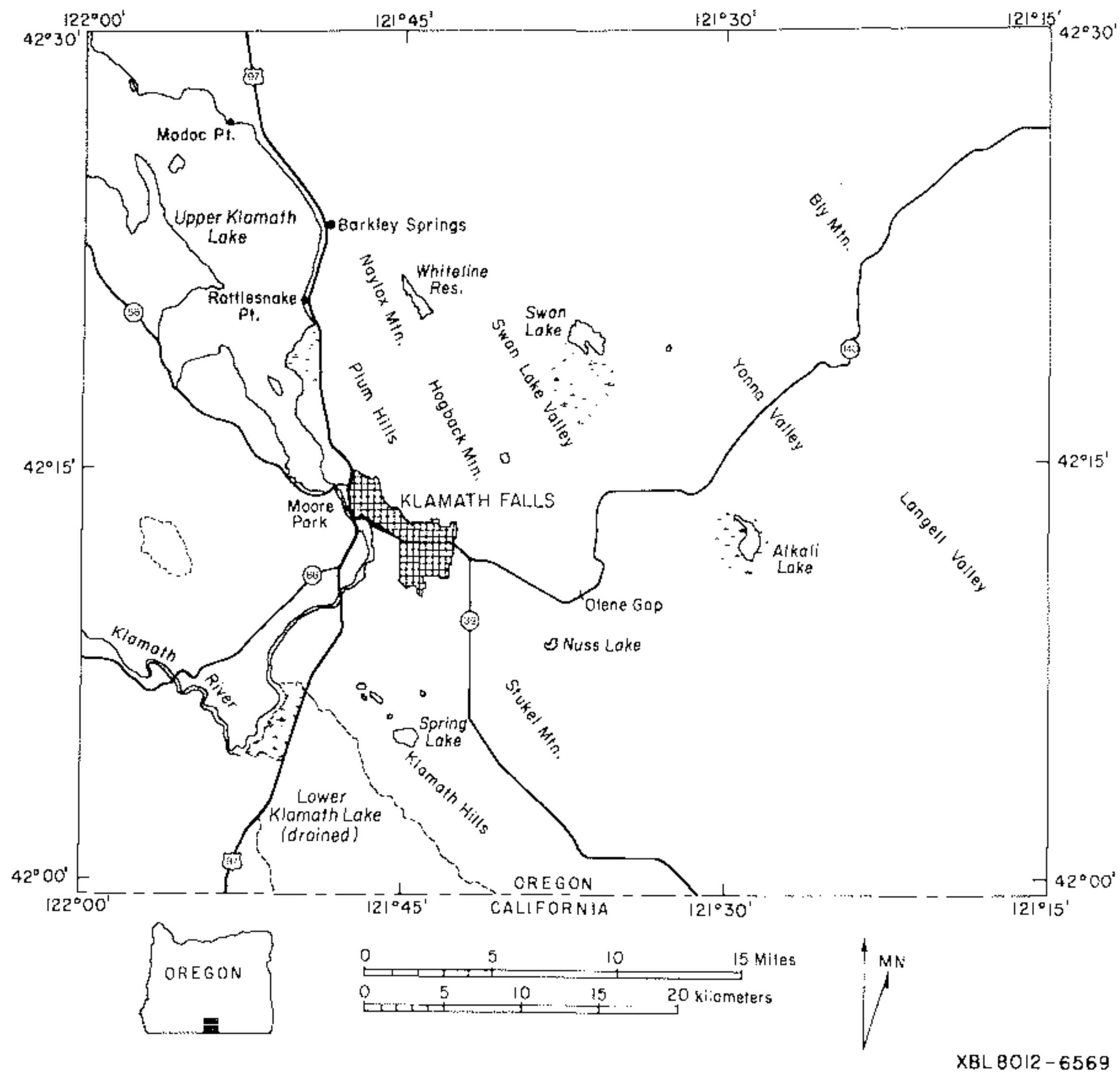


Figure 43. Location map, Klamath Falls geothermal resource.

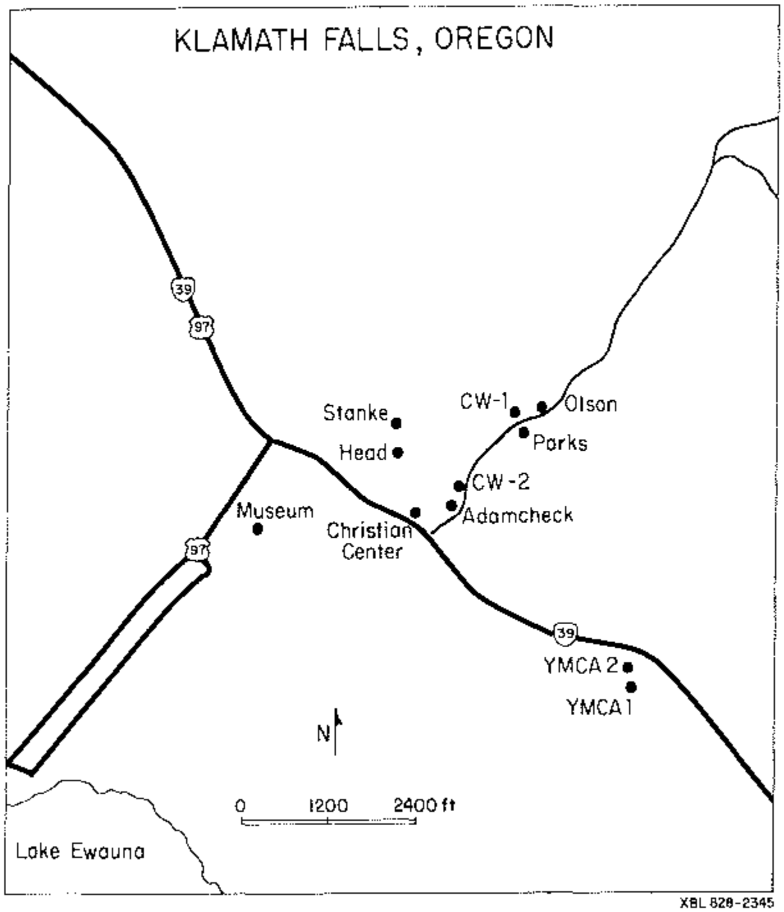


Figure 44. Well location map, Klamath Falls geothermal resource.

Table 25. Klamath Falls geothermal resource, Oregon.

Location:	Klamath Falls, south-central Oregon				
Reservoir Temperature:	60° - 110°C				
Geologic Setting:	Alternating layers of basalt flows, lake sediments, volcanic ash and tuff with considerable faulting, fracturing, and thermal alteration				
Fluid Characteristics:	Nonartesian; liquid water				
Test Wells and Approximate Depths:	City Well #1	110 m		Glen Head	76 m
	City Well #2	302 m		Olson	91.5 m
	YMCA Well #2	367 m		Stanke	52.3 m
	Parks	272 m		Christian Center	N/A
	Adamcheck	71 m			

YMCA #2 Interference Test (October 2, 1979)

YMCA Well #2 was pumped for 9.5 hours at stepwise variable rates of 16.4, 19.5, and 12.6 l/s while interference effects were monitored in YMCA Well #1, located 150 m away (Fig. 45 and Table 26). Approximately one week of background data were recorded in the observation well by a Paroscientific pressure transducer set at a depth of 245 m. A maximum drawdown of 3.8 psi was recorded during production.

In the production well, a maximum fluid temperature of 88°C was recorded. A Productivity Index ($Q/\Delta P$) of 3.2×10^{-8} $m^3/s \cdot Pa$ was obtained for this well.

[abstracted from Benson, 1982b]

Table 26. YMCA #2 Interference Test, October 2, 1979.

WELL Classification	TEST DESCRIPTION Fluid Flow	ΔP (psi)	Distance to Production Well(s) (m)	INSTRUMENTATION (P) Pressure (T) Temperature (Q) Flowrate	ANALYSIS * kh/μ md·ft/cp (m^3/Pa·s)	φch ft/psi (m/Pa)
YMCA #2 production	9.5 hrs stepwise variable @ 16.4-19.5-12.6 l/s			(T) mercury thermometer at wellhead (Q) orifice plate	P.I. = 3.2×10^{-8} $m^3/s \cdot Pa$	
YMCA #1 observation		3.8	152	(P) Paros. downhole (245 m)	6.4×10^5 (1.9×10^{-7}) possible barrier boundary	4.0×10^{-4} (1.8×10^{-8})

* computer-assisted analysis

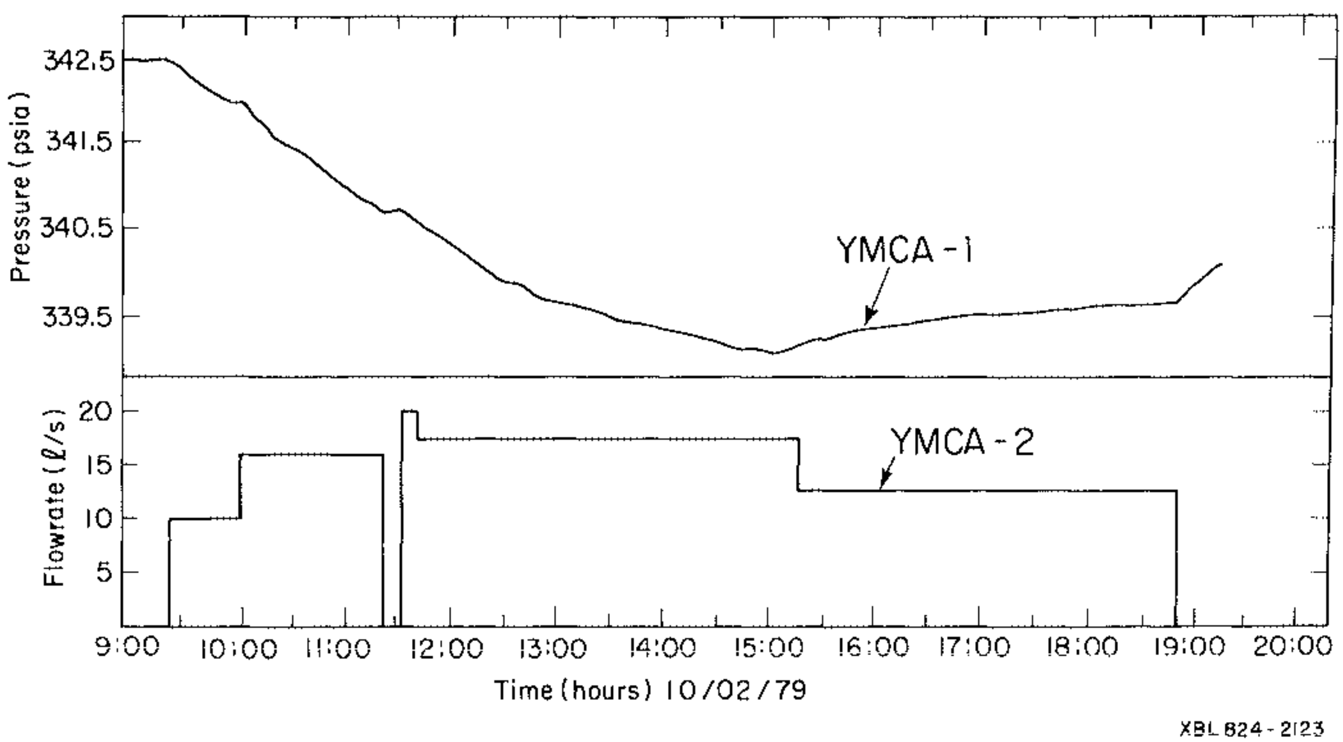


Figure 45. YMCA #1 interference data (YMCA #2 interference test).

City Well #1 Interference Test (October 24-25, 1979)

This test involved pumping City Well #1 at stepwise variable rates of 16, 30, 35 and 43 l/s, for a total of 15 1/2 hours, while interference effects were monitored in the Parks, Adamcheck and Glen Head wells, 55 m, 305 m, and 430 m away, respectively (Figs. 46 and 47 and Table 27). A maximum flowrate of 43 l/s was held constant for 7 1/2 hours, during which a maximum drawdown of 33 psi was recorded in the well by electric probe. A Productivity Index ($Q/\Delta P$) of 2.0×10^{-7} $m^3/s \cdot Pa$ was obtained for this well.

Water-level changes in the Adamcheck and Glen Head wells were monitored with Leupold-Stevens continuous-recording water-level devices. A downhole Paroscientific pressure transducer was used in the Parks Well. Background data were obtained from the wells for several months prior to the test. Analyses of data indicate extremely high reservoir permeability, which is attributed to the fractured nature of the reservoir rock.

[abstracted from Benson et al., 1980b and Benson, 1982b]

Table 27. CW-1 Interference Test, October 24-25, 1979.

WELL Classification	TEST DESCRIPTION Fluid Flow	ΔP (psi)	Distance to Production Well(s) (m)	INSTRUMENTATION (P) Pressure (T) Temperature (Q) Flowrate	ANALYSIS * kh/μ md·ft/cp (m^3/Pa·s)	ϕch ft/psi (m/Pa)
CW-1 production	15.5 hrs stepwise variable @ 16-30-35-43 l/s	33		(T) RTD at wellhead (Q) orifice plate and bourdon tube		
Parks observation		0.52	55	(P) Paros. downhole	3.3×10^7 (9.9×10^{-6} possible barrier boundary	9.1×10^{-4} (4.0×10^{-8})
Adamcheck observation		0.25	305	(P) L.-S. water-level recorder †	2.6×10^7 (7.8×10^{-6}) possible barrier boundary	1.1×10^{-3} (4.8×10^{-8})
Glen Head observation		0.25	430	(P) L.-S. water-level recorder †	1.7×10^7 (5.1×10^{-6})	1.4×10^{-3} (6.2×10^{-8})

* type curve analysis

† in nonartesian wells, pressure changes are recorded by measuring changes in water level in the wells

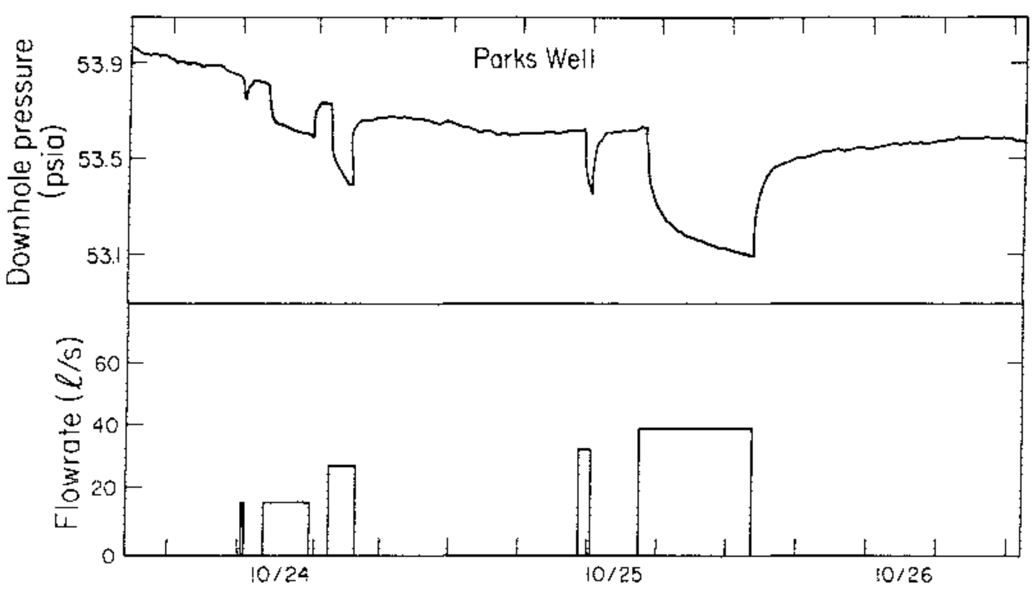


Figure 46. Parks well interference data (CW-1 interference test).

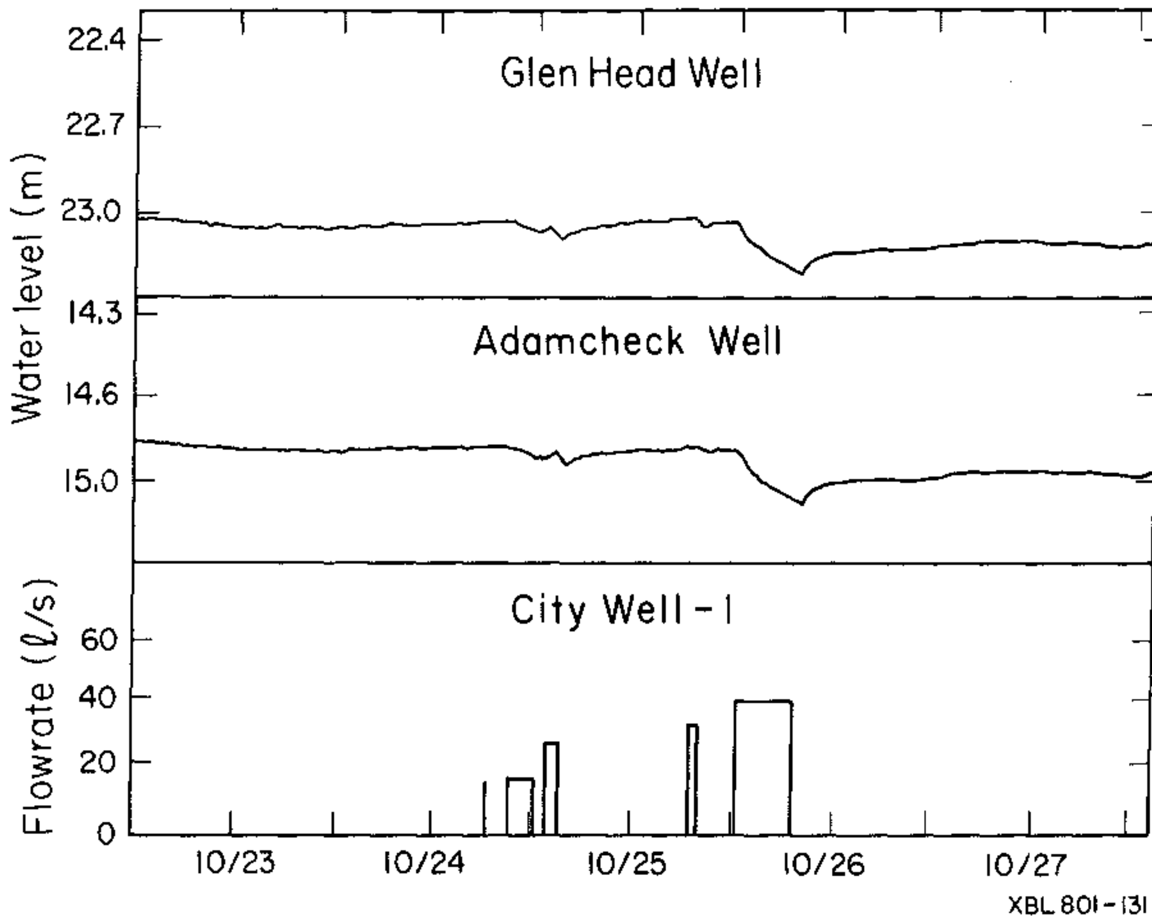


Figure 47. Glenhead/Adamcheck interference data (CW-1 interference test).

City Well #1 /City Well #2 Interference Test (September 29-30, 1981)

City Well #1 (CW-1) and City Well #2 (CW-2) were pumped at intermittent, variable flowrates for a combined total of 16 hours, over a period of 2 days. Pressure changes at the Parks, Olson, Christian Center and Stanke wells were monitored continuously for one day prior to production, throughout the test, and for 14 hours after the test (Figures 48-50 and Table 28). Distances between these wells and the two production wells can be found in Table 28. Drawdown and water-level changes in the observation wells were measured with a sensitive Paroscientific Digiquartz transducer.

For the first day of the test, CW-1 and CW-2 were produced independently of each other, with CW-1 stabilizing at 31.5 l/s, and CW-2 at 48-50.5 l/s. On day 2, both wells were pumped at a combined rate of 60.5-62.0 l/s. Concurrent to the pumping of CW-1 and CW-2, the produced fluid was reinjected into the County Museum well.

The very small pressure drawdown, seasonal pressure transients (see Figs. 48-50) and variable flowrates made analysis difficult. Only the data from the Parks well were suitable for conventional analysis. The reservoir transmissivity was calculated as 2.7×10^7 md-ft/cp and the storativity, 2.5×10^{-3} ft/psi.

[abstracted from Benson, 1982b]

Table 28. CW-1/CW-2 Interference Test, September 29-30, 1981.

WELL	TEST DESCRIPTION			INSTRUMENTATION	ANALYSIS *	
Classification	Fluid Flow	Δp (psi)	Distance to Production Well(s) (m)	(P) Pressure (T) Temperature (Q) Flowrate	kh/μ md·ft/cp (m^3/Pa·s)	φch ft/psi (m/Pa)
CW-1 Production	9/29/81 4 hours highly variable (0-31 l/s) 9/30/81 5 hours 23 l/s †			(P) Bourdon tube at wellhead (T) thermocouple (Q) photoelectric turbine-type flow meter		
CW-2 Production	9/29/81 2 hours 48 l/s 9/30/81 5 hours 38 l/s †			(P) Bourdon tube at wellhead (T) thermocouple (Q) photoelectric turbine-type flow meter		
Parks Observation		0.6	45 m (to CW-1)	(P) Paros. downhole	2.7×10^7	2.5×10^{-3}
Olson Observation		0.13	185 m (to CW-1) 500 m (to CW-2)	(P) Paros. downhole		
Stanke Observation		0.2	425 m (to CW-1) 335 m (to CW-2)	(P) Paros. downhole		
Christian Center Observation		0.08	565 m (to CW-1) 290 m (to CW-2)	(P) Paros. downhole		

* computer-assisted analysis
† flow rate from 9/30/81 production estimated from combined flow rate of approximately 61 l/s

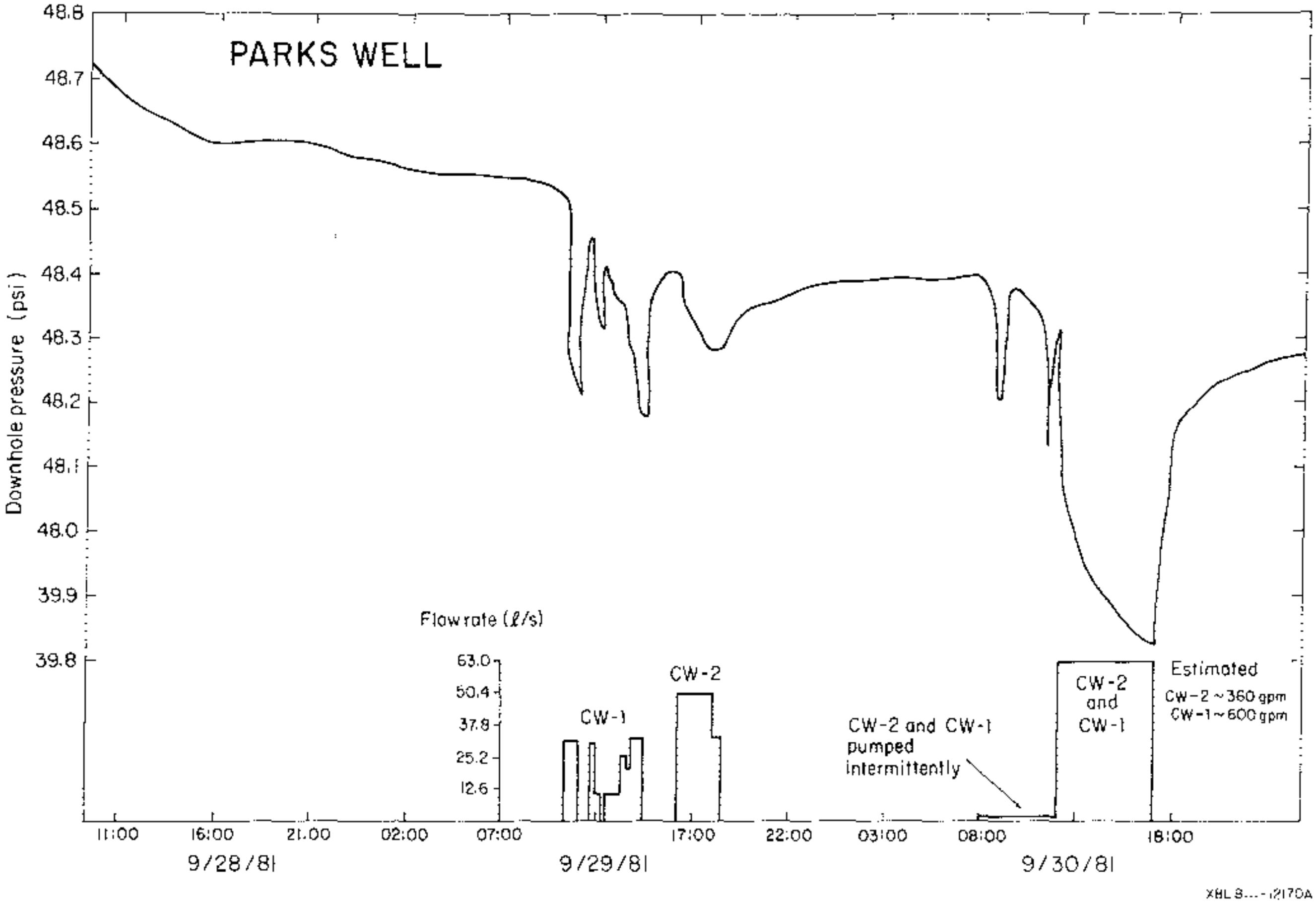


Figure 48. Parks well interference data (CW-1/CW-2 interference test).

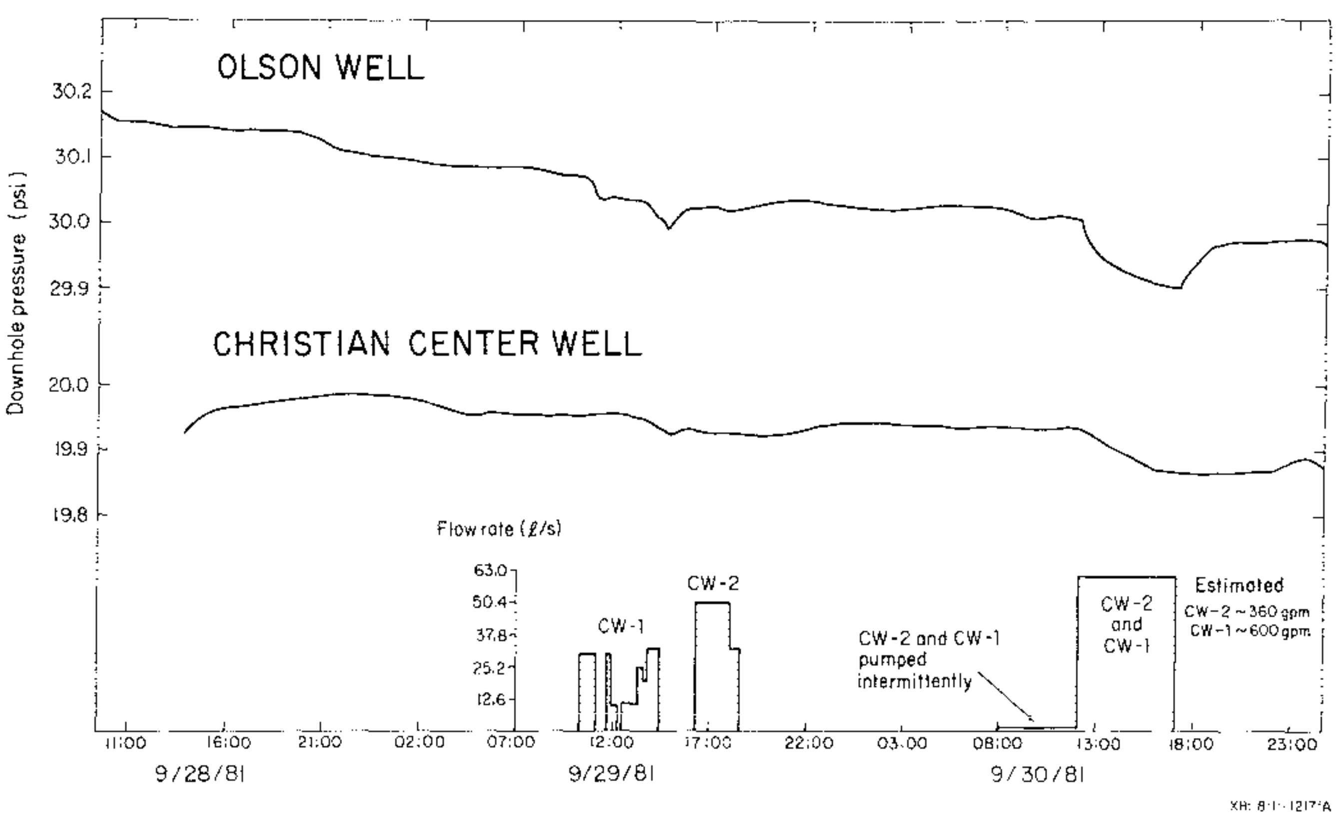


Figure 49. Olson/Christian Center interference data (CW-1/CW-2 interference test).

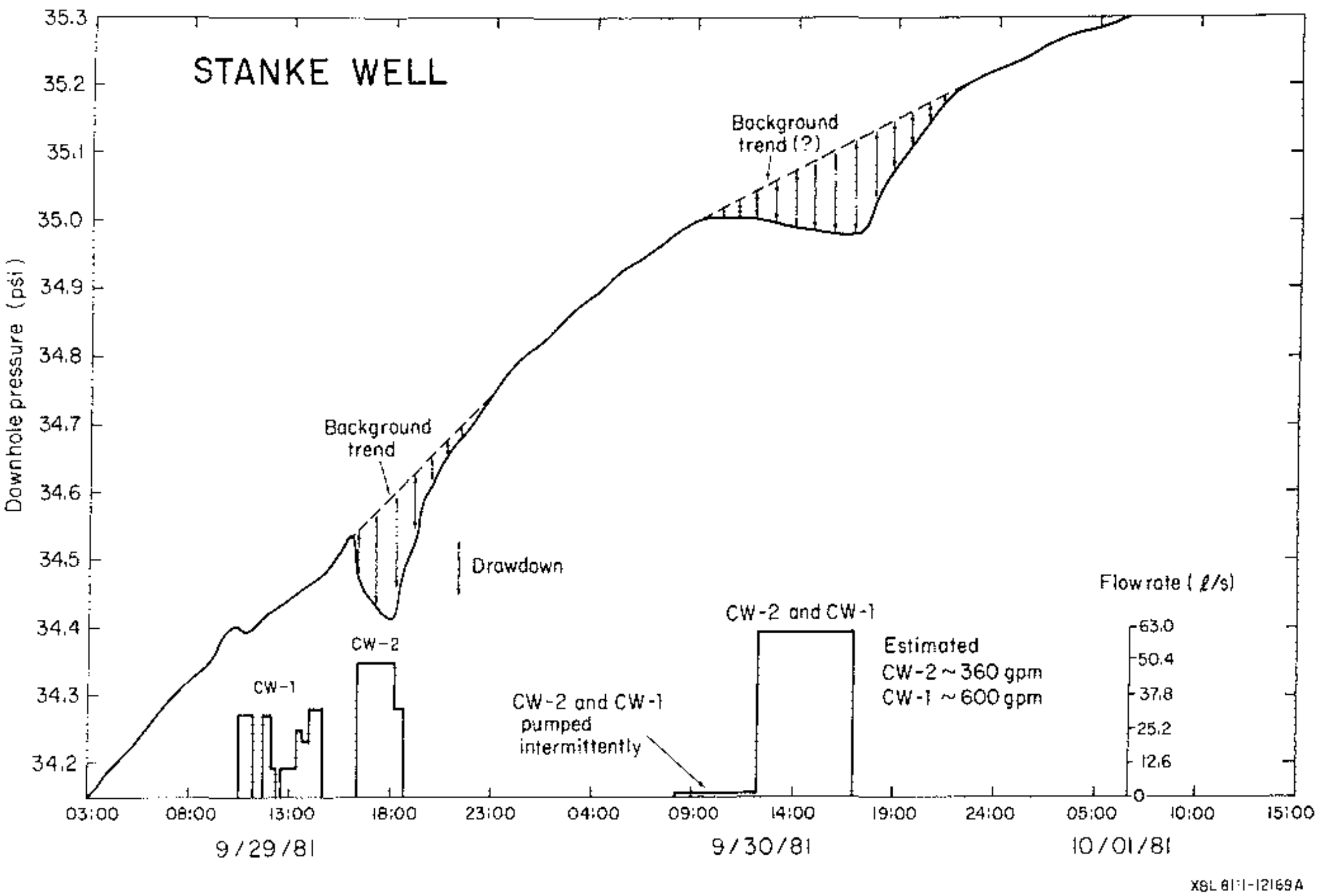


Figure 50. Stanke interference data (CW-1/CW-2 interference test).

City Well #2 Interference Test (February 8-12, 1982)

City Well #2 (CW-2) was produced for 92 hours at a constant rate of 34 l/s, while interference effects were observed in the Parks, Stanke, Olson, and Christian Center wells (see Fig. 51 and Table 29). These wells are located 305, 335, 500, and 290 m, respectively, from CW-2. The observation wells were monitored for 12 to 36 hours prior to production, during production, and for 4 days after CW-2 was shut in. (No buildup data was available for the Parks well due to equipment failure.) The produced fluid from CW-2 was injected into the County Museum well.

The observation wells were instrumented for pressure response with Paroscientific Digiquartz downhole transducers. Pressure drawdowns for the Parks, Stanke, Olson, and Christian Center wells were 0.3, 0.25, 0.1, and 0.13 psi, respectively. Pressure response was measured in the production well with a Bourdon tube wellhead gauge, which recorded a 1.95 psi drawdown. Analysis of drawdown data from the Parks, Stanke, and Christian Center wells indicate a reservoir transmissivity of approximately 2.0×10^7 md·ft/cp (6.0×10^{-6} m^3/s·Pa).

[abstracted from Benson, 1982b]

Table 29. CW-2 Interference Test, February 8-12, 1982.

WELL Classification	TEST DESCRIPTION Fluid Flow	ΔP (psi)	Distance to Production Well(s) (m)	INSTRUMENTATION (P) Pressure (T) Temperature (Q) Flowrate	ANALYSIS * kh/μ md•ft/cp (m^3/Pa•s)	ϕch ft/psi (m/Pa)
CW-2 Production	94 hrs @ 34 l/s	1.95		(P) Bourdon tube at wellhead (T) thermocouple (Q) photoelectric paddle wheel		
Museum Injection	94 hrs @ 34 l/s		838	(P) Bourdon tube at wellhead (T) thermocouple (Q) photoelectric paddle wheel		
Parks Observation		.3	305	(P) Paros. downhole	2.0×10^7 (6.0×10^{-6})	
Stanke Observation		.25	335	(P) Paros. downhole		
Olson Observation		.1	500	(P) Paros. downhole		
Christian Center Observation		.13	290	(P) Paros. downhole		

* semilog analysis

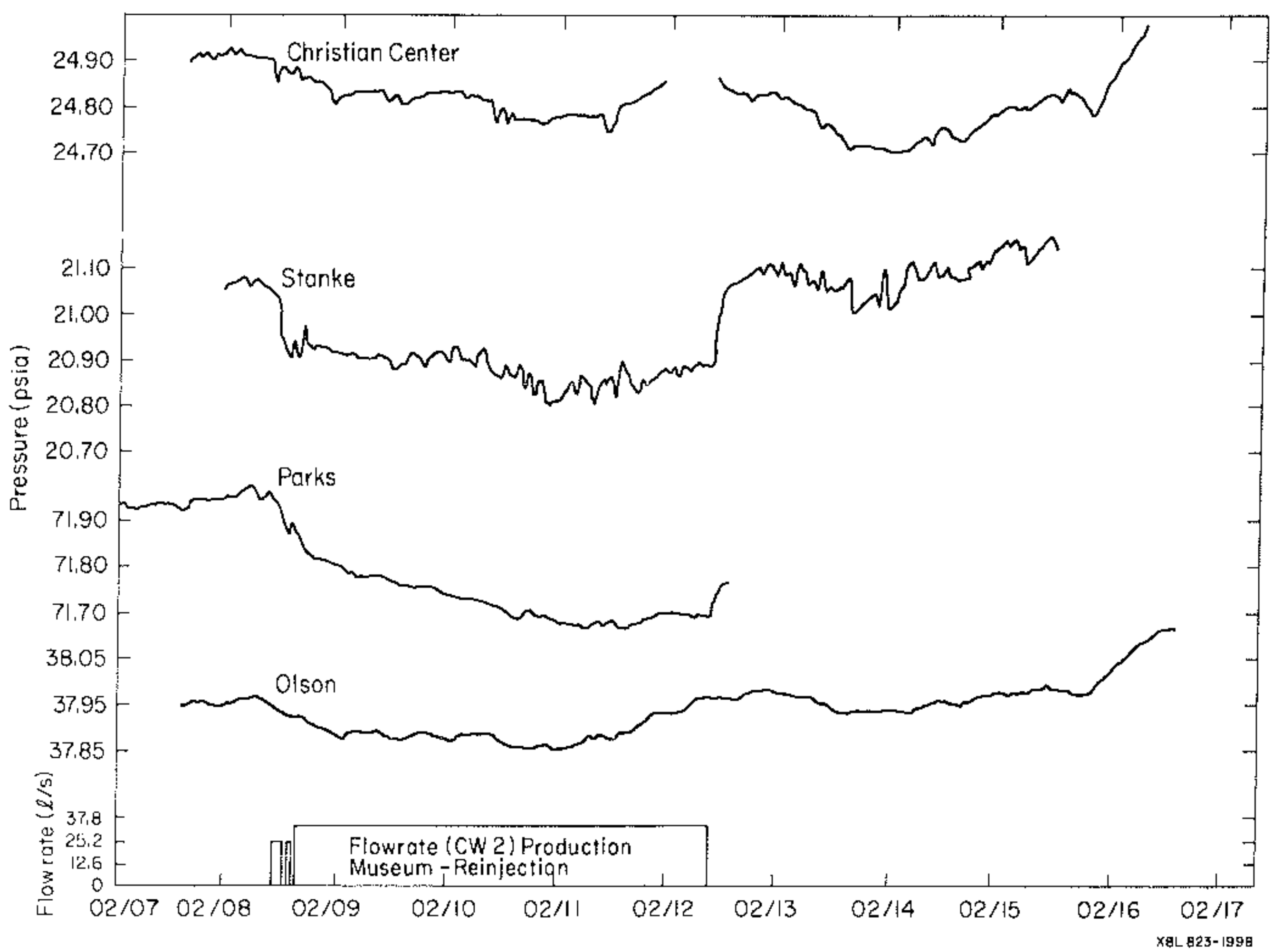


Figure 51. Christian Center, Stanke, Parks, Olsen interference data (CW-2 interference test).

NOMENCLATURE

Symbol	Definition	Unit
C	total compressibility	ft^{-1} (Pa^{-1})
h	reservoir thickness	ft (m)
k	permeability	md (m^2)
P	pressure	psi (Pa)
Q	volumetric flow rate	l/s
T	fluid temperature	°C
φ	porosity	fraction
μ	dynamic viscosity	cp (Pa·s)

ABBREVIATIONS

G.O.	Gearhart-Owen Temperature Gauge
H.P.	Hewlett Packard Quartz Pressure Gauge
L.-S.	Leupold-Stevens Water-Level Recorder
Paros.	Paroscientific Digiquartz Transducer
S.S.	Sperry Sun Pressure Transmission System

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A variety of instruments were used to collect the data discussed in the preceding sections. The higher quality of data from the more recent tests reflects an increased familiarity with the intricacies of geothermal well testing, and in particular, well test instrumentation. In the early tests, two primary downhole data-collection systems were used. (See Table A-1 for a description of the instruments.) The Hewlett Packard Downhole Pressure Gauge was used for production and interference tests in low- to moderate-temperature wells (less than 150°C). For tests involving temperatures exceeding 150°C, the Sperry Sun Downhole Transmission System was used. The Sperry Sun system relies on a gas- or liquid-filled capillary tube to transmit the downhole pressure to the surface, where it is measured and recorded. Experience soon exposed drawbacks to these systems and they were gradually replaced or modified to better suit the requirements of geothermal well testing.

Early comparison between downhole and wellhead data in artesian wells (see Raft River interference tests) showed that measurements taken at the wellhead are as good as those taken downhole for interference testing in geothermal wells if the temperature of the wellbore fluid is equilibrated with the surrounding rock. Because wellhead instrumentation is easier to maintain, wellhead pressure transducers were used in all subsequent interference tests in artesian wells. The Paroscientific Digiquartz transducer proved to be the most reliable and accurate gauge for this purpose. Based on these qualities, the gauge was later incorporated into a downhole instrument package for interference testing in non-artesian geothermal wells and for production testing in wells with maximum temperatures of 107°C (Solbau et al., 1981). The Hewlett Packard gauge is still used to test wells with temperatures between 100°C and 150°C. Design changes by Hewlett Packard reduced the noise problems associated with the gauge (see East Mesa tests, 1976). Recent tests with the Hewlett Packard gauge have produced excellent quality data (see WEN-1 production test, 1982).

Downhole pressure measurements remain a problem in high-temperature geothermal reservoirs. The gas- or liquid-filled capillary tube system for pressure measurement has the advantage that downhole pressure transducers, electronics, and temperature sensors are not required. However, the effect of wellbore heating on the fluid in the capillary tubing and the delay in transmission of the pressure signal obscure the early pressure transients that are so important to well test interpretation (Miller and Haney, 1978). Even today, the mechanical gauges, such as the Kuster and Amerada gauges, are the most reliable and commonly used instruments for measuring downhole pressures and temperatures in high-temperature geothermal wells.

Table A-1. Well Test Instrumentation

Transducer (Model Number)	Accuracy	Range	Temp. Limits (°C)	Resolution	Comments
Paroscientific Digiquartz Pressure Transducer (Model 2400-A)	0.01% FS	0-400 psi	107	.001 psi	Temperature sensitivity (null shift) 0.0004%FS/°F; Sensitivity shift 0.0026% FS/°C
Paroscientific Digiquartz Pressure Transducer (Model 2900-A)	0.01% FS	0-900 psi	107	.001 psi	Temperature sensitivity (null shift) 0.0004%FS/°F; Sensitivity shift 0.0026% FS/°C
Hewlett Packard Quartz Pressure gauge (HP-2813B)		12,000 psi	150	0.01 psi	Surface electronics: Gearhart-Owen pressure data processor Model PDP-401
Hewlett Packard Quartz Pressure gauge (HP-2811B)		12,000 psi	150	0.01 psi	Same as above
Gearhart-Owen Temperature Probe	±1°C	0-240°C	200	~.1°F	Used in tandem with Hewlett Packard pressure gauge
Sperry Sun Pressure Transmission System (Surface Recorder)	0.05% FS	0-5000 psi	Surface gauge	0.005% FS	Used with downhole capillary tubing
Sperry Sun Pressure Transmission System (Digital Pressure Monitor)	0.05% FS	0-5000 psi	Surface gauge	0.005% FS	No automatic recording device; used with downhole capillary tubing
Doric Temperature Trendicator 400A Digital	±1°C	-200-600°C	Surface gauge		Wellhead temperature gauge; iron-constantan thermocouple
Leupold Stevens Waterlevel Recorder (Model 71 Type A)			Surface gauge		Float type; accuracy and resolution dependent on depth to water level, float size and counterweight
Resistance Temperature Detector (RTD)	0.1°C	-260-900°C	Surface gauge		
Photoelectric turbine meter	1%	0-1000 gpm	Surface gauge		Turbine meter with photoelectric pickup

FS: Full scale

APPENDIX B: CONVERSION TABLES

Table B-1. Permeability (ρ_ω = 1, viscosity = 1 centipoise)

	m^2	ft^2	Darcy	cm/s	ft/s	ft/y	gpd[U.S.]/ft^2
m^2	1	$1.076x10^3$	$1.014x10^{12}$	$9.804x10^8$	$3.216x10^7$	$1.015x10^{15}$	$1.845x10^{13}$
ft^2	$9.29\ x10^{-2}$	1	$9.47\ x10^{10}$	$9.109x10^7$	$2.988x10^6$	$9.430x10^{13}$	$1.714x10^{12}$
Darcy	$9.862x10^{-13}$	$1.062x10^{-11}$	1	$9.66\ x10^{-4}$	$3.173x10^{-5}$	$1.001x10^3$	$1.82\ x10^1$
cm/s	$1.020x10^{-9}$	$1.097x10^{-8}$	$1.035x10^3$	1	$3.281x10^{-2}$	$1.035x10^6$	$2.118x10^4$
ft/s	$3.109x10^{-8}$	$3.347x10^{-7}$	$3.152x10^4$	$3.048x10^1$	1	$3.156x10^7$	$5.736x10^5$
ft/y	$9.852x10^{-16}$	$1.060x10^{-4}$	$9.990x10^{-4}$	$9.662x10^{-7}$	$3.169x10^{-8}$	1	$1.818x10^{-2}$
gpd[U.S.]/ft^2 (Meinzer)	$5.420x10^{-14}$	$5.834x10^{-13}$	$5.494x10^{-2}$	$4.721x10^{-5}$	$1.743x10^{-6}$	$5.500x10^1$	1

Dimensions: k, Absolute Permeability [L^2]
K, Hydraulic Conductivity [L/t]
K/μ, Mobility [L^3t/M]

Table B-2. Compressibility (Lt^2/M)

	m^2/N (Pascals)$^{-1}$	m^2/kg	psi^{-1}	$bars^{-1}$	atm^{-1}	(ft of water)$^{-1}$ at 68°F
m^2/N (Pascals)$^{-1}$	1	9.807	$6.897x10^3$	10^5	$1.0133x10^5$	$2.984x10^3$
m^2/kg	$1.020x10^{-1}$	1	$7.031x10^2$	$1.0197x10^4$	$1.0332x10^4$	$3.042x10^2$
psi^{-1}	$1.450x10^{-4}$	$1.4223x10^{-3}$	1	14.504	14.696	0.4327
$bars^{-1}$	10^{-5}	$9.8068x10^{-5}$	$6.895x10^{-2}$	1	1.01325	$2.984x10^{-2}$
atm^{-1}	$9.8692x10^{-6}$	$9.6787x10^{-5}$	$6.805x10^{-2}$	0.98692	1	$2.94x10^{-2}$
(ft of water)$^{-1}$ at 68°F	$3.351x10^{-4}$	$3.287x10^{-3}$	2.311	33.512	33.956	1

Table B-3. Flow Rate [L^3/t] or [M/t]

	m^3/s	l/min	bbl/day	gal/min (U.S.)	ft3/s	klb/hr (ρ_ω=1.0)
m^3/s	1	$6x10^4$	$5.43x10^5$	$1.585x10^4$	35.315	$7.9x10^3$
l/min	$1.667x10^{-5}$	1	9.058	0.2642	$5.885x10^{-4}$	$1.32x10^{-1}$
bbl/day	$1.840x10^{-6}$	$1.10x10^{-1}$	1	$2.917x10^{-2}$	$6.49x10^{-5}$	$1.46x10^{-2}$
gal/min (U.S.)	$6.31x10^{-5}$	3.785	34.28	1	$2.2280x10^{-3}$	0.50
ft^3/s	$2.8317x10^{-2}$	$1.699x10^3$	$1.539x10^4$	$4.4888x10^2$	1	$2.25x10^2$
klb/hr (ρ_ω=1.0)	$1.26x10^{-4}$	7.56	68.5	2.00	$4.45x10^{-3}$	1

Table B-4. Temperature (°C to °F)

°C	°F	°C	°F	°C	°F	°C	°F	°C	°F
0	32	100	212	200	392	300	572	400	752
5	41	105	221	205	401	305	581	405	761
10	50	110	230	210	410	310	590	410	770
15	59	115	239	215	419	315	599	415	779
20	68	120	248	220	428	320	608	420	788
25	77	125	257	225	437	325	617	425	797
30	86	130	266	230	446	330	626	430	806
35	95	135	275	235	455	335	635	435	815
40	104	140	284	240	464	340	644	440	824
45	113	145	293	245	473	345	653	445	833
50	122	150	302	250	482	350	662	450	842
55	131	155	311	255	491	355	671	455	851
60	140	160	320	260	500	360	680	460	860
65	149	165	329	265	509	365	689	465	869
70	158	170	338	270	518	370	698	470	878
75	167	175	347	275	527	275	707	475	887
80	176	180	356	280	536	380	716	480	896
85	185	185	365	285	545	385	725	485	905
90	194	190	374	290	554	390	734	490	914
95	203	195	383	295	563	395	743	495	923

Table B-5. Pressure (M/Lt^2)

	N/m^2 (Pascals)	psi	bars	atm	ft of water (at 68°F)	m of water (at 68°F)
N/m^2 (Pascals)	1	1.450×10^{-4}	10^{-5}	9.869×10^{-6}	3.351×10^{-4}	1.021×10^{-4}
psi	6.895×10^{3}	1	6.895×10^{-2}	6.805×10^{-2}	2.311	0.7042
bars	10^{5}	14.504	1	0.98692	33.512	10.214
atm	1.0133×10^{5}	14.696	1.01325	1	33.956	10.349
ft of water (at 68°F)	2.984×10^{3}	0.4328	2.984×10^{-2}	2.945×10^{-2}	1	0.3048
m of water (at 68°F)	9.794×10^{3}	1.419	9.790×10^{-2}	9.662×10^{-2}	3.281	1

Table B-6. Viscosity (dynamic)

Pa·s	$lbf·s/in^2$	$lbf·s/ft^2$	$kgf·s/m^2$	lbm/ft·s	$dyne·s/cm^2$	cP	lbm/ft·h
Pa·s	6.894 757 E+03	4.788 026 E+01	9.806 650 E+00	1.488 164 E+00	1.0 E-01	1.0 E-03	4.133 789 E-04

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