GL00502

9.0 FLOW TESTS AND WELL PRODUCTIVITY

9.1 INTRODUCTION

A suite of injectivity and flow tests were performed to assess the potential productivity of different intervals in the State 2-14 borehole. The last of these, a long-term flow test, was completed as part of the Phase-2 program. All of these tests are described in detail elsewhere and are briefly summarized here.

9.2 INJECTIVITY TESTS

Injectivity tests were performed on two suspected production zones at drilling depths of 4,684 ft and 5,418 ft. The decision to test was based on projected temperatures and large amounts of epidote, a geothermal alteration product, in cuttings samples. The first, or "mini-injection," test consisted of circulating 200 bbls of 2 percent KCl-treated canal water in the open hole, pulling the drill string into the casing, closing the rams, and injecting fluid through the kill line. The open-hole test interval extended from 3,519 ft (13-3/8 in. casing shoe) to 4,710 ft (TD at the time). Fluid was injected at rates of 2 barrels per minute (BPM), increasing to 5 BPM, with shut-in periods at mid test and at the end to measure pressure decline. Results indicated very low permeability and, therefore, no production potential. The test was terminated after fifteen minutes and drilling proceeded to 5,418 ft.

The second, or "maxi-injection," test was performed at a depth of 5,418 ft with about 2,000 ft of open hole. The test consisted of displacing the well fluid with 2 percent KCl- and BaCl-treated canal water, then injecting 2 percent KCl water at the rate of 85 BPM, using both rig pumps. The test lasted approximately one hour, including the shut-in period to measure pressure decline. This test resulted in the loss of 1,000 barrels of treated water into the formations, an indication of potential for flowing the well at this depth. Temperature logs by the U.S. Geological Survey recorded a bottom-hole temperature of 376.4°F. A possible fault zone was identified from 4,640 ft to 5,070 ft and water loss was attributed to this possible fault zone and to deeper zones. No promising flow zone was suggested by the temperature logs. The net results showed no significant production potential and drilling proceeded to the casing point at 6,000 ft. Results of the injectivity tests are included in Report P of Appendix A.

9.3 FIRST FLOW-TEST SUMMARY

The first flow test was conducted from December 28 to 30, 1985, after encountering partial loss of circulation between 6,100 and 6,227 ft-depth, while drilling out below the 9-5/8 inch casing shoe at 6,000 ft. During the flow test, the well was discharged to an atmospheric muffler. Well output was determined by use of the James lip-pressure method combined with water-flow measurements across a weir (GeothermEx, Inc., 1986a; Report R of Appendix A). The test plans called for the collection of fluid samples, temperature and pressure data. A detailed report of the flow test is presented in Report R, Appendix A. Raw field data recorded by the USGS are presented in Report S.

Conclusions from GeothermEx, Inc. (1986a; Report R of Appendix A) follow:

1) A permeable zone was encountered from 6,100 to 6,227 ft-depth. A reservoir temperature of 581°F (305°C) was measured downhole. This corresponds to lost circulation and lithologic evidence of a production zone between depths of 6 ,110 and 6 ,130 ft.

2) The produced fluid had a calculated, preflash, total dissolved solids (TDS) content of approximately 27 weight-percent and an estimated enthalpy of 400 Btu/lb. At atmospheric pressure, this resulted in a steam fraction of 26.5 weight-percent and a 37 weight-percent TDS content in the separated brine.

3) Measurements of the preflash TDS content by GeothermEx (27. 2 weight-percent) and by D. Michels (24.5 weight-percent) are in reasonable agreement. Michels also estimated the preflash gas content to be 0.17 weight-percent, consisting of about 99.6 percent carbon dioxide. Chemical analyses based on samples collected by Kennecott are suspect, since the TDS of samples collected at 460 and 195 psig are not in agreement. The sample collected at 460 psig appears to have been diluted by excess steam.

4) Under throttled conditions, the flow rate stabilized at approximately 140,000 lbs/hr, at a wellhead pressure of 450 psig. No stabilized data were obtained with the well flowing fully open because of the short discharge time. Data collected during this time showed a decrease in wellhead pressure from 245 to 190 psig, with a corresponding decrease in flow rate from 490,000 to 360,000 lbs/hr. Because of the steep rate of pressure and mass-flow decline, no estimate of stabilized conditions was made.

5) The producing zone had a productivity index of 300 lbs/hr/psi, based on a pressure survey conducted with the well flowing at 140,000 lbs/hr.

6) Pressure buildup data were analyzed using both constant-pressure, outer-boundary and infinite outer-boundary models. The formation flow capacity was estimated to be 6,500 and 11,700 millidarcy-feet (md-ft), respectively, from the two models, with skin factors of +6 and +10, respectively. The positive skin factors suggested that the reservoir was damaged.

7) Temperature and pressure data from surface and downhole measurements were adequate to define the boiling point curve for the brine. Some of the data, however, follow the pure-water boiling point curve. This suggests that separation of brine and steam occurred in the flow line between the wellhead and the sampling loop. Pressure and temperature gauges were recommended to be installed at the bottom of the flow line prior to the next flow test to confirm this interpretation.

During the flow test, extreme mineral deposition resulted in several problems with the operation of the James tube, muffler and weir box. GeothermEx, Inc. (1986a) recommended a number of mechanical modifications and changes in operational procedures to improve observations and the accuracy of the test data for subsequent tests (Report R of Appendix A). These changes were implemented prior to the second flow test (Report T of Appendix A).

9.4 SECOND FLOW-TEST SUMMARY

Well State 2-14 was completed to a total depth of 10,564 ft on March 17, 1986. After the first flow test (at 6,227 ft), drilling continued with several partial losses of circulation at 6,637 ft, 8,095 ft, 8,948 ft, 9,458 ft, and 10,400 ft. These partial losses of circulation (with the exception of the last one) were treated either with lost circulation materials or squeezed cement in order to continue drilling with full mud returns to the surface (GeothermEx, Inc., 1986b; Report T of Appendix A).

At 10,475 ft, a total loss of circulation occurred. At this point, it was decided to stop drilling and prepare for the second flow test. The bottom-hole loss zone was cemented and a 7-in., 29 lb/ft blank liner was hung at 5,700 ft inside the 9-5/8 in. casing from 5,700 to 10,135 ft-depth. After drilling out the cement plug with a 6-1/8 in. bit, circulation was again lost and the well was drilled blind to a total depth of 10,564 feet. Wellhead equipment was then installed in preparation for the flow test.

A detailed report of the second flow test was submitted by GeothermEx, Inc. (1986b) and is listed as Report T in Appendix A. The conclusions stated below are taken from that report. Raw field data recorded by graduate students from the University of California, Riverside, are contained in Report U of Appendix A.

1) The well was flowed for a total period of 38 hours. The calculated total flow rate and enthalpy data, and the measured wellhead-pressure data indicated that the well had not stabilized and productivity was improving with time.

2) Calculations based on the James method indicated that the well, in the flow test configuration, was capable of producing 710,000 lbs/hr at a wellhead pressure of 375 psig. The discharge enthalpy under these conditions was estimated to be 460 Btu/lb.

3) Data from downhole temperature logs indicated that the well was producing a significant amount of fluid from behind the liner during the flow test.

4) The James-method calculations were based on the measured brine flow rate in the weir box and the lip pressure measured at the James tube. An orifice plate was also provided upstream of the James tube to provide a second method for estimating the total flow rate and enthalpy, but problems were encountered with the calculation procedure used for the orifice calculations.

5) During the test, there was a general decline in discharge enthalpy from 560 Btu/lb to 440 Btu/lb. This decline was probably due to comingled production from more than one production zone and/or changes in brine salinity during discharge.

6) The temperature and pressure data collected from the surface gauges during the flow test were used to define the boiling point curve for the discharged brine. When plotted, the data were found to fall between the curve for pure water and the brine curve defined from the first flow test conducted from December 28 to 30, 1985.

7) Analysis of pressure buildup data collected after the well was shut in indicated that the formation flow capacity was 16,000 md-ft and the skin factor was -5.5. The negative skin factor suggests the well was producing from fractures. To adequately match the measured pressure data, it was necessary to use a double-porosity model for the calculations, indicating that the well was producing from a fracture and matrix system.

8) The productivity index for the well was calculated to be 2,970 lbs/hr/psi, based on the flowing pressure log obtained immediately before the well was shut in and the initial pressure calculated from analysis of the pressure buildup data.

9.5 SHORT FLOW-TEST; PHASE-2

A short flow test was conducted on August 31, 1987, after completing the well-rework activities for Phase-2, described in Section 6 of this report. The purpose of the test was to ensure that State 2-14 could be used as the production well for an injection experiment, then planned in combination with the Imperial 1-13 well, by the Idaho National Engineering Laboratory (INEL).

The State 2-14 well was flowed for 12 hours, averaging about 569,000 lbm/hr of total flow (steam plus liquid). The maximum production rate was estimated to be 1,222,000 lbm/hr, during the last 32 minutes of the test, when the throttling valve was fully open. A more detailed report of the short flow test of the State 2-14 well is included in Report D (listed in Appendix A).

Table 9.1 summarizes the results of both the Phase-1 and Phase-2 short-term flow tests. The maximum flow rates achieved by the three tests ranged from 600,000 to 1,220,000 lbm/hr (272,000 to 553,000 kg/hr), indicating a highly productive well. Wellhead temperatures were generally 460°F (238°C) and higher, after warmup; therefore, downhole temperatures, before fluid flashes, were quite high. The total dissolved solids (TDS) content is consistent with values for other hypersaline wells in the Salton Sea area. The geothermometers Na/K, Na/Ca, and Ca/K have different values for the March 1986 test from those for the test in December 1985; this indicates that other zones, in addition to the one at 6,120 ft, were apparently contributing to the production.

9.6 CONSTRUCTION OF FLOW-TEST FACILITY

Two major objectives of the SSSDP were to determine well productivity through a long-term flow test, and to investigate, in detail, the chemistry of reservoir fluids accessed by the borehole. To achieve these objectives, a specialized flow-test facility was required. The flow-test facility used at State 2-14 was originally designed, constructed, and used in 1982 to test a geothermal well of the CU-1 Venture in the South Brawley geothermal resource area, under the DOE Geothermal Loan Guarantee Program. The flow-test equipment was subsequently disassembled, moved, reassembled, and used to test two wells of the Parsons-Republic joint venture in the Niland, California geothermal resource area, also under the Geothermal Loan Guarantee Program. After the tests at Niland, the equipment was again disassembled, moved, and stored at the DOE Geothermal Test Facility at East Mesa, California.

9.6.1 Description Of Flow-Test Facility

Figure 9.1 shows a simplified flow diagram of the flow-test facility, and Figure 9.2 shows a plot plan.

Two-phase geothermal fluid produced by the State 2-14 well flowed to the high-pressure separator, V-1. Start-up piping was provided for bypassing the separator and sending flow to the brine pond, through either a vent silencer, V-4; the atmospheric flash tank, V-3; or directly to the brine pond through the blooie line.

The normal flow path admitted two-phase flow to the separator, where liquid and steam were disengaged by centrifugal force. The liquid entering the separator spiraled downward along the walls and exited the separator from the bottom, while the steam exited through the top.

A hand-operated valve used to throttle flow was installed in the two-phase flow line between the State 2-14 well and the high-pressure separator. This valve allowed operating with wellhead pressures greater than the pressure in the separator. Thus, wellhead pressure could safely exceed the allowable operating pressure of the separator (500 psig or 3.45 MPa); this condition was most likely when adjusting the system for a low well-flow rate. The throttling valve also allowed use of low separator pressure at high well-flow rate. This helped minimize carryover of liquid droplets in the steam leaving the atmospheric flash tank; relatively low enthalpy and low flow rate of brine from the separator (due to low operating pressure in the separator) limited the steam-flow rate from the atmospheric flash tank.

Steam-flow rate was measured using an orifice meter. Pressure was then reduced by a pressure control valve that regulated the separator pressure. Steam was vented to the atmosphere through the vent silencer, V-4.

Separated brine exiting from the bottom of the separator flowed through one of two parallel

Table 9.1

Summary of Results from Short-Term Flow Tests

Date of Test	*December 1985 during drilling*	*March 1986 after well completion*	*August 1987 after second workover*
Well Depth, ft	6,227	10,564	10,564
Estimated Flow-Zones Depth, ft	6,120	6,100 6,600 8,800 10,475	6,100 6,600 8,800 10,475
Duration of Flow Test, hours	29	32	12
Total Brine Produced, lbm	5,570,000	10,045,000	6,830,000
Average Well-Flow Rate, lbm/hr	192,000	314,000	569,000
Maximum Well-Flow Rate, lbm/hr	600,000	700,000	1,220,000
Range of Wellhead Temperatures, °F	400 to 460	445 to 490	355 to 465
Range of Wellhead Pressures, psig	200 to 450	310 to 485	118 to 388
Total Dissolved Solids, mg/kg	255,000	251,000	236,000
Geothermometers			
Na/K	3.19	4.09	No data
Na/Ca	1.99	1.86	No data
Ca/K	1.61	2.20	No data

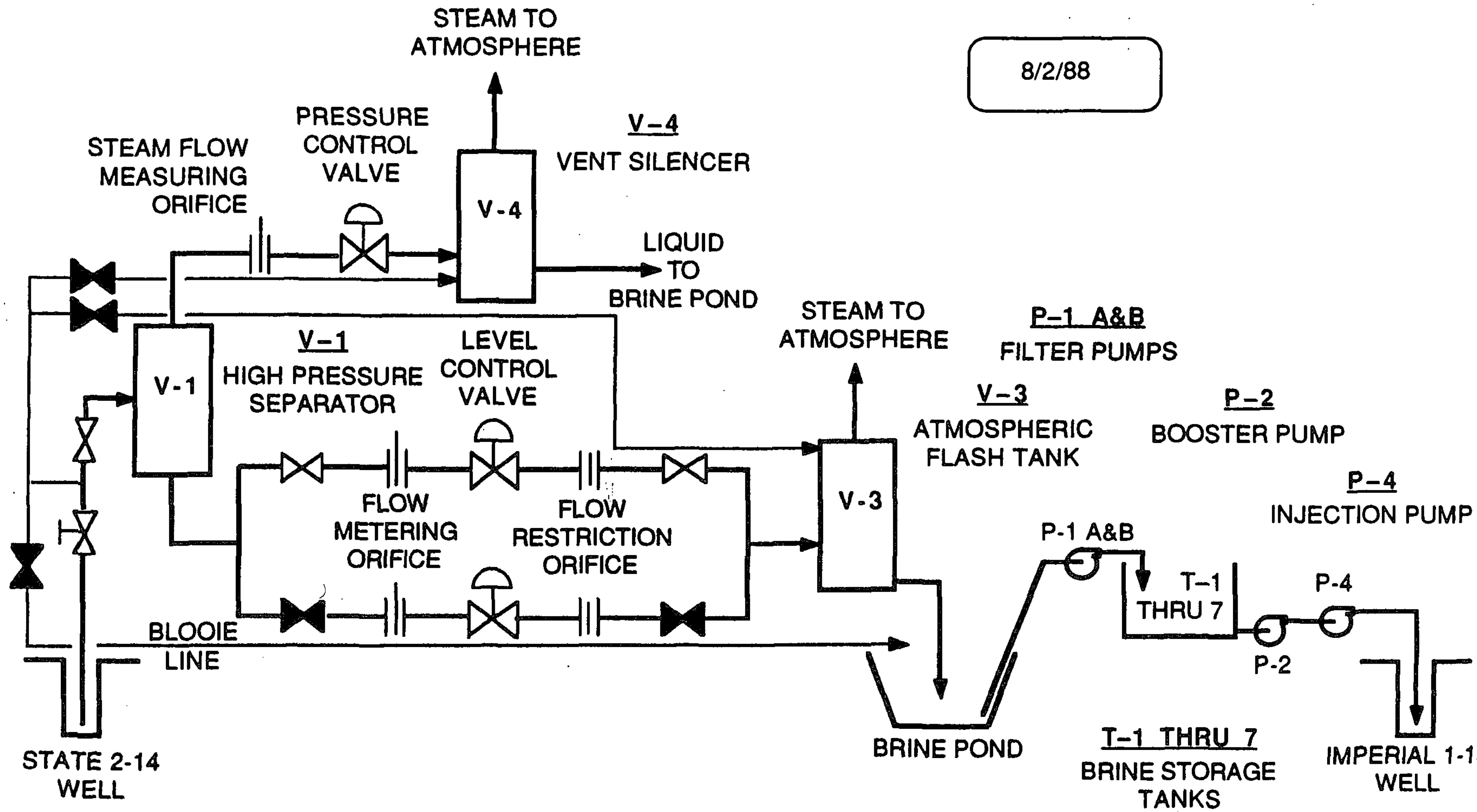

Figure 9.1 Simplified Diagram of Flow-Test Facility
(from report EE, Appendix A)

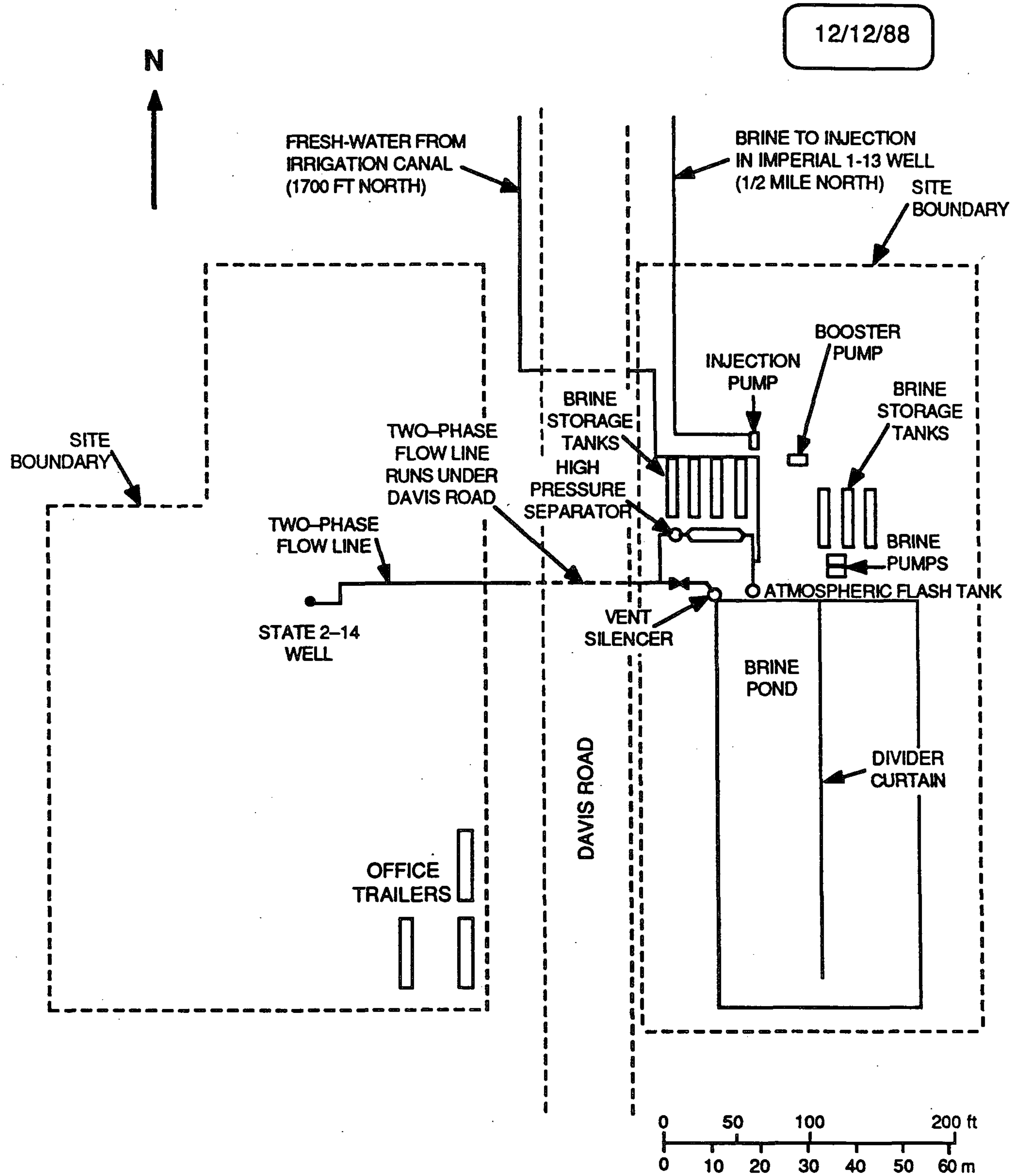

Figure 9.2 **Plot Plan of Flow-Test Facility**
(from Bechtel, 1988)

measuring loops. Each of the two loops contained an orifice meter, a level-control valve, and a flow-restriction orifice. Two loops were provided for reliability because of the high potential for scaling in the brine flow line from the separator. Use of a redundant control loop allowed continuing a flow test while inspecting and performing maintenance work on one of the loops. The two sets of metering and restriction orifices downstream of the separator were sized to handle the complete range of expected flow rates, without disassembling either loop to insert different orifice plates. Low-pressure brine leaving the flow-restriction orifice was a mixture of steam and liquid that flowed to the atmospheric flash tank, V-3.

The atmospheric flash tank separated the two phases that entered from the flow-restriction orifice. Steam escaped to the atmosphere through the top of the flash tank. Liquid exited from the bottom and flowed into the brine pond.

The brine pond served two functions in the process. First, it provided surge capacity (i.e., storage) so that the production rate of the State 2-14 well and the injection rate into the Imperial 1-13 well were not required to be exactly equal at all times. Second, it provided residence time for solid particles to precipitate and settle from the brine. A vertical divider curtain, made of reinforced polyethylene, was designed to force brine to flow to the south end of the pond and then back to the north end, as it traveled from the pond inlet to the brine-suction pump. The brine pond measured 112 by 287 ft (34 by 87 m), by 8 ft deep (2.4 m), and held 1.1 million gallons (4.2 million liters) of brine. It was made of impermeable native soil.

Liquid from the brine pond was pumped to brine storage tanks, T-1 through T-7, by one of the two brine pumps, P-1 A or B. Two full-capacity brine pumps were installed to provide high reliability. Seven 500 bbl (80 m^3)-capacity tanks were connected in parallel. The tanks provided large volume with low brine velocity for sludge to settle. Thus, these served as safeguards against plugging the injection well with sludge, inadvertently entrained in brine pumped from the brine pond. One booster pump, P-2, and one injection pump, P-4, took brine from the brine storage tanks and injected it into the Imperial 1-13 well.

An evaluation by Kennecott indicated that the Imperial 1-13 well could be used for injecting unfiltered brine, during a 30-day test, without undue hazard from plugging. Another resource developer had successfully injected unfiltered brine into the same stratum.

9.6.2 Construction — Fall, 1987

Construction of the flow-test facility at the State 2-14 well site was accomplished in two stages. The first stage was in the fall of 1987; the second in May 1988.

When construction of the flow-test facility began in September 1987, the objective of the flow test was to perform a combined production-injection experiment, using the nearby Imperial 1-13 well. For this experiment, the State 2-14 well would operate at virtually a constant and uninterrupted flow rate, to furnish brine for injection into the Imperial well. This required connecting four of the 500-bbl tanks for use as media filters and installing spare booster and injection pumps to provide a highly reliable supply of filtered brine for injection.

The existing brine pond, two-phase flow line, and vent silencer were used without modification. The remainder of the flow-test equipment was installed at the north end of the brine pond.

Site Preparation. Soil in the area where the flow-test facility was installed consists of sand and clay loam. The water table is 3 to 4 ft (about 1 m) below grade during dry periods, and it may be virtually at grade when the Salton Sea level is high. The foundation for the high-pressure separator was excavated to a depth of 12 in. (30 cm) and filled with rock, covered with 3 in. (8 cm) of soil, and compacted. For the other equipment, no foundations were needed. The vessels were set on the ground after clearing the sparse vegetation from the limited testing area. A new entrance to the area was established to provide better access during inclement weather.

Initial Condition of Vessels, Piping, and Instruments. The high-pressure separator was coated with rust and other corrosion products on the inside. On the outside, the insulation sheathing was crumpled and dented, but the insulation was in place. The supporting skirt was coated with rust over about one-third of its surface area. The platform near the top of the high-pressure separator was bent so badly that it was virtually destroyed. The high-pressure separator was the only pressure vessel in the test facility, and it was hydrostatically tested to 1,200 psig (8.3 MPa) before it was moved from the storage area. This test demonstrated the structural integrity of the separator for pressures in excess of the design test pressure. The brine outlet-pipe elbow from the separator was noticeably thinned from erosion during previous use, but ultrasonic inspection confirmed that enough steel remained for safe use at the design operating pressure of 500 psig (3.4 MPa).

The atmospheric flash tank and the vent silencer were coated inside and out with rust from previous use and storage. The tanks for media filters and brine storage were covered with rust on the inside, but the paint on the outside showed only isolated areas of rust. The amount of material removed from these open-top vessels by corrosion did not jeopardize their use for atmospheric pressure operation.

The major piping was badly rusted and corroded; some was also lined with scale. None of the valves were operational: many of the handles and stems were broken. Numerous flange connecting bolts were galled and had to be replaced. Some sample ports and pressure taps had been seal-welded and, because of corrosion, many of the remainder were virtually without thread to withstand operating pressures.

The instrumentation was in poor condition. The flow and level recorders were in such bad shape that renting replacements for the flow test was less expensive than reconditioning. The flow orifices were either missing or had to be replaced due to erosion, corrosion, or bending. Most of the temperature and pressure indicators were in storage, but required calibration before use in the flow test.

Reconditioning. All valves were reconditioned before installation. The four 12-in. valves that isolated the measurement loops downstream of the separator were sent to a local valve shop for replacement of stems, handles, and packing; the internals were sandblasted as part of this reconditioning. All valves were disassembled and cleaned; defective parts were either replaced or reconditioned by hand. Valves that were beyond cost-effective reconditioning were replaced.

Installation. The high-pressure separator was set in place on a cross-shaped support made of 10-in. pipe to spread the load over a large bearing surface; the support was filled with concrete for ballast. Other vessels were set in place on the ground without foundations. Because the pumps were rental items, these were not installed immediately.

Usable piping-spool assemblies were reconnected in the previous configuration. All flanges were broken open, cleaned, regasketed, and reassembled. New piping sections, as required, were fabricated and installed. All piping was installed on temporary wooden-block supports. These temporary supports were replaced with concrete and steel supports during the second phase of construction in May 1988.

In early November 1987, projections indicated that mid-January 1988 would be the earliest date for starting a flow test. With a period of at least two months before start of testing, instrument storage was better than having the instruments installed and exposed to the weather.

Construction of the flow-test facility was suspended in mid-November 1987 for budgetary reasons. Construction activity was shut down and all personnel left the site, awaiting restart of flow-test preparation.

9.6.3 Construction in May 1988

Construction of the flow-test facility resumed on May 1, 1988. Due to funding constraints, plans were made for a 30-day flow test to characterize the State 2-14 well and reservoir; the injection experiment was cancelled. The scheduled start date for the well-flow test was June 1, 1988. Performance of the hydrostatic-leak tests of the surface facility was such a significant milestone that construction activities may be separated for discussion as occurring before or after hydrostatic testing, as follows:

- Before hydrostatic-leak tests

  Review of the facility during the period from November 1987 to May 1988 indicated that elbows in the existing two-phase flow line could erode so rapidly that a 30-day flow test would be jeopardized. Such rapid erosion had been observed at other geothermal facilities in the Imperial Valley. Therefore, eight elbows in the 10-in., two-phase flow line were removed and tees, with one of the straight connections capped, were installed. By orienting the tees with the remaining straight connection in the direction of incoming flow, the capped connection served as a liquid-filled cushion to turn the flow 90 degrees without eroding the walls of the piping.

  The four 12-in. gate valves that isolated the measuring loops, downstream of the separator, were initially installed with the valve stems vertical. Review and discussion of this orientation indicated that these large valves should be oriented with the stems about 45 degrees from horizontal, to enable manual operation. This orientation allowed use of a person's weight as part of the turning force. With such large valves, this weight component is often required, unless a mechanical operator is installed on the valve. Therefore, the metering loops were disassembled and the four large valves reoriented. During reassembly, the piping was found to be badly misaligned, and considerable cutting and rewelding was needed to straighten the measuring loops.

  A 10-in. valve for throttling the two-phase flow was installed in the existing 10-in., two-phase flow line from the State 2-14 well to the high-pressure separator.
  The wooden, temporary pipe supports were replaced with more substantial supports, typically a tee-shaped member, fabricated of steel pipe, held in place by a poured-in-place concrete base.

  The railing for the platform near the top of the high-pressure separator was repaired to improve worker safety.

  Approximately 100 ft of 6-in. piping was connected from the injection pump location to the injection line that led to the Imperial 1-13 well. The Imperial well was approximately one-half mile north of the flow-test facility.

  A fresh-water supply line was installed to draw water from an irrigation canal and transport it to the flow-test facility. The fresh-water supply system consisted of a pump driven by a stationary engine and a 4-in. diameter temporary pipeline. The fresh-water pipeline was laid on the ground for the 1,700 ft (518 m) distance from water source to test facility. Large quantities of fresh water were used before the test for hydrostatic leaks, during the test for brine dilution, and after the test for cleaning the equipment.

• Hydrostatic-leak tests

Two hydrostatic-leak tests were performed on May 25, 1988, to demonstrate the structural integrity of the high-pressure vessels and piping.

First, the high-pressure separator and the piping from the State 2-14 well to the 12-in. valves, at the downstream end of the measuring loops, were qualified for operating pressures up to 500 psig (3.4 MPa) and at operating temperatures to 470 °F (243 °C). The actual hydrostatic-test pressure at ambient temperature was 900 psig (6.2 MPa).

After the first hydrostatic test was concluded, the throttling valve in the two-phase flow line was closed, the high-pressure separator and piping downstream of the throttling valve were vented, and the two-phase flow line, upstream of the throttling valve, was pressurized further to qualify it for operation to its design pressure of 700 psig (4.8 MPa), at temperatures to 500 °F (260 °C). The actual hydrostatic-test pressure was 1,260 psig (8.7 MPa).

• Post hydrostatic-leak tests

After the hydrostatic-leak tests, a rupture disk rated for 590 psig (4.1 MPa) was installed to limit pressure in the high-pressure separator.

Calibration and installation of the flow-test instrumentation and controls was completed, and the compressed-air system to operate the controls was installed. Most of the recorders were found to be unusable, and rental units were obtained for the flow test. One of the flow-control valves was installed from the brine storage tanks to the brine pond, so that the tanks could not be overfilled.

The divider curtain, made of 6-mil reinforced polyethylene, was installed in the north-south direction across the brine pond. Heavy scrap-steel cable was attached as weight to hold the bottom edge of the curtain along the bottom of the pond. The top was supported with a cable anchored at one end and attached to a hand-operated winch for adjusting the tension at the other end.

The pumps were rented, along with a diesel engine to drive each pump. Each pump-engine combination was attached to a trailer to facilitate transportation. Each pump was connected with reinforced hose on both the intake and the outlet. The pumps were the last major equipment items installed before the test began.

Flow from the State 2-14 well began on June 1, 1988. Initally, flow bypassed the separator and entered the brine pond, first through the blooie line and later through the atmospheric flash tank. Installation of pumps and piping to transfer brine from the pond to the brine storage tanks was completed on June 3. Installation of the booster pump on the injection line was completed the next day and injection began. On June 6, two-phase flow was admitted to the high-pressure separator. This concluded the construction phase of the flow-test facility.

9.7 LONG-TERM FLOW TEST: PHASE-2

9.7.1 Test Plan

The objectives of the flow test in June 1988 were to:

• Investigate the long-term production characteristics of the well and reservoir system

- Obtain well-flow data and downhole measurements needed to perform reservoir engineering analyses of well performance and determine near-well reservoir properties

- Obtain samples of brine, steam, and noncondensible gases for chemical analyses to characterize the reservoir fluid, calculate physical and thermodynamic properties, and analyze for changes in composition associated with flow-rate changes

- Measure the preflash temperature of the brine and obtain other data to calculate the enthalpy of the fluid produced and the rate of energy production for the well

- Provide opportunities for other experimenters to perform tests in conjunction with the flow test. The following scientific research projects were conducted during the flow test in June 1988:

  - Particle-meter testing by Battelle Pacific Northwest Laboratories

  - Chemical sampling and analysis to characterize the brine by Electric Power Research Institute

  - Seismic monitoring by Lawrence Livermore National Laboratory

  - Metal ion concentrations by New Mexico State University

  - Transport of platinum-group elements, gold, and sulfur in the Salton Sea Geothermal brines by University of California at Riverside

  - Uranium-series isotope measurements by University of Southern California

  - Liquid and gas sampling by University of Utah Research Institute

  - Chemistry of scale deposits by Idaho National Engineering Laboratory

The flow test of the State 2-14 well in June 1988 was originally planned as a 30-day step-rate test, with three rate-steps scheduled as follows, and as shown in Figure 9.3:

	Planned Duration (days)	Planned Flow Rate (lbm/hr, total flow)*
First rate-step	7	200,000 to 250,000
Second rate-step	7	400,000 to 500,000
Third rate-step	16	600,000 to 750,000

* 1,000 lbm/hr= 454 kg/hr

Three previous short-duration flow tests, during and after drilling, were conducted with a simple test facility that held the residual brine in a brine pond without injection. These tests were limited to 29-, 32-, and 12-hours duration by the capacity of the brine pond. To perform a longer-term (i.e., 30-day) flow test, the more elaborate test facility described in Section 9.6 was required. This facility provided the necessary capability for brine injection and the advantages of steam-brine separation for separate metering and sampling of the two phases.

The step-rate test is a standard reservoir engineering method for obtaining the downhole pressure response data for determining reservoir properties, while obtaining wellhead data to define a deliverability curve (i.e., graph of production rate versus wellhead pressure). The planned duration

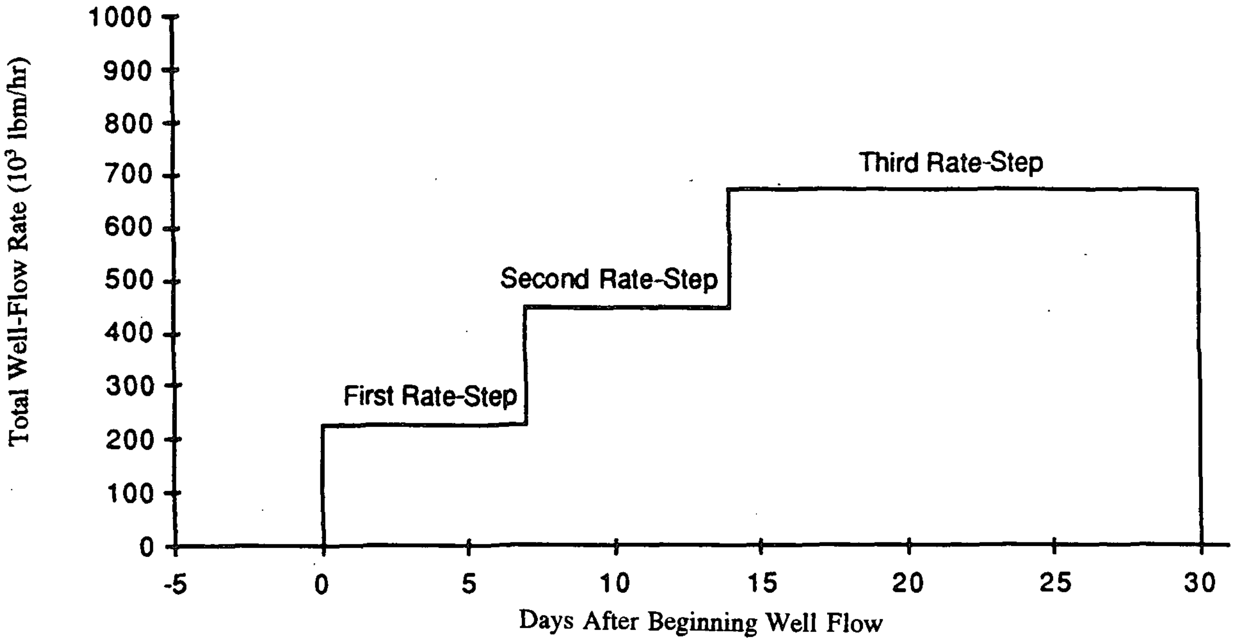

Figure 9.3 Planned Schedule for 30-Day Flow Test
(from Bechtel, 1988)

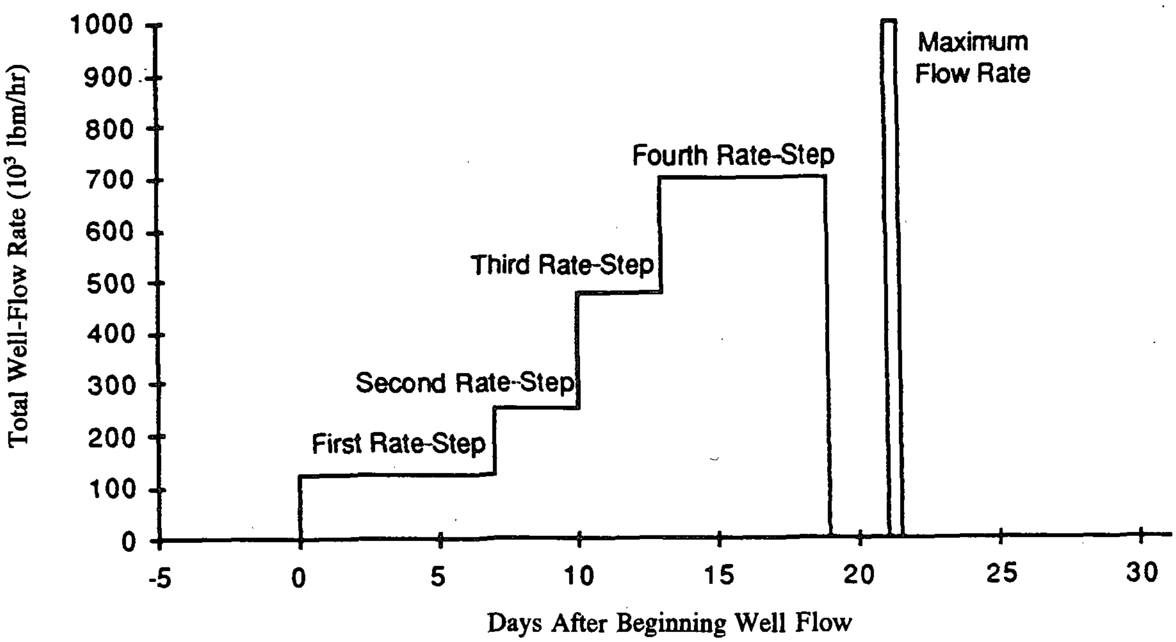

Figure 9.4 Revised Schedule for Flow Test
(from Bechtel, 1988)

of each rate-step was estimated to be adequate for the well to reach stable operation with respect to flow rate, pressure and chemistry. The schedule for increasing flow rates also facilitated operation of the flow-test facility by allowing a step-wise approach to the higher flow rates.

A total of five downhole pressure and temperature surveys were planned to acquire data for reservoir engineering analysis and for characterization of the brine before flash. Production logs that would normally be run to delineate and quantify zones of inflow were not planned because of concern about the mechanical condition of the deeper part of the well.

The schedule for flow rates and durations of the steps was revised during the first week of the test for the following reasons:

- The budget could not support 30 days of testing.
- The State 2-14 well was confirmed as a high productivity well and flow conditions stabilized within hours after a rate change. For purposes of reservoir engineering analysis and for defining the deliverability characteristics of the well, shorter duration flow-steps would suffice.
- The well was clearly capable of high flow rates, and the initial rate-step was about one-half the planned rate, because brine could not be injected early in the test. To define the useful range of flow rates for the well, three additional rate-steps (for a total of four) were considered necessary.
- The maximum flow rate of the well would be limited by the capacity of the test facility. Therefore, the full flow-rate potential of the well would be determined by a maximum-rate flow test, directly to the brine pond. To accomplish this without compromising the reservoir and well-performance analysis, a separate, full flow-rate test was scheduled, following the four rate-steps and a shut-in period. Because brine production would exceed the injection rate, the test at full flow rate was to last only a few hours, as determined by the maximum injection rate and the brine-pond capacity.

The revised schedule for the flow test is summarized below and shown in Figure 9.4:

	Planned Duration (days)	Planned Flow Rate (lbm/hr, total flow)
First rate-step	7	125,000
Second rate-step	3	250,000
Third rate-step	3	450,000 to 500,000
Fourth rate-step	6	650,000 to 750,000
Shut in to monitor pressure buildup	2	Zero
Test at full flow	<1	Maximum flow rate probably >1,000,000

1,000 lbm/hr= 454 kg/hr

9.7.2 Reservoir Test Results

9.7.2.1 *Test Operating Conditions*

Figure 9.5 shows the flow rates during the test. In this plot, the flow rate during each step is

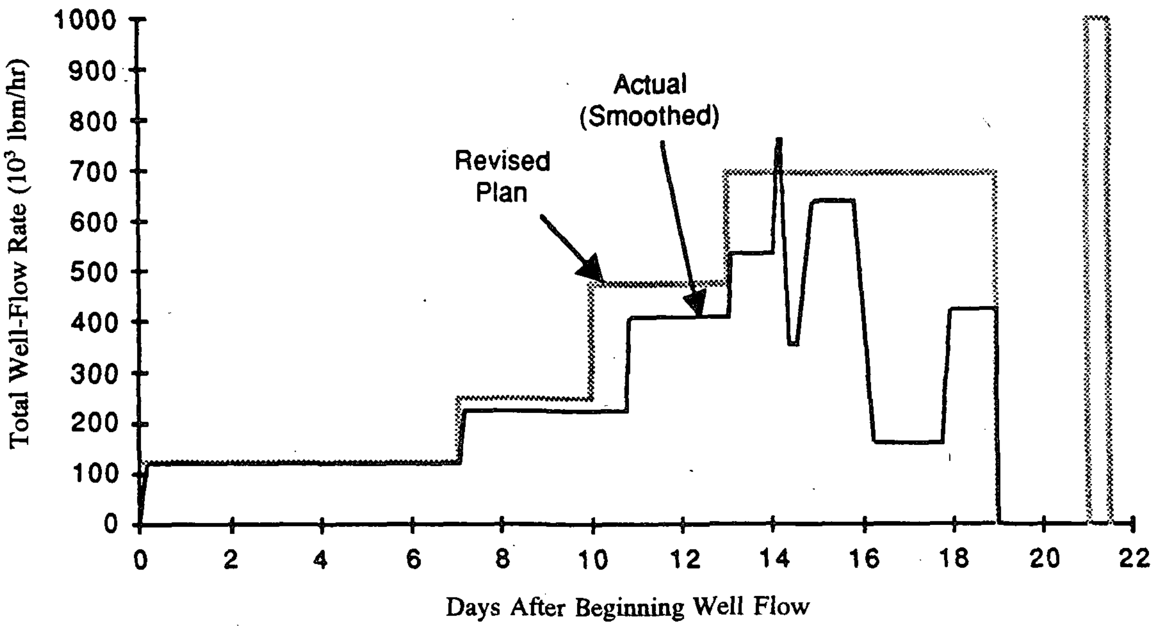

Figure 9.5 **Total Well-Flow Rate During June 1988 Test**
(from Bechtel, 1988)

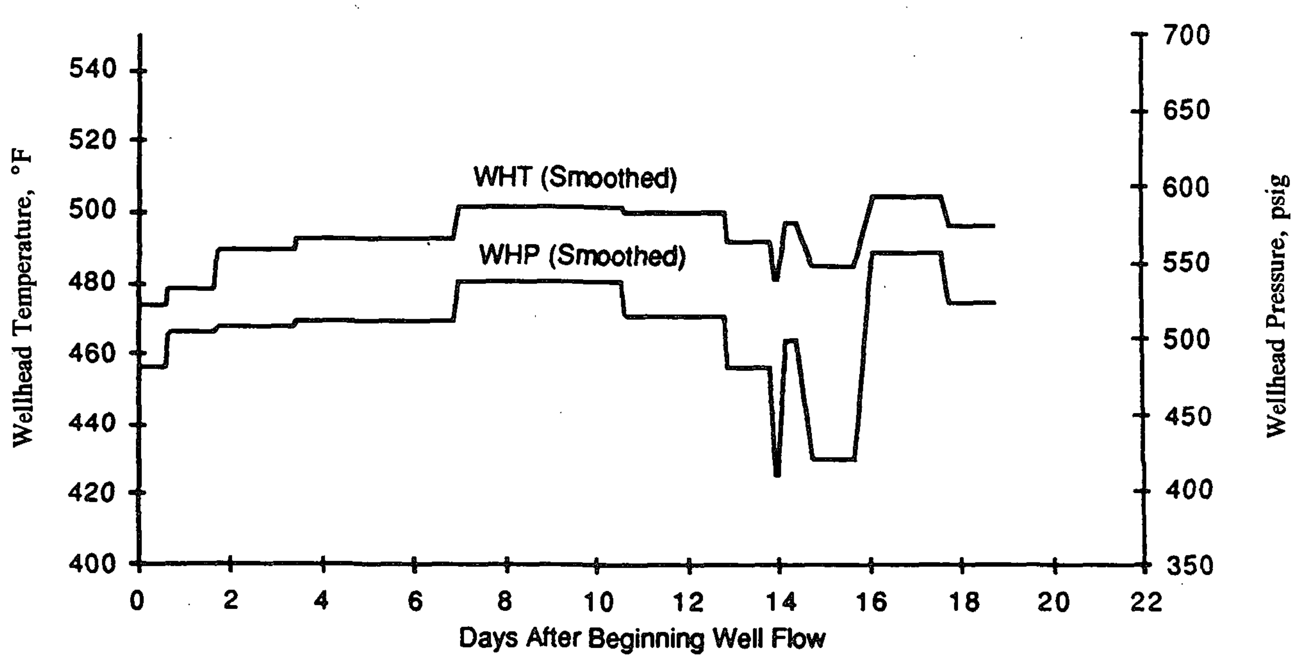

Figure 9.6 **Smoothed Wellhead Temperature and Pressure During June 1988 Test**
(from Bechtel, 1988)

smoothed; that is, the flow rate is averaged during each step to focus on the flow-rate trends. Figure 9.6 shows the wellhead temperature and pressure (smoothed) during the test. Detailed plots of flow rate, wellhead temperature, and wellhead pressure at 2-hour intervals are given in the well-test engineering report (Report FF, Appendix A).

The test was planned and conducted as a step-rate test, but there were some deviations from the ideal of long periods with constant flow rate. Although the well showed no appreciable pressure decline, there was a tendency for the flow rate to drift downward, probably because of scale deposition in the throttle valve. Occasional adjustments of the throttle valve were required to achieve the desired flow rate. This commonly occurs in well testing in the Salton Sea field and did not significantly affect the results.

The highest rate of 768,000 lbm/hr (348,000 kg/hr) was maintained for less than 1 hour because the separator control was not functioning properly. Therefore, the deliverability data at that rate do not represent a fully stabilized condition. Nevertheless, the results are adequate to achieve the reservoir engineering test objectives.

The well was initially produced at about 125,000 lbm/hr (57,000 kg/hr), significantly lower than the planned initial rate of 200,000 to 250,000 lbm/hr (91,000 to 113,000 kg/hr). This lower flow rate was used because the residual brine had to be retained in the brine pond until the injection system was completed on June 4. Ideally, test start up would have waited for completion of the injection system, but budgetary and schedule considerations necessitated the June 1 start.

Once the injection system was operational, the production rate was held at about 125,000 lbm/hr (57,000 kg/hr) until June 8 to complete the planned 7-day period for the lowest flow-rate step. Late on June 8, the flow rate was increased to 250,000 lbm/hr (113,000 kg/hr), and the durations of succeeding rate-steps were shortened, as indicated in the revised test schedule (Figure 9.4).

Downhole temperature- and pressure-profile surveys were conducted on June 5, 12, 14, and 20. These surveys measured stabilized flowing pressure at the 5,000 ft (1,524 m) datum, at various flow rates, to define the well-inflow performance. Also measured were flowing temperature and pressure profiles between the surface and 5,000 ft (1,524 m), to provide data for thermodynamic flash calculations and to establish whether a relationship existed between brine temperature and flow rate. The temperature surveys were conducted with Amerada-type Kuster instruments, and pressure data were obtained with a helium-filled capillary tube, downhole, and a Paroscientific digital-quartz pressure transducer at the surface.

Pressure drawdown was recorded as flow rate was increased on June 12 and 14, and pressure buildup was recorded for 44 hours after shut-in on June 20. Data from these pressure-response measurements were used to calculate near-well reservoir properties.

Typically, a flow test would involve a static, downhole temperature and pressure survey to establish equilibrium shut-in conditions before the test. This was not done immediately prior to the June 1988 flow test because: 1) a suitable static survey was run in November 1987; 2) brine in the wellbore had been displaced with fresh water in April 1988, possibly distorting the static, downhole pressure measurements; and 3) budgetary constraints.

9.7.2.2 *Well Performance*

Flow rates and wellhead-pressure measurements were used to plot a deliverability curve. Stable wellbore pressures, measured at 5,000 ft (1,524 m) before and after step-rate changes, were used to plot a productivity curve and calculate the productivity index.
Deliverability. Figure 9.7 shows the deliverability curve for the State 2-14 well. The following points should be noted about this plot:

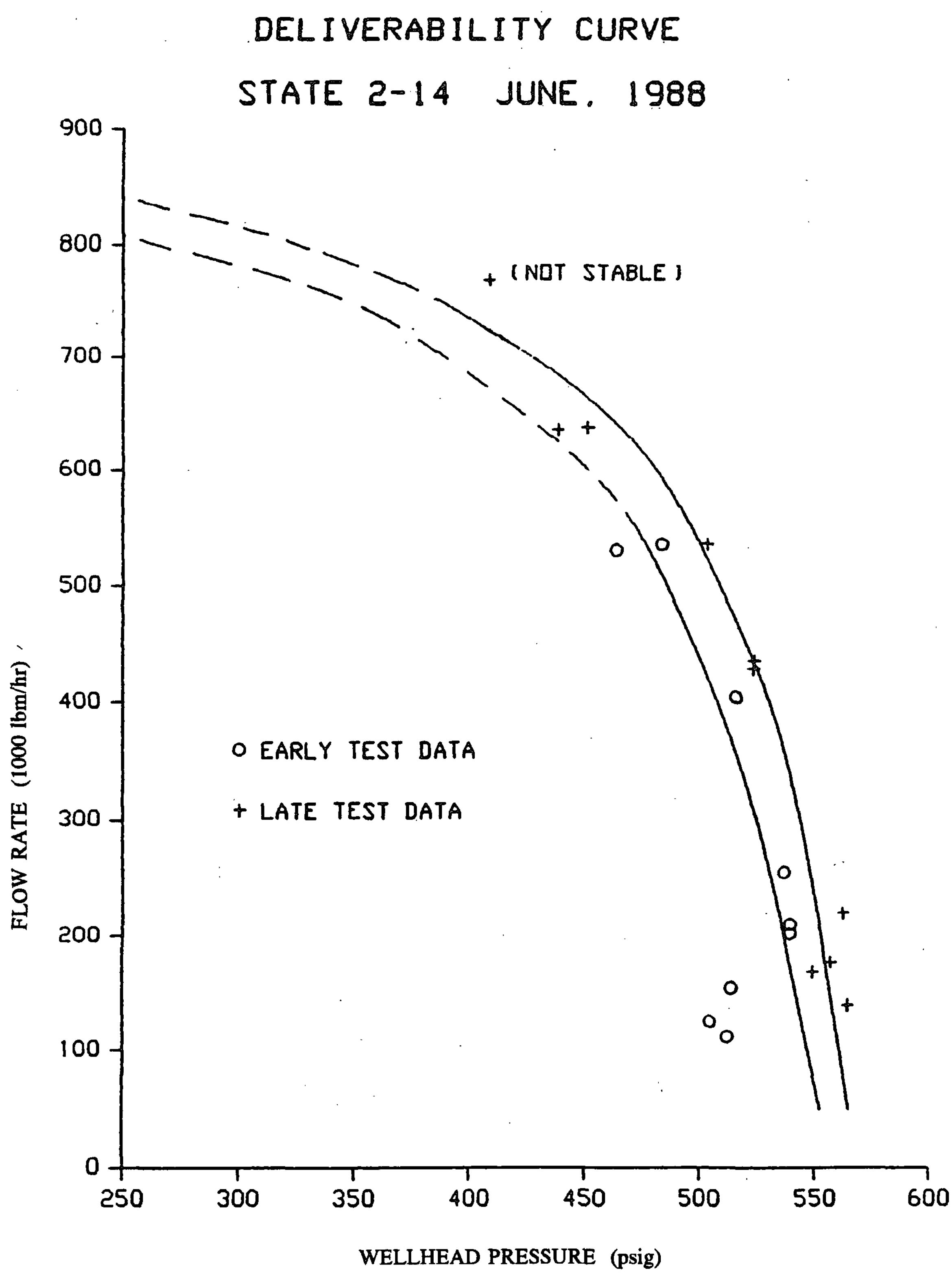

Figure 9.7 **Deliverability Curve, State 2-14, June 1988**
(from report FF, Appendix A)

- The dashed line represents the shape of the projected curve to lower wellhead pressures. For example, at typical commercial-operating wellhead pressure of 250 psig (1,724 kPa), about 800,000 lbm/hr (400,000 kg/hr) could be produced.

- Increased well deliverability observed later in the test suggests that productivity improved during the course of the test. It is likely that flowing the well at higher rates may have cleaned drilling solids from the reservoir rock and also may have opened additional flow paths, unavailable at the start of the test.

- At low flow rates, deliverability curves often show a curve toward the origin just before the lowest sustainable flow rate. Points on this curve for low flow rates at the beginning of the test are more likely representative of the improved wellbore condition noted above.

Productivity. Well productivity was assessed using pressure measurements made in the liquid column at 5,000 ft (1,524 m). This is shallower than the suspected primary entry zone at 6,200 ft (1,890 m). During flow conditions, this should not have influenced the reliability of either productivity or pressure-drawdown measurements, because temperature in the flowing, single-phase liquid column is subject to only slight cooling by heat loss.

Figure 9.8 shows flow rate plotted against downhole pressure for three stabilized flow rates. The productivity index of a well is usually defined as the flow-rate change per unit change in downhole pressure. An average productivity index of 1,527 lbm/hr per psi (100 kg/hr per kPa) was calculated using these data.

The productivity curve is a straight line through the three points, which would be expected from matrix permeability alone. However, reserviors in the Salton Sea field, typically, are extensively fractured and have significant matrix storage capacity. Because well improvement was noted from other data during the flow test and an available static-pressure measurement does not fall on the productivity line, the straight-line productivity curve does not necessarily imply matrix-only permeability. The permeability is, no doubt, affected by fracturing, in addition to matrix permeability.

Wellbore effects. Downhole pressure drop includes not only pressure changes in the reservoir under flowing conditions, but also pressure losses as fluid enters the wellbore (i.e., skin effects) and pressure changes due to differences in the amount of fluid stored in the wellbore (i.e., wellbore storage). For geothermal wells, separating pressure losses due to skin effects and wellbore storage is almost impossible; therefore, these are generally lumped together and calculated as a "skin factor."

Horner-plot analysis of the buildup data yielded a calculated skin factor of +23.1. Positive values indicate large pressure losses as fluid enters the wellbore. These can be caused by wellbore damage, pressure drop across liners or through perforations, partial penetration completions, wellbore-storage effects, closing of fractures as pressure decreases, and turbulent flow as fluid enters the wellbore at high rates. The State 2-14 well, no doubt, sustained wellbore damage during drilling and rework activities; however, high flow rates into the wellbore probably contributed to the apparent skin effect.

Attempted High Flow-Rate Test. A high flow-rate test (>1,000,000 lbm/hr), with production directly to the brine pond, was planned for June 23-24, after the final shut-in on June 20. The purpose was to define a higher point on the deliverability curve, within the expected commercial operating range. The well would not flow spontaneously when the valves were opened, and two attempts to induce flow were unsuccessful. Mesquite Group Inc. (1988; Report FF of Appendix A) interpreted the cause to be cooling of the wellbore during shut-in, rather than an indication of well damage or depletion. Common techniques of pressurizing the well with air at the wellhead and displacing brine from the wellbore with fresh water were employed. More effective methods,

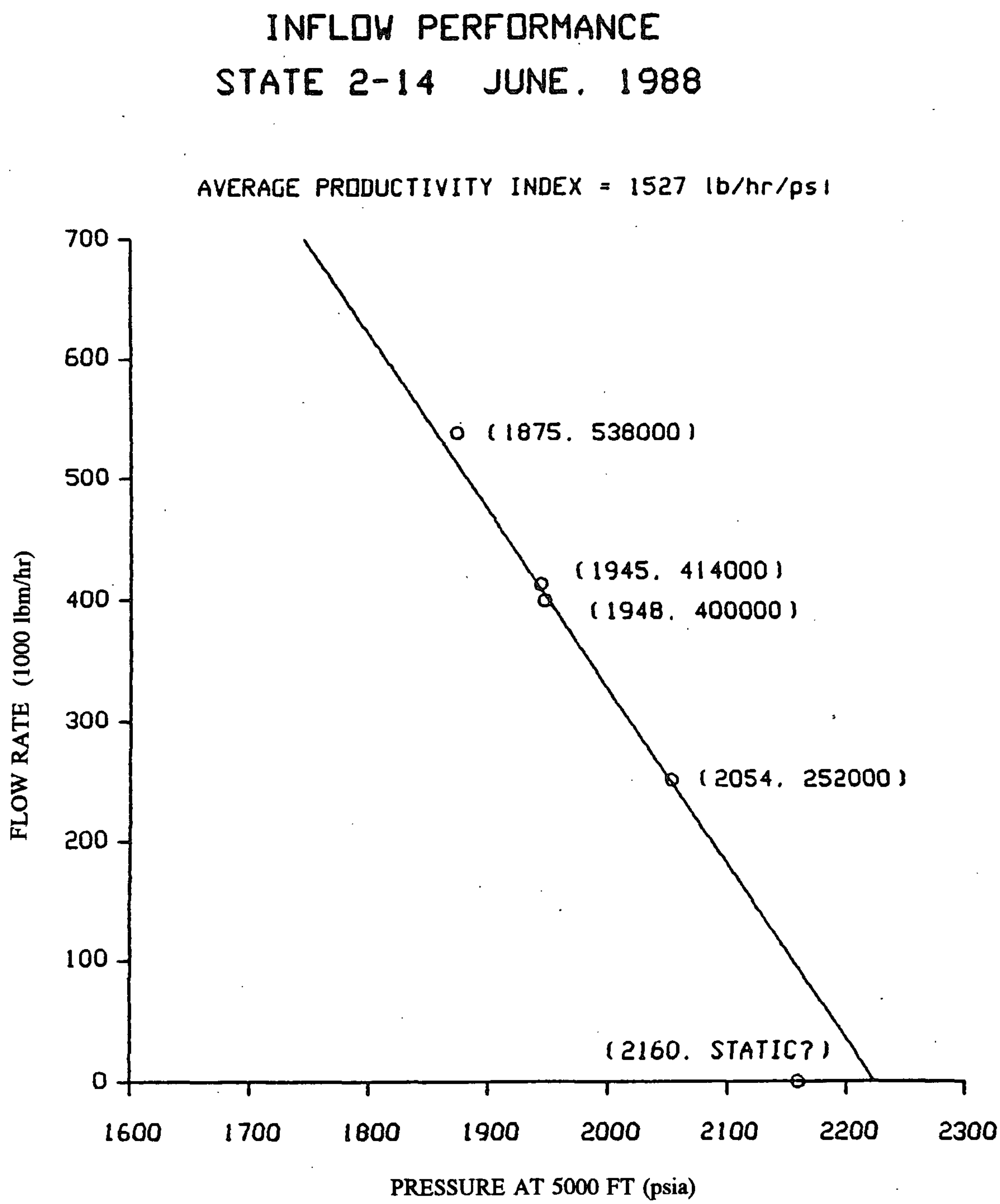

Figure 9.8 **Total Well-Flow Rate as a Function of Downhole Pressure**
(from report FF, Appendix A)

such as nitrogen lift or allowing the well to heat up for a few days with fresh water in the wellbore, would have involved more time and expense and were precluded by budget constraints. It is unlikely that the casing constriction discussed in Section 9.7.2.6 prevented the well from flowing.

9.7.2.3 *Reservoir Performance*

Two measurements of drawdown were made during flow-rate changes, with the following results:

- June 12.
  - Flow-rate change: 210,000 to 414,000 lbm/hr (95,000 to 188,000 kg/hr)
  - Initial drawdown: 104.1 psi (718 kPa). Recovered rapidly; then began to draw down again
  - Maximum drawdown: 113.6 psi (783 kPa) at 95 minutes after rate change
  - Recovery: 9.5 psi (66 kPa) in 18.5 hr

- June 14.
  - Flow-rate change: 404,000 to 538,000 lbm/hr (183,000 to 244,000 kg/hr)
  - Initial and maximum drawdown: 115.5 psi (796 kPa) at 20 minutes after rate change
  - Recovery: 42 psi (290 kPa) in 14 hr

Pressure recovery following drawdown, when additional drawdown should be expected, is further evidence of well improvement during the flow test. Unfortunately, it makes both drawdown curves difficult to analyze accurately for quantitative reservoir parameters.

At shut-in on June 20, the beginning of pressure buildup was not detected at 5,000 ft (1,524 m) until 6 minutes after shut-in, because of the effects of wellbore storage and the slow rate at which the valves could be closed. Initial buildup was 163 psi (1,124 kPa) within an hour. This was followed by a slow pressure decrease of about 0.05 psi/hr (0.34 kPa/hr) for the next 44 hours. This decrease was probably due to cooling of the fluid between the bottom of the pressure tool and the inflow zone, largely the result of density changes in the wellbore.

The following semiquantitative estimates of reservoir-performance factors and skin effect were made using a Miller-Dyes-Hutchinson semilog plot:

- Transmissivity. 233,600 md-ft

- Skin factor. +23.1

The reservoir- and well-performance estimates indicate that the reservoir has high permeability and adequate storage capacity, capable of producing at high flow rates for extended periods. However, because the data were not amenable to boundary analysis, it was not possible to estimate the life of the reservoir or the total production capacity.

9.7.2.4 *Injection-Well Performance*

The Imperial 1-13 well was used as the injection well throughout the test, with total injected brine of 72.6 million lbm (32.9 million kg).

From the start of injection, injectivity (flow rate per unit of wellhead pressure) began to decline. Injectivity at the end of the test was only about 20 percent of the initial value.

Brine injection directly from the brine pond, without residence in the brine storage tanks, occurred following interruption of the fresh-water supply on June 15, and concentration of suspended solids in the brine was probably higher for two or three days following this upset.

The observed progressive-injectivity decrease is typical of a well undergoing formation plugging by suspended solids. Injection of unfiltered fluid with some suspended solids throughout the test no doubt explains much of the reduced injectivity.

9.7.2.5 *Adverse Test Conditions and Incidents*

A number of adverse test conditions and incidents occurred during the flow test. These situations are discussed here to assist others in the geothermal industry in planning and conducting flow tests in the Imperial Valley and wherever produced brines of high TDS content occur. The events are discussed in chronological order, with indicated effects on the flow test and possible remedies.

Test start before all systems were completed. The well initially produced at a rate significantly lower than the planned initial rate. This lower flow rate was used because budgetary and schedule constraints necessitated the June 1 start before completion of the injection system. The injection system was completed on June 4. The initial low flow rate was about 60 percent of the planned rate, and its duration was longer than necessary. This longer operation at low flow rate reduced the time available for testing at higher flow rates, where more useful well and reservoir information could be obtained.

The obvious remedy is to delay test startup until completion of the injection system.

Fresh water dilution was not used at the start of the test. The short flow test in August 1987 produced little salt precipitation in the piping, vent silencer, or brine pond. Therefore, fresh water was not used at the start of the flow test in June 1988, awaiting appearance of salt precipitation to indicate the need for dilution water.

One result was that salt began to accumulate rapidly on the divider curtain in the brine pond, probably contributing to its failure and short circuiting, as discussed below.

A remedy is to begin fresh-water dilution at the start of a flow test, rather than waiting for the appearance of salt precipitate.

Plugging of pressure taps. The pressure taps for the wellhead pressure gauge and for one of the brine orifice meters plugged during the flow test. When this happened, a rodding tool was used for cleaning the ports, without shutting down the line; this allowed the test to proceed essentially without interruption. The pressure taps were promptly cleaned; therefore, the consequences of these events were insignificant.

The use of a rodding tool is an appropriate remedy for plugged pressure taps. The piping and valve for the tap must be straight and short enough to permit use of the rodding tool.

Failure to log downhole data during one rate change. When the test schedule was revised and the flow rate was changed with short forewarning on June 8, the logging contractor was unable, because of other commitments, to furnish the equipment needed for measuring downhole pressure and temperature during this drawdown period. The consequences of this particular adverse event were virtually negligible, primarily because it occurred at one of the changes at low flow rate. Some well and reservoir performance data were lost, but not enough to affect the overall results.

An apparent low-cost remedy is to set a test schedule and rigidly implement it. However, flow tests never proceed exactly as expected, and some flexibility to change the timing of events should be maintained to gain the most useful information. Another remedy is to have the necessary logging tools available throughout the flow test.

Interruption of fresh water supply. On June 15, the pump supplying fresh water for dilution of the spent brine ran out of fuel and was out of service for 4 hours. During this outage, salt precipitate formed in the atmospheric flash tank, weir box, and brine pond. During June 16 and 17, the injectivity of the injection well dropped dramatically, although it increased somewhat on June 18.

The consequences of this event were: 1) formation of salt precipitate caused operational problems for a day or two and contributed to decisions to temporarily reduce flow rate; 2) plugging the injection well may have been accelerated; and 3) salt deposition on the divider curtain may have been accelerated, contributing to divider-curtain failure, as discussed below. Although this adverse event brought about frenzied activity for a few days and may have contributed to later problems, it did not materially alter the overall test outcome.

An appropriate remedy is to monitor pump fuel consumption and maintain a reserve. This should be a high priority item for operations personnel.

Failure of the divider curtain. The divider curtain accumulated so much salt and sludge that, on June 15, brine flowed over the top of the curtain near the brine-pond inlet, short-circuiting the longer path to the opposite end of the brine pond and back. This allowed brine from the pond inlet to flow directly to the brine-pump inlet.

The consequences of this situation were that: 1) hot brine, no doubt, contributed to cavitation problems with the brine pumps, limiting the rate at which brine could be pumped from the brine pond; 2) a large amount of sludge built up near the brine-pump intake; and 3) sludge, entrained with the brine, probably increased and was eventually injected into the injection well, accelerating the plugging process.

Remedies for this adverse condition include: 1) a different design for the divider curtain, possibly using floats instead of a tensioned cable to support the curtain or; 2) a permanent baffle, such as an earthen dike, to serve the same function as the divider curtain.

Pump cavitation. Cavitation occurred at the intake of the brine and booster pumps at one time or another during the flow test. It was most severe for the brine pumps, especially when hot brine began to flow over the divider curtain directly from the brine-pond inlet.

Results of this situation were that: 1) high well-flow rate could be maintained for only short periods, because cavitation limited the rate of brine removal from the brine pond; and 2) flow rate was reduced occasionally for a few hours to permit changing or maintaining pumps.

There are several solutions to this problem—each is likely to help, but none is a complete cure: 1) pump inlets should be large, short, and free of unnecessary valves, elbows, tees, and other pipe fittings; 2) the brine-pump inlet line should be imbedded in the brine-pond berm rather than going over the top of it; 3) pumps should be kept as low as feasible; in this regard, skid mounting is better than trailer mounting; and 4) brine should be allowed to cool before arriving at the pump inlet.

Capacity of the atmospheric flash tank. The limitation for maximum flow rate of the flow-test facility was the capacity of the atmospheric flash tank. For well flow greater than about 640,000 lbm/hr (290,000 kg/hr), carry-over of brine droplets in the steam from the atmospheric flash tank was experienced. Greater flow rates increased the liquid carry-over.

The consequence of this limitation was that testing at high flow rates was not feasible .

An obvious remedy is to install an atmospheric flash tank with sufficient capacity for the maximum flow rate expected from the well. Another strategy that extends the capacity somewhat is to operate the high-pressure separator at the lowest pressure feasible; this flashes more steam in the high-pressure separator and reduces both the flow rate of separated brine and its enthalpy, thus reducing the steam flashed in the atmospheric separator. This approach is limited, however, because reducing the operating pressure of the high-pressure separator reduces its flow-rate capacity, such that it can become the limiting factor on the facility flow capacity.

Debris in the steam-flow meter. After the flow test was completed, the steam-flow meter (orifice plate) was found to be obstructed by some debris, pieces of metal or scale apparently dislodged upstream. This caused all the steam flow-rate readings to be erroneously high.

The obstruction apparently occurred early in the flow test. A correction factor was calculated by matching the indicated flash fraction with the flash fraction calculated using a computer model for hypersaline brines. By applying the correction factor to stream flow-rate data, the effect on the data was minimized.

Remedies for such flow-meter obstruction include: 1) the upstream piping should be completely disassembled (if used equipment is installed) and cleaned; corroded or scaled components should be replaced, if they cannot be thoroughly cleaned; 2) the indicated flash fraction should be compared with theoretical values early in the test period, and discrepancies should be traced and remedied to within the expected accuracy of the flow meters; and 3) provisions should be made to isolate and disassemble flow meters without affecting well flow.

9.7.2.6 *Casing Constriction*

On August 8, 1988, 44 days after the end of testing, Kennecott attempted to run a casing inspection caliper log in the State 2-14 well. Caliper tools having outside diameters of 7-1/4 and 3-1/2 in. (18.4 and 8.9 cm) stuck at approximately the same place in the 9-5/8 in. casing. The upper end of the constriction occurs about 26 in. (66 cm) below the upper end of the casing string, where the casing comes through the casing head. A television camera having a diameter of 2- 1/8 in. (5.4 cm) was run through the constriction to a point 2 ft (60 cm) below the point where the logging tools stuck. The video tape shows what may be interpreted as a heavy buildup of white scale. Unsuccessful attempts were made to obtain samples of the scale for analysis.

Because the constriction apparently did not exist at the time of the casing inspection log in April 1988, it probably formed during the flow test in June 1988. The possibility of development after the flow test is remote.

Two explanations for formation of the constriction are apparent, but both are flawed:

- Scale buildup. Normally, heavy scale buildup would be reflected in declining well deliverability, but deliverability actually increased as the test progressed. This implies that either: 1) the constriction formed early in the flow test, or 2) factors increasing the deliverability more than offset the increasing flow resistance from scale accumulation.

  Abrupt scale buildup would be expected only in a region where a high-pressure gradient exists; no such high-pressure gradient would be expected at the location of the constriction. The constriction could result from flashing in the well at these depths.

- Casing collapse. Casing collapse could occur at the beginning of a flow period because of thermal expansion of water trapped in the annulus outside the 9-5/8 in. casing. Although this is a common failure mode for production casing or tieback strings in geothermal wells, it did not occur in three previous flow tests of the well, and valves to vents of the annulus were left open during the flow test. Furthermore, casing collapse from thermal expansion of trapped water is much less likely at the upper end of the casing than it is further down the wellbore, because venting the water without casing damage is more likely near the upper end.

In short, the cause of the constriction cannot be determined with confidence with data presently available. Physical inspection of the casing section where the constriction occurred would be necessary to explain why the constriction developed.

Estimates of fluid velocity through the constriction indicate that the constriction did not constitute a critical choke during the flow test. Further evidence that the flow restriction was not severe is obtained from the pressure surveys; extrapolations of pressure profiles to the surface do not reveal any gross mismatches with measured wellhead pressures, as would be expected for a large, localized pressure drop through the constriction.

If the constriction existed during the flow test, its effect on well deliverability was not severe. The downhole-pressure profiles, as discussed above, suggest that the actual pressure drop through the constriction was small.

The constriction did not prevent the well from flowing spontaneously for the attempted high-rate flow test on June 23 and 24. A constriction causes pressure drop only when flow passes through it. Therefore, a constriction could cause apparent low deliverability because of a large pressure drop, or it could limit the maximum flow rate as a critical choke, but it would not prevent the well from flowing.

9.8 REFERENCES

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Bechtel National, Inc., December 1988, Salton Sea Scientific Drilling Program Phase 2 Well Rework and Flow Testing: (Draft) Final Report; Prepared for U.S. Department of Energy, 94 p.

GeothermEx, Inc., 1986a, First Flow Test Report, 42 p.

GeothermEx, Inc., 1986b, Second Flow Test Report, 102 p.

Mesquite Group, Inc., 1988, Well Test Results

10.0 FLUID CHEMISTRY

10.1 INTRODUCTION

The sampling and analysis of geothermal fluids, both brine and contained gases, deep within the Salton Sea Geothermal System was one of the main objectives of the SSSDP (Elders and Sass, 1988). More than 20 geochemists participated in the sampling and /or analysis of the brine, steam, and related materials from three flow tests. Other data resulted from the study of fluids obtained from a downhole sampler and from fluid inclusions from core and cuttings. The flow tests give rise to two different data sets: a) short-term flow test chemistry, and b) long-term flow test chemistry. Results of the chemical studies have been widely reported, primarily in the *Transactions of the Geothermal Resources Council*, in *EOS*, and in the *Journal of Geophysical Research*. The principal results of these studies are summarized in this section.

10.2 GENERAL CHEMISTRY AND GEOTHERMOMETRY

10.2.1 Short-Term Flow Tests

Fluid samples were obtained on December 29-30, 1985, when fluids were produced from the depth interval of 6,000 to 6,227 ft (Michels, 1986). The total depth of hole was 6,227 ft (1898 m) at the time, and the estimated formation temperature was 305°C. Little fluid had been lost to the formation being tested, and the produced fluid showed no visual trace of drilling mud after two hours of production (Thompson and Fournier, 1988). A second flow test was conducted March 20-21, 1986, when the hole depth was 10,564 ft and a liner was suspended to a depth of 10,135 ft. Brine contaminated with drilling mud and diesel oil was produced during this test and the test was terminated before the contamination could be flushed from the system. Most results from the short-term flow tests focus on the first flow test. Michels (1986) and Thompson and Fournier (1988) describe the sampling apparatus, test conditions, and sampling and analytical procedures. Six sample ports and eight pressure and temperature measurement points were available.

Analytical results by Thompson and Fournier (1988), which are somewhat different from those of Michels (1986), are reproduced in Table 10.1 and Table 10.2.

The calculated preflash composition of the brine, indicated by selected elements in fluids from the December 1985 flow test, is shown in Table 10.2 (after Thompson and Fornier, 1988). The agreement with Michels' (1986) results is good, except for calcium, where the difference exceeds 10 percent.

The brines are Na-Ca-K-Cl-type waters with very high metal and low SO_4 and HCO_3 contents. The preferred value for total dissolved solids of the reservoir fluid is 25.05 weight-percent. The calculated specific density of the preflashed reservoir fluid at 305°C and 1870 m-depth ranges from 0.9980 (no thermal loss prior to sampling) to 1.0107 +/-0.0023 g cm^{-3} (10 percent thermal loss). The Na-K-Ca geothermometer gives a temperature of 310°C, close to the measured 305°C (Thompson and Fournier, 1988). Michels (1986) obtained brine-free steam samples through in-line separator devices built into the test spools. A summary of the gas contents from Michels' study is shown in Table 10.3.

Table 10.1 Analytical Results for Brines Collected During the December 29, 1985, Flow Test of the State 2-14 Well (Thompson and Fournier, 1988).

	Port 2	Port 3	Port 4	Port 5	Port 6
Hour	~1930	1600–1610	1626–1633	1805–1815	1640–1650
Temperature, °C	235	221	189	164	154
Pressure, bars	32.5	19	9.5	5	3.5
Density (weight)	1.222	1.236	1.245	1.252	1.261
Density (hydrometer)	1.225	1.241	1.246	1.252	1.263
pH	5.47	5.44	5.06	3.08	3.89
SiO_2*	322	340	428	251	236
Fe*	1,430	1,640	1,630	1,890	. . .
Mn*	1,730	1,830	2,050	2,150	. . .
Ca*	36,100	38,600	40,900	42,500	43,200
Mg*	42.6	46.5	49.5	52.6	51.9
Sr*	495	545	580	586	590
Ba*	234	271	187	219	184
Na*	57,100	62,300	60,300	62,700	69,500
K*	18,800	20,000	20,300	21,800	22,600
Li*	241	250	270	286	281
Rb*	132	139	156	155	161
Cs*	42	43	49	46	47
Zn*	547	610	625	614	634
Cu*	6.0	8.2	8.6	8.7	9.4
HCO_3*	217	187	78	0	0
SO_4*	0	0	0	0	0
Cl*	170,800	186,200	185,100	190,000	196,800
F*	17	15	19	12	15
B*	530	411	420	437	528
Sum, wt %	28.84	31.32	31.30	32.36	33.44
TDS (measured), wt %	29.23	30.27	34.00(?)	32.22	33.33
Sum anions, equivalents	4.75	5.15	5.18	5.40	5.76
Sum cations, equivalents	4.81	5.25	5.22	5.36	5.55
Cl/Na†	2.99	2.99	3.07	3.03	2.83
Cl/K†	9.09	9.31	9.12	8.72	8.71
Cl/Ca†	4.73	4.82	4.53	4.47	4.56
Cl/Mg†	4,010	4,000	3,740	3,610	3,790
Cl/Li†	708	744	685	664	700
Ca/Na†	0.63	0.62	0.68	0.68	0.62
Ca/K†	1.92	1.92	2.01	1.95	1.91
Ca/Mg†	847	830	826	808	832
Ca/Li†	149	154	151	148	153

*In milligrams per kilogram.
†By weight.

(Tables 10.1 and 10.2 from Thompson and Fournier, JGR v. 93, B11, 1988, published by the American Geophysical Union)

Table 10.2 Calculated Preflash Concentrations of Selected Elements in Brine from a Depth of 1829-1898 m in the State 2-14 Well, December 1985 Flow Test. (Thompson and Fournier, 1988).

	Sample				
	A Dec. 29	B Dec. 29	C Dec. 29	D Dec. 29	E Dec. 30
SiO_2,* mg/kg	808	776	803	793	795
Ca, mg/kg	31,600	33,200	31,900	27,100	26,500
Mg, mg/kg	39.1	41.0	39.4	37	36
Na, mg/kg	50,600	53,100	50,900	52,800	52,700
K, mg/kg	16,500	17,300	16,700	16,700	16,500
Li, mg/kg	211	221	212	193	190
Cl, mg/kg	148,900	156,100	150,000	153,400	153,700
Total dissolved solids, wt %	24.86†	26.25†	25.05†	25.54	25.46

A, this study, assumed no thermal losses; B, this study, assumed 10% thermal losses; C, this study, reservoir fluid with density = 1 g cm^{-3}; D, reported by *Michels* [1986*b*]; E, reported by *Michels* [1986*b*].

*Calculated by the method of *Fournier* [1983].

†TDS may be as much as about 0.5 wt % greater owing to other dissolved constituents.

Table 10.3 Summary of Gas Contents, December 1985 Flow Test

Sample Port	3	4	5	6
Temp (°F)	455	395	346	328
Steam Fraction	.10513	.15474	.17781	.18522
CO_2 (ppm)				
Steam	15524	10521	9462	8988
Total Flow	1662	1638	1687	1668
H_2S (ppm)				
Steam	--	46.2	38.3	--
Total Flow	--	7.15	6.86	--

Averages on a total-flow basis: CO_2 1,664± 20, H_2S 7.01

10.2.2 Long-Term Flow Test

A long-term flow test was conducted on well State 2-14 by Mesquite Group, Inc. (Report FF of Appendix A) from June 1-20, 1988. The primary production zone was thought to be about 6,000 to 6,200 ft, with preflash reservoir temperatures of 562°F (294°C). The longer test duration and specialized flow-test equipment made possible a systematic fluid-sampling effort.

Chemical sampling was supervised by Kennecott, and the primary chemical analyses were conducted for the Electric Power Research Institute (EPRI) by Combustion Engineering, Inc., using the EPRI Mobile Geothermal Chemistry Laboratory that was on-site during the flow test. Details of the EPRI sampling and analytical procedures, and analytical results, are contained in Report JJ of Appendix A. David K. Mulliner, a consultant to Kennecott, completed the interpretation of brine chemistry data (Report GG of Appendix A) and prepared several tables and illustrations that follow in this section (Bechtel, 1988).

Three types of sampling were used during the flow test. Signature samples were taken three different times to establish the chemical and physical characteristics of total well flow. Tracking samples were taken and analyzed daily to observe changes in selected properties as a function of time. Special tests were conducted as needed to investigate flow streams or equipment of special interest. The terms—signature, tracking and special samples—are defined below.

- Signature Samples. The flow-test program was planned to stabilize flow in three rate-steps. Fluid sampling for signature analyses was conducted at each of the three rate-steps, as shown in Figure 10.1. In each case, sampling was performed significantly after the flow stabilized, usually near the end of each rate-step.

  For the signatures, samples of separated brine and separated steam were collected from the brine- and steam-outlet lines leaving the high-pressure separator. Characterizing the total well flow involved combining measurements of both brine and steam.

  The signature analyses included measurement of 64 separate chemical species. Raw condensate samples were collected to measure pH, conductivity, Eh, dissolved oxygen, anions, and carbonate. Acidified samples (1-percent nitric acid) were collected for analysis of 30 metals, by inductively coupled argon-plasma spectrophotometry. Trapping solutions were used to trap and measure hydrogen sulfide and carbon dioxide. Noncondensible gases were collected at approximately atmospheric pressure and ambient temperature for analysis by gas chromatography.

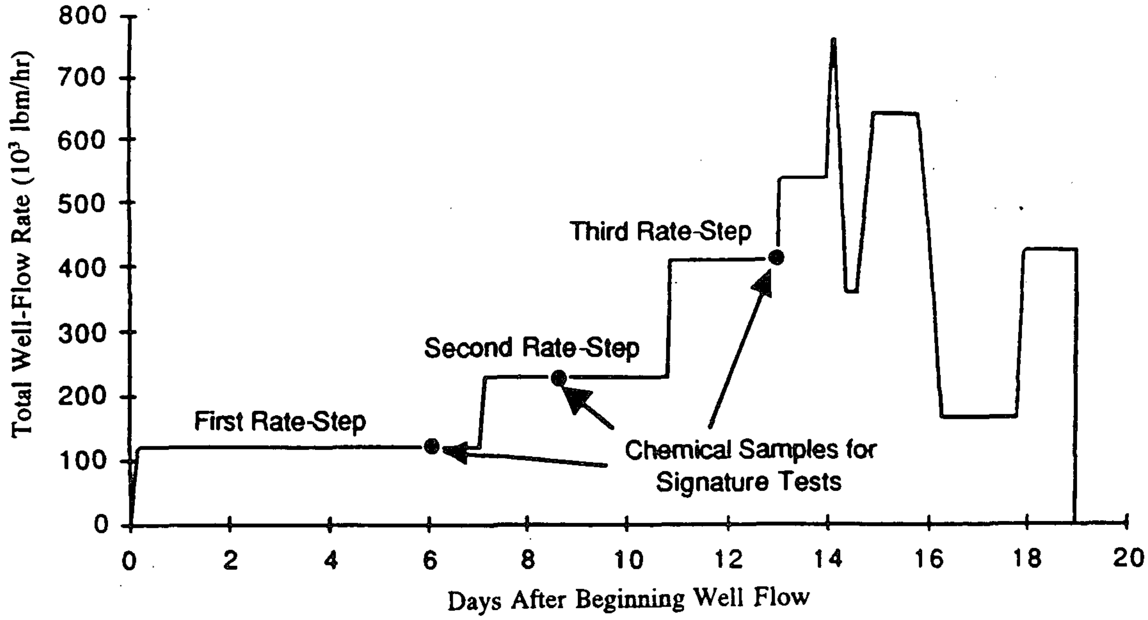


Figure 10.1 **Smoothed Flow Curve Showing Times for Collection of Samples for Signature Tests** (from report GG, Appendix A)

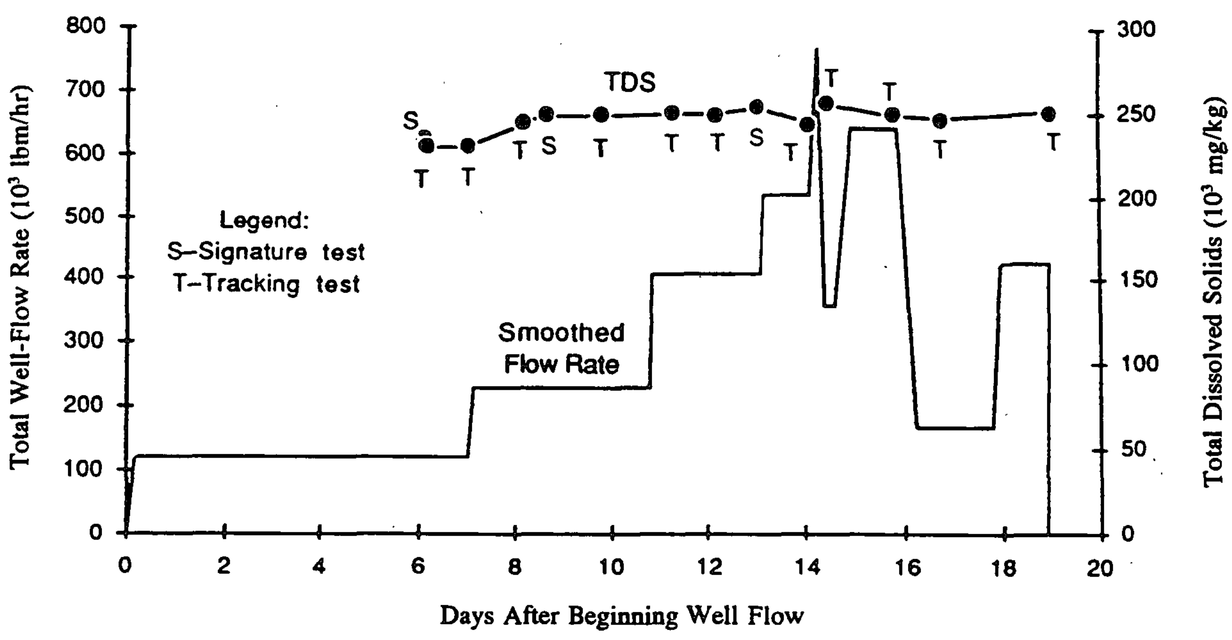


Figure 10.2 **Total Dissolved Solids of Brine Samples Taken During Long-Term Flow Test, June 1988.**
(from report GG, Appendix A)

- Tracking samples. Raw samples of separated brine were taken for immediate measurement of pH, conductivity, Eh, dissolved oxygen, and chloride. Collected samples were acidified for subsequent analysis of 30 metals by inductively coupled argon-plasma spectrophotometry.

- Special Samples. Tests for total suspended solids were conducted to provide data to help estimate the rate of sludge accumulation in the brine pond.

This section focuses on results of the signature and tracking analyses for information needed to characterize the brine produced by the State 2-14 well. It presents results of the signature tests for each flow-rate step, explores reservoir conditions inferred from the brine chemistry, and compares brine from the State 2-14 well with others in the area.

Chemical Analyses for Each Flow-Rate Step. Signature-sampling results were converted to a mass-ratio basis (i.e., mg of component per kg of total well flow) by one of the following procedures:

- Noncondensible Gases. The concentration of each noncondensible gas (NCG) component is stated in the laboratory reports as mg of component per kg of steam, downstream of the separator. Multiplying these results by the mass-fraction of steam (ratio of steam-flow rate to total well-flow rate) converts these to mg of NCG per kg of total well flow. This assumes that the amount of NCG dissolved in the separated brine is negligible.

- Dissolved Components. The concentration of each dissolved component is stated in the laboratory reports as mg of component per liter of separated brine (cooled to ambient temperature) and mg of component per liter of steam condensate. These results were first converted to mg of component per kg of separated brine by dividing the mg per liter by the density of the separated brine or steam condensate at ambient temperature. A value of 1.22 kg/L was used throughout as an average value for the density of separated brine, and 1.00 kg/L was used as the density of steam condensate.

  The concentrations in mg of component per kg of separated brine or steam condensate were then multiplied by the mass fraction of separated brine (ratio of separated brine-flow rate to total well-flow rate) and mass fraction of steam, respectively, and added to convert to mg of component per kg of total well flow. Carbonate and sulfide were converted using this procedure, even though the flash-separator conditions (i.e., carbon dioxide and hydrogen sulfide in the steam) could affect the result; therefore, the values stated for these ions should be considered as only rough indications.

Brine chemistry results from analyses of samples taken during the three rate-steps appear in Table 10.4. The following observations are readily drawn from these results:

- Total dissolved solids (TDS) increased for the second and third rate-steps. This variation of TDS is examined and discussed in more detail below.

- Sodium and potassium increased 7 and 12 percent, respectively, from the first to the third rate-step, but calcium increased 31 percent.

Noncondensible-gas content and composition results appear in Tables 10.5 and 10.6.

Noncondensible-gas content is rather high. Concentrations of the half-percent magnitude (3,928 to 5,731 mg/kg) reported here would force extensive and probably expensive measures, such as a high-capacity, noncondensible-gas removal system or reboilers for high-pressure steam, in the construction and operation of a power plant using this brine. Additional testing should confirm

Table 10.4

Brine Chemistry
State 2-14 Geothermal Well; June 1988 Flow Test
(from Mulliner, 1988; report GG, Appendix A)

	First Rate-Step Concentration in Total Well Flow (mg/kg)	Second Rate-Step Concentration in Total Well Flow (mg/kg)	Third Rate-Step Concentration in Total Well Flow (mg/kg)
Aluminum	0.159	0.202	0.199
Antimony	0.43	0.65	0.68
Arsenic	5.76	6.49	11.4
Barium	112	71	93
Boron	396	No data	No data
Cadmium	0.45	0.521	0.44
Calcium	23,093	29,650	30,220
Cobalt	0.032	0.027	0.034
Chromium	0.079	0.021	0.20
Copper	1.58	2.60	3.62
Gold	No data	No data	0.00005
Iron	1,275	1,294	1,425
Lead	77	71	69
Lithium	154	162	171
Magnesium	14.40	13.5	13
Manganese	1,158	1,105	1,113
Mercury	< 0.002	< 0.002	< 0.002
Molybdenum	0.023	0.015	0.020
Nickel	0.018	0.031	0.031
Potassium	13,304	13,077	14,868
Selenium	< 0.001	< 0.001	0.0008
Silicon	195	175	176
Silver	0.142	0.164	0.19
Sodium	49,013	51,677	52,280
Strontium	333	321	364
Tin	< 0.01	< 0.06	< 0.06
Titanium	< 0.01	< 0.01	< 0.01
Tungsten	2.96	3.15	3.19
Vanadium	0.26	0.333	0.346
Zinc	414	396	452
Carbonate	356	194	346
Chloride	142,000	147,000	147,000
Sulfate	76	No data	No data
Sulfide	5	4	No data
TDS	232,000	245,000	249,000
NCG, mass %	0.57	0.39	0.40*
Ammonia, mg/kg	370	No data	No data
Well flow rate, lbm/hr	127,000	227,000	402,000

* From 6/20/88 with 435,000 lbm/hr well-flow rate
NCG analysis data not available for third rate-step

Table 10.5

Noncondensible-Gas Content, State 2-14 Geothermal Well; June 1988 Flow Test. From Mulliner (1988); report GG, Appendix A

	First Rate-Step Concentration in Total Well-Flow (mg/kg)	Second Rate-Step Concentration in Total Well-Flow (mg/kg)	Sample on 6/20/88* Concentration in Total Well-Flow (mg/kg)
Carbon dioxide	5,642	3,897	4,005
Hydrogen	3.1	0.55	0.77
Hydrogen sulfide	22	2.2	6
Nitrogen	8.6	5.5	15
Methane	12.7	7.3	6.0
Other hydrocarbons	43	16	8.86
Total NCG	5,731	3,928	4,041
Well-flow rate, lbm/hr	127,000	227,000	435,000

*NCG analysis data not available for third rate-step

Table 10.6

Noncondensible-Gas Composition, State 2-14 Geothermal Well; June 1988 Flow Test. From Mulliner (1988); report GG, Appendix A

	First Rate-Step Concentration mass-% of NCG	Second Rate-Step Concentration mass-% of NCG	Sample on 6/20/88* Concentration mass-% of NCG
Carbon dioxide	98.44	99.21	99.10
Hydrogen	0.05	0.01	0.02
Hydrogen sulfide	0.38	0.06	0.14
Nitrogen	0.15	0.14	0.38
Methane	0.22	0.18	0.15
Other hydrocarbons	0.75	0.40	0.22
Total NCG	100.00	100.00	100.00
Well-flow rate, lbm/hr	127,000	227,000	435,000

*NCG analysis data not available for third rate-step these results before designing a power plant to use brine from this well.

Carbon dioxide comprises more than 98 percent of the noncondensible gases; this is often the case for geothermal fluids.

Hydrogen sulfide is reported as 22, 2.2, and 6 mg/kg for the three rate-steps. Additional testing to quantify the hydrogen sulfide is appropriate before application of this brine for power production. This should be done to assess whether and to what degree hydrogen sulfide abatement may be needed.

Reservoir Chemistry. Nine possible production zones were encountered during the drilling process at 2,619 to 3,160; 5,450 to 5,460; 6,110 to 6,130; 6,635 to 6,650; 8,090 to 8,100; 8,580; 8,950; 9,095 to 9,125; and 10,475 to 10,564 ft (798 to 963; 1,661 to 1,664; 1,862 to 1,868; 2,022 to 2,027; 2,466 to 2,469; 2,615; 2,728; 2,772 to 2,781; and 3,193 to 3,220 m). A 9-5/8 in. casing was cemented to a depth of 6,000 ft (1,829 m), preventing the two shallow zones from producing. However, with open-hole sections and uncemented liner below 6,000 ft (1,829 m), the seven deeper zones are all possible sources of geothermal fluids with different compositions and physical properties.

The TDS concentration and the geothermometers, Na/K, Na/Ca, and Ca/K, were examined for indications that various zones were producing in different proportions as flow rate was varied during the flow test. Results for the June 1988 flow test were compared with similar indicators from the flow test of the zone from 6,000 to 6,200 ft (1,829 to 1,890 m) in December 1985 and the flow test of zones from 6,000 to 10,564 ft (1,829 to 3,220 m) conducted shortly after well completion in March 1986. An interpretation of these data follows.

Total-Dissolved Solids. The TDS concentration is plotted in Figure 10.2, as a function of time, for the June 1988 flow test. The TDS data from the three rate-steps are supplemented in this plot with estimates of TDS concentration from the tracking tests. The chloride concentration was measured in the tracking tests, and TDS concentration was calculated from the measured chloride content. The ratio of TDS to chloride is virtually constant for highly-saline geothermal wells in the Imperial Valley. For the signature-sample results, this ratio varies from 1.63 to 1.69 for the three rate-steps. Therefore, a value of 1.66 was used to estimate TDS for plotting Figure 10.2.

A slight increase in TDS concentration apparently occurred as the well-flow rate was increased. Initially, the TDS concentration was about 232,000 mg/kg, which increased to about 249,000 mg/kg.

Figure 10.3 shows the TDS concentration, as a function of instantaneous flow rate, at the time a brine sample was taken for chemical analysis. This perspective of the TDS flow rate information leads to the same conclusion as indicated above. TDS varied little during the flow test even though the smoothed flow rate varied over a range of 7:1. For well-flow rates somewhat greater than 100,000 lbm/hr (45,359 kg/hr), the TDS concentration was about 232,000 mg/kg, increasing to about 249,000 mg/kg as the flow rate increased to 400,000 lbm/hr (181,400 kg/hr).

Geothermometers. Table 10.7 shows values for the geothermometer-cation ratios, Na/K, Na/Ca, and Ca/K, for the three rate-steps and for earlier tests in March 1986 and December 1985.

The short flow test in December 1985 was conducted with the well drilled to a depth of about 6,200 ft (1,890 m) and with casing installed and cemented to 6,000 ft (1,829 m). Thus, it was a test of the zone from 6,000 to 6,200 ft (1,829 to 1,890 m), primarily from 6,110 to 6,130 ft (1,862 to 1,868 m).

The short flow test in March 1986 was conducted shortly after completion of the well to a depth of 10,564 ft (3,220 m). At that time, the well had a cemented casing from the surface to a depth of

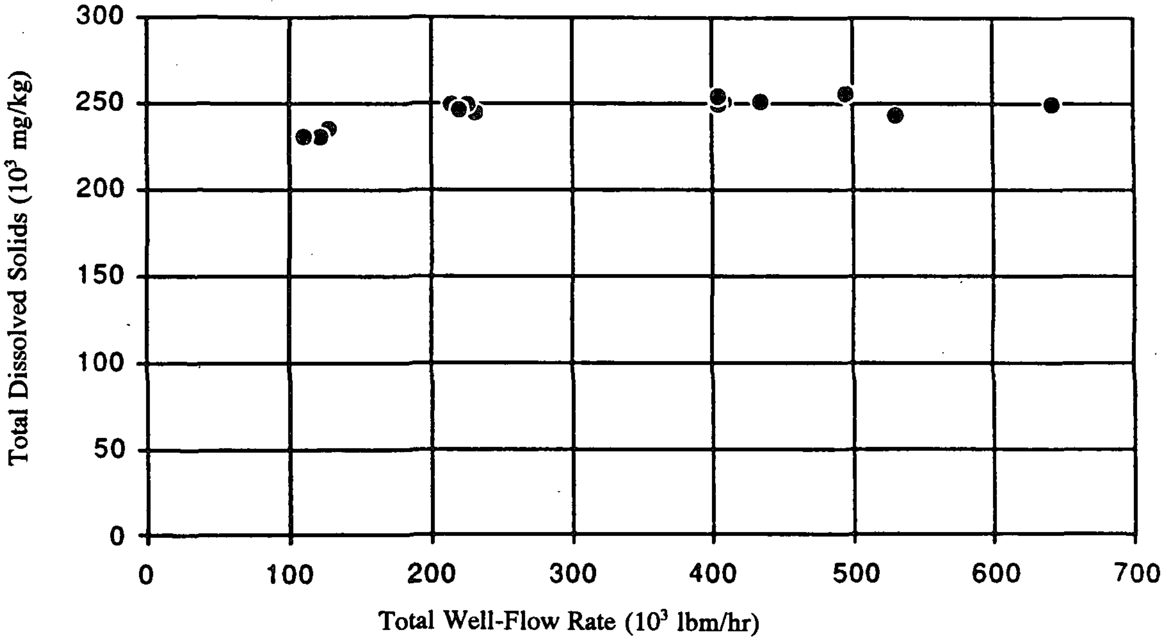


Figure 10.3 **Variation of Total Dissolved Solids with Flow Rate**
(from report GG, Appendix A)

Table 10.7

Geothermometer Cations,
State 2-14 Geothermal Well
Flow Tests of June 1988, March 1986, December 1985
[After Mulliner (1988); report GG, Appendix A]

	First Rate-Step	Second Rate-Step	Third Rate-Step	Flow Test In Mar 1986#	Flow Test In Dec 1985
Sodium (Na), mg/kg	49,013	51,677	52,280	Not available	52,661
Potassium (K), mg/kg	13,304	13,077	14,868	Not available	16,502
Calcium (Ca), mg/kg	23,093	29,650	30,220	Not available	26,515
Na/K	3.68	3.95	3.52	4.09	3.19
Na/Ca	2.12	1.74	1.73	1.99	1.99
Ca/K	1.74	2.27	2.03	2.20	1.61
TDS, mg/kg	232,000	245,000	249,000	251,000	255,000
Total well flow, lbm/hr	127,000	227,000	402,000	569,000	100,000 (approximate)

Sample may be contaminated.

6,000 ft (1,829 m) and an uncemented liner from 5,748 to 10,136 ft (1,752 to 3,089 m). Thus, any zone from 6,000 ft (1,829 m) to bottom-hole could have contributed to the flow.

During the flow test in June 1988, sodium and potassium increased slightly from the first to the third rate-step (sodium, 7 percent; potassium, 12 percent). However, calcium increased by 31 percent. Thus, the Na/Ca and Ca/K ratios changed considerably (-18 and +17 percent, respectively) while the Na/K ratio changes were less dramatic (+7 percent from the first to second rate-steps, -4 percent from the first to the third).

These changes in the geothermometer cations, Na/K, Na/Ca, and Ca/K, lead to the following conclusions:

- More than one zone is producing a significant portion of the total well flow.
- The various zones are producing different proportions of the total flow as well flow is increased.

Comparison of Na/K, Na/Ca, and Ca/K ratios for the second rate-step, during the June 1988 flow test, with the corresponding ratios for the March 1986 test shows very little difference. Therefore, production zones and relative contributions were essentially the same for the two test conditions.

Information from the December 1985 test and data from the flow test in June 1988 permit comparison of fluids produced from 6,000 to 6,200 ft (1,829 to 1,890 m)-depth with fluids from several different zones. In December 1985, fluid produced from the zone from 6,000 to 6,200 ft (1,829 to 1,890 m) appears higher in potassium and roughly equal in sodium, calcium, and TDS concentrations to fluids produced in June 1988.

Is the Brine Hazardous? Bechtel (1988) evaluated analytical results obtained by EPRI (Report JJ of Appendix A) to determine if the brine should be considered potentially hazardous. Table 10.8 compares the concentrations in

- total well flow;
- brine remaining after flash to atmospheric pressure, and;
- residue that would remain after totally drying the brine, after flash to atmospheric pressure

for 14 of the 17 hazardous metal species with the respective California Department of Health Services regulatory limits. No data were reported for beryllium, chromium (VI), and thallium.

None of the concentrations exceeds the total threshold limit concentrations (TTLC). Therefore, neither the brine nor its residue would be classified as hazardous with respect to total concentrations.

The concentrations of four metals (arsenic, barium, lead, and zinc) exceed the soluble threshold limit concentrations (STLC). However, this does not necessarily mean that the brine should be considered hazardous. The data reported lump soluble and insoluble concentrations together, without resolving these into the quantities that are soluble and insoluble in cold water. The comparisons with STLC in Table 10.8 are interpreted as indicators of possible hazardous concentrations. Additional chemical analyses would be required to quantify the soluble concentrations.

The following additional data, following perscribed analytical procedures, are needed to classify

TABLE 10.8

Concentrations Compared to Hazardous Limits

(From Bechtel 1988; Analytical Results by EPRI, Report JJ, Appendix A)

Substance	Concentration in Total Well Flow (mg/L)	Solubles + Insolubles in Brine Flashed to Atm Pressure (mg/L)	STLC* (mg/L)	Concentration in Total Well Flow (mg/kg)	Concentration in Brine Flashed to Atm Pressure (mg/kg)	Concentration in Dried Residue (mg/kg)	TTLC** (mg/kg)
Antimony	0.84	1.14	15	0.68	0.93	3	500
Arsenic	13.9	18.8	5.0	11.4	15.4	46	500
Barium	137	187	100	112	153	460	10,000
Beryllium	No data	No data	0.75	No data	No data	No data	75
Cadmium	0.636	0.856	1.0	0.521	0.701	2	100
Chromium (VI)	No data	No data	5	No data	No data	No data	500
Chromium	0.097	0.132	560	0.079	0.108	< 1	2,500
Cobalt	0.041	0.056	80	0.034	0.046	< 1	8,000
Copper	4.42	6.02	25	3.62	4.93	< 1	2,500
Lead	93	128	5.0	77	105	< 1	1,000
Mercury	< 0.002	< 0.002	0.2	< 0.002	< 0.002	< 1	20
Molybdenum	0.029	0.039	350	0.023	0.032	< 1	3,500
Nickel	0.038	0.052	20	0.031	0.042	< 1	2,000
Selenium	< 0.001	< 0.001	1.0	< 0.001	< 0.001	< 1	100
Silver	0.23	0.31	5	0.19	0.25	1	500
Thallium	No data	No data	7.0	No data	No data	No data	700
Vanadium	0.422	0.574	24	0.346	0.471	1	2,400
Zinc	551	750	250	452	615	1,844	5,000

* STLC—Soluble Threshold Concentration Limit (California)

** TTLC—Total Threshold Concentration Limit (California) the brine as hazardous or nonhazardous with respect to the California limits:

- Soluble concentrations of the metals for which the total concentration exceeds the STLC (arsenic, barium, lead, and zinc)
- Total and soluble concentrations of the metallic species that were not reported (beryllium, chromium (VI), and thallium)

Analytical results for the brine-pond sludge are described in detail in section 12.

Comparison with Other Wells in the Area. The fluid chemistry and static (non-flowing) temperatures for the State 2-14 well were compared with those for 11 other wells in the vicinity, for which data are available as nonproprietary information.

Chemistry. Table 10.9 lists chemical composition data for the State 2-14 well (for the third rate-step) and 11 other wells shown in Figure 10.4. Comparing the order of listing in Table 10.9 with the locations in Figure 10.4 shows that the wells are listed left to right in Table 10.9 in roughly a southwest-to-northeast direction. Additional information about relative depths of the wells is shown in Figure 10.5, using the same order as in Table 10.9. The comparisons may be summarized as follows:

- TDS. In general, wells in the northeast part of this area have higher TDS concentrations. Although depth has often been reported as an important factor with respect to TDS, the River Ranch No. 1 and Sportsman No. 1 wells produced fluids with relatively high TDS concentrations from relatively shallow production zones, starting at about 4,000 ft (1,219 m)-depth.

- Sodium, Potassium, and Calcium. Wells in the northeast part of this area tend to have lower Na/K ratios, except for the State 2-14 well; this may be due, at least in part, to the greater depth of its production zones. Likewise, wells in the northeast part of this area tend to have lower values of Na/Ca ratio. Generalizations concerning Ca/K are not apparent.

- The sodium, potassium, and calcium concentrations for fluids produced during the December 1985 test of the State 2-14 well and those from the Hudson No. 1 well, about one-half mile away, are strikingly similar, as shown below:

	Hudson No. 1	State 2-14
Sodium, mg/kg	52,250	52,661
Potassium, mg/kg	16,500	16,502
Calcium, mg/kg	26,917	26,515
Na/K	3.17	3.19
Na/Ca	1.94	1.99
Ca/K	1.63	1.61

In December 1985, an interval between 6,000 and 6,200 ft (1,829 to 1,890 m) of the State 2-14 well was tested, and the production zone in the Hudson No. 1 well was at about 6,000 ft (1,829 m). Thus, the same reservoir zone may be involved in production from both wells.

Although TDS concentrations reported in the two cases are different (273,000 mg/kg for Hudson No. 1 and 255,000 mg/kg for State 2-14), there may be no real difference. An anion-cation check of the two data sets revealed that the report for Hudson No. 1 shows apparent excess chloride of about 30,000 mg/kg, and the data set for State 2-14 implies an apparent 10,000 mg/kg excess chloride. Subtracting the calculated excess chloride from the reported TDS concentrations yields virtually equal values for TDS concentrations: 243,000 mg/kg for Hudson No. 1 and 245,000 mg/kg for State 2-14.

Table 10.9

Brine Chemistry of State 2-14 and Nearby Geothermal Wells
(mg/kg of total well flow)
[After Mulliner, 1988; Report GG, Appendix A, as reported in Bechtel, 1988]

	Sinclair No. 4	Sinclair No.3	Magmamax No. 1	Woolsey No. 1	Elmore No. 1	State No. 1	IID No. 2	IID No. 1	Sportsman No. 1	River Ranch No. 1	**State 2-14**	Hudson No. 1
Ammonia	—	283	304	254	342	—	—	341	—	—	370	—
Arsenic	8	8	—	—	—	—	—	10	—	—	11	—
Barium	—	—	—	—	—	—	208	196	—	167	93	—
Boron	633	450	117	121	—	158	325	325	124	—	396	—
Calcium	22,492	12,125	17,583	13,250	26,083	17,667	24,000	23,333	28,725	31,667	30,220	26,917
Chloride	128,825	78,042	109,417	95,667	153,333	105,833	129,167	129,167	167,500	173,333	147,000	173,333
Copper	—	—	0.8	1	—	2	3	7	—	—	4	—
Iron	—	—	233	121	3,833	1,000	1,667	1,742	3,500	1,750	1,425	1,667
Lead	34	67	39	24	74	67	67	70	—	81	70	—
Lithium	239	41	42	54	233	150	175	179	125	250	171	267
Magnesium	613	650	92	142	150	23	8	45	15	183	13	—
Manganese	850	342	529	363	825	792	1,142	1,250	—	1,583	1,113	1,833
Potassium	12,425	6,517	8,667	7,500	18,917	11,667	13,750	14,583	20,000	18,583	14,868	16,500
Silicon	75	—	200	125	—	—	333	333	4	—	176	—
Silver	—	—	0.3	—	—	1	—	1	—	—	0.19	—
Sodium	48,700	30,283	42,750	36,083	53,500	39,833	44,167	42,000	58,333	57,167	52,280	52,250
Strontium	358	300	—	296	608	—	367	500	—	700	364	650
Zinc	—	—	183	92	—	417	417	658	—	—	452	—
TDS	215,000	129,000	180,000	154,000	258,000	178,000	216,000	215,000	278,000	285,000	249,000	273,000
pH	5.3	5.3	5.6	6.0	—	—	—	5.2	—	—	5.3	

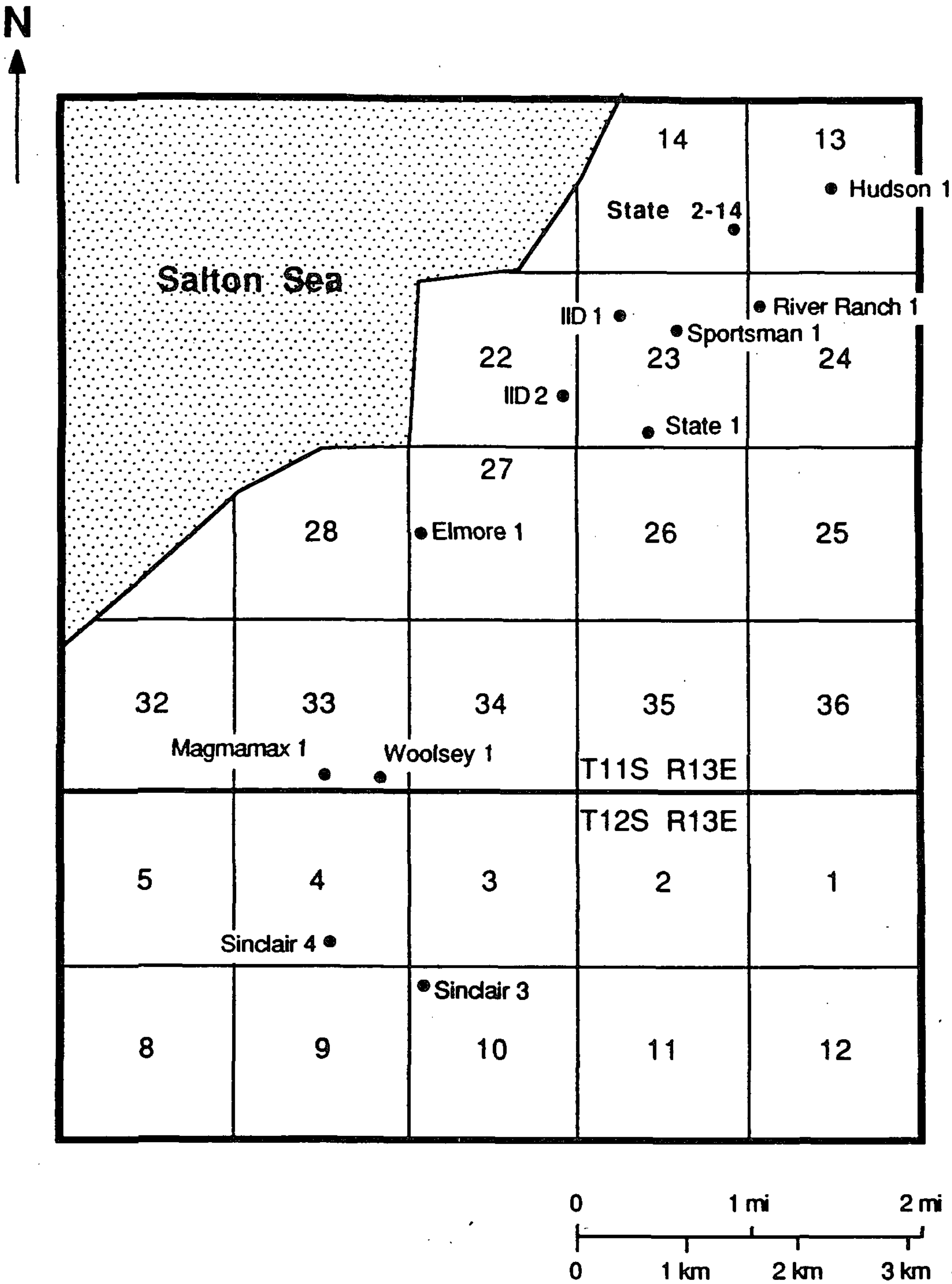
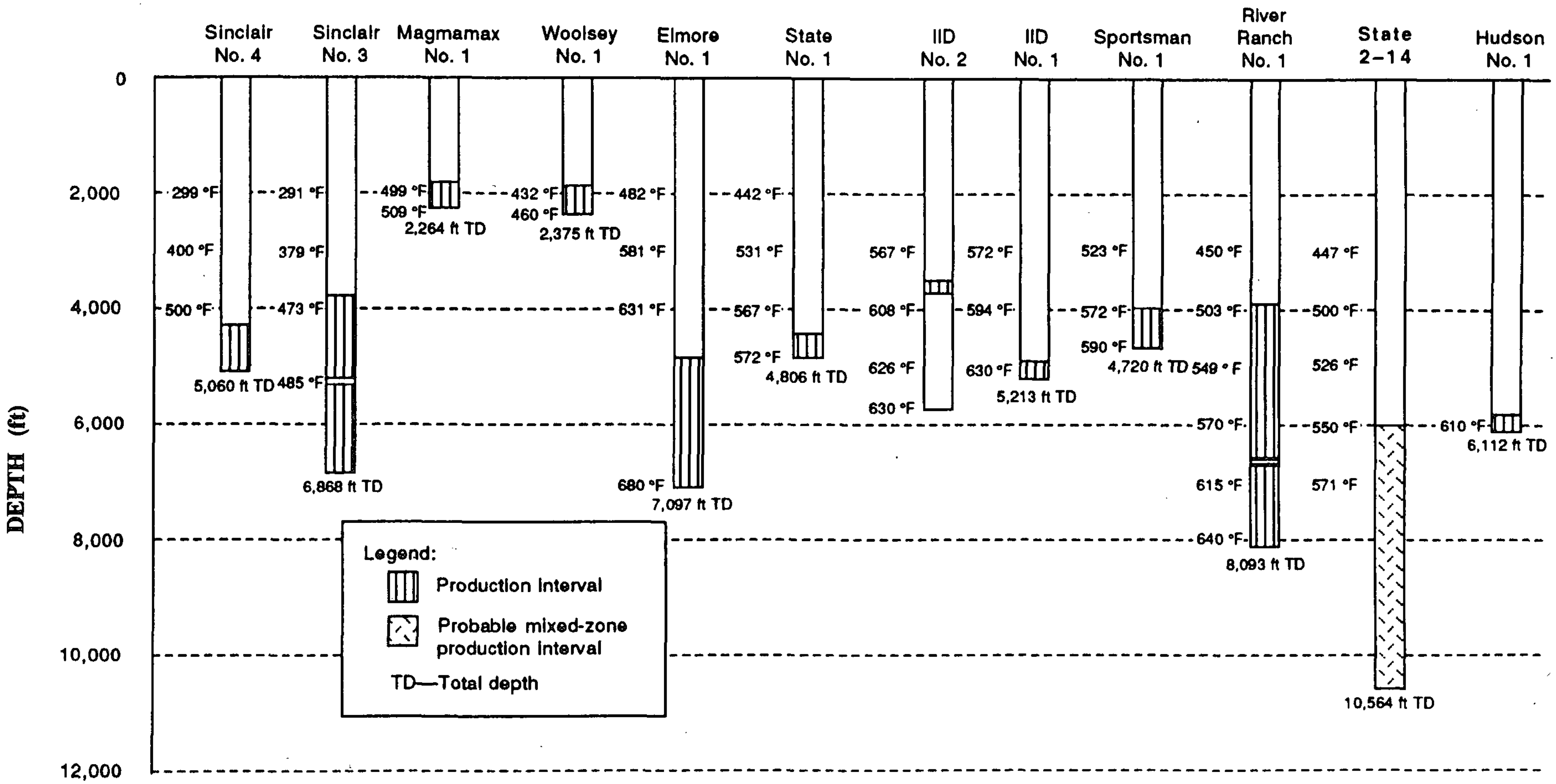


Figure 10.4 Locations of Other Wells in the Salton Sea Field in Relation to the State 2-14 Well (from report GG, Appendix A)



	Sinclair No. 4	Sinclair No. 3	Magmamax No. 1	Woolsey No. 1	Elmore No. 1	State No. 1	IID No. 2	IID No. 1	Sportsman No. 1	River Ranch No. 1	State 2-14	Hudson No. 1
Na/K	3.92	4.65	4.93	4.81	2.83	3.41	3.21	2.88	2.92	3.08	3.52	3.17
Na/Ca	2.17	2.50	2.43	2.72	2.05	2.25	1.84	1.80	2.03	1.81	1.73	1.94
Ca/K	1.81	1.86	2.03	1.77	1.38	1.51	1.75	1.60	1.44	1.70	2.03	1.63
TDS, mg/kg	215,000	129,000	180,000	154,000	258,000	178,000	216,000	215,000	278,000	285,000	253,000	273,000

Figure 10.5 **Characteristics of Fluids from Geothermal Wells in the Vicinity of State 2-14**
(from report GG, Appendix A)

Therefore, geothermal fluid produced from the zone between 6,000 to 6,200 ft (1,829 to 1,890 m)-depth in the State 2-14 well and fluid produced by the Hudson No. 1 well probably come from the same source.

Temperatures. Figure 10.5 shows static temperatures at depths from 3,000 to 7,000 ft (914 to 2,134 m). Temperatures in the State 2-14 well track those in the nearby River Ranch No. 1 well from 3,000 to 5,000 ft (914 to 1,524 m). At 6,000 and 7,000 ft (1,829 and 2,134 m), the temperatures are 23 and 20 °F (13 and 11 °C) higher, respectively, in the River Ranch No. 1 well.

Temperatures in the State 2-14 well are 120 to 130 °F (67 to 72 °C) lower than those in the Elmore No. 1 well for all depths from 3,000 to 7,000 ft (914 to 2,134 m). Likewise, temperatures in the State 2-14 well are 80 to 120 °F (44 to 67 °C) lower than those in the IID Nos. 1 and 2 wells from 3,000 ft (914 m), to total depths for the IID wells: 5,213 ft (1,589 m) for IID No. 1, and almost 6,000 ft (1,829 m) for IID No. 2.

10.2.3 Chemical Sampling — University of Utah Research Institute (UURI)

The University of Utah Research Institute (UURI) completed an independent sampling and analytical experiment during the long-term flow test. Analyses of three samples taken during a one hour period from 9:00 to 10:00 a.m. on June 8, corresponding to the lowest flow rate of the test, are shown in Table 10.10. Sampling procedures, described in Report OO of Appendix A, were designed to evaluate and prevent the precipitation of silica during collection. Comparison of the silica concentrations for the low-flow portions of the test, shown in Table 10.10, indicates that silica precipitated in the 1/4-in. cooling coil when sample MA-52 was taken. Silica concentrations were similar for both methods in Samples MA-50 and MA-51. However, the variability of the silica concentrations from sample to sample in a closely spaced time interval indicated that silica may be precipitating in the wellbore, or, more likely, the separator.

Gas analyses for the three low flow-rate samples, and four high flow-rate samples, (taken 9:30-11:30 a.m., June 17) are shown in detail in Table 10.11.

10.3 OTHER GEOCHEMICAL STUDIES

A number of specialized studies have been completed on the geothermal brines. Some key results are indicated here.

10.3.1 Downhole Fluid Sampling

Solbau et al. (1986) describe a high-temperature, downhole fluid sampler that was modified to extend the temperature rating to 350°C. The ability of the sampler to operate at high temperatures in harsh downhole conditions was demonstrated by retrieving a bottom-hole (10,200 ft) sample from well State 2-14 where other samplers had been run numerous times with little success.

The results of all downhole fluid-sampling efforts are reported by Grigsby et al. (1987). A total of three sampling runs were made to depths of 1,800 m and temperatures of 300°C in December 1985, and ten sampling runs were made to 3,150 m and 350°C in March 1986. The uncontaminated brine from the March test at 351°C and 296 bars is characterized by: ρ= 0.998 (g/cm3); 0.77, SiO_2, 29.9 Ca, 57.2 Na, 18.9 K, 1.56 Fe, 1.40 Mn, 157 Cl, 2.33 HCO_3, 0.16 H_2, 0.017 N_2, 0.33 CH_4, 0.004 H_2S, 0.007 SO_4, 0.30 B, 0.11 Br, 0.27 NH_4, 0.58 Zn, 0.12 Pb, 0.004 Ag (all in g/Kg); and -75.0 δD and +2.00 $\delta^{18}O$ (o/oo).

Table 10.10
UURI Analyses from the State 2-14 Well; June 8, 1988

The samples listed were taken through a 1/4 in. stainless-steel cooling coil. Concentrations are in mg/kg. The conditions at the time these samples were taken were: wellhead temperature = 490 deg F; wellhead pressure = 508 psig; separation temperature = 400 deg F; separation pressure = 204 psig; combined steam and brine flow = 126,108 lbs/hr (from UURI, report OO, Appendix A).

Sample	MA-50	MA-51	MA-52
Na	60789	60479	59568
K	18944	19208	18944
Ca	30777	30325	29984
Mg	47.7	50.4	48.2
Fe	1893	1874	1846
SiO_2	575	441	386
B	448	456	449
Li	238	240	236
Sr	459	461	456
Zn	565	579	565
Ag	1.34	N.D.	1.88
As	15.6	19.5	17.8
Ba	253	262	256
Cd	2.55	2.72	2.56
Cu	3.74	3.25	3.01
Mn	1634	1660	1637
Pb	118	124	122
NH_4	395	N.A.	412
HCO_3	10.0	N.D.	N.D.
Cl	163000	162000	162000
F	3.19	2.94	2.91
SO_4	N.D.	N.D.	N.D.
Br	103	110	104
I	5.00	6.70	2.9
Density	1.22	1.22	1.22

Table 10.11
UURI Gas Analyses from the State 2-14 Well; June 8, 1988

Concentrations are in parts per million, by weight. WHT = wellhead temperature (deg F); WHP = wellhead pressure (psig); SEP T = separation temperature (deg F); SEP P = separation pressure (psig); TOTAL FLOW = combined steam and brine flow rates (lbs/hr), measured downstream of the separator (from UURI, report OO, Appendix A).

Sample	MA-53	MA-54	MA-55	MA-61	MA-62	MA-65	MA-66
Date	6/8/88	6/8/88	6/8/88	6/16/88	6/16/88	6/16/88	6/16/88
Time	10:00	10:10	10:23	09:45	10:10	11:50	12:00
WHP	508	508	508	504	504	505	505
WHT	490	490	490	498	498	498	498
SEP P	204	204	204	216	216	237	237
SEP T	400	400	400	415	415	415	415
STEAM FRACT	0.15	0.15	0.15	0.13	0.13	0.15	0.15
TOTAL FLOW	126,108	126,108	126,108	535,756	535,756	496,075	496,075
H_2O	9.76E+5	9.76E+5	9.75E+5	9.84E+5	9.84E+5	9.85E+5	9.85E+5
CO_2	2.30E+4	2.34E+4	2.45E+4	1.52E+4	1.57E+4	1.47E+4	1.47E+4
H_2S	1.88E+2	1.91E+2	1.96E+2	1.02E+2	1.14E+2	7.36E+1	1.36E+2
NH_3	4.22E+2	4.28E+2	4.31E+2	4.2E+2	4.29E+2	3.45E+2	3.77E+2
Ar	3.09E-1	3.61E-1	1.04E+0	8.28E-1	1.47E-2	1.51E-1	4.84E-2
N_2	3.65E+1	4.91E+1	4.68E+1	5.75E+1	2.73E+1	3.02E+1	2.44E+1
CH_4	4.92E+1	5.23E+1	6.80E+1	2.40E+1	1.90E+1	2.38E+1	2.39E+1
H_2	9.22E+0	9.69E+0	9.89E+0	2.10E+0	1.43E+0	1.96E+0	1.84E+0

10.3.2 Fluid-Inclusion Studies

Roedder and Howard (1988) completed a comprehensive study of 191 fluid inclusions in calcite, quartz, K-feldspar, and epidote from small subcores and cuttings from depths of 604-2,560 m in State 2-14. The temperatures of homogenization (Th) range from a minimum of 208°C to >500°C, but most samples fall in the 250°-340°C range. The samples vary widely in salinity. The Th of four vapor-rich inclusions, homogenizing in the vapor phase, ranges from 427° to >500°C.

An examination of Th-versus-depth shows that the bulk of the Th values, both for primary and secondary inclusions, are rather close to present well temperatures. Th values at 604 m (1,983 ft) exceed the well temperatures by about 70°C, suggesting temperatures have dropped since the inclusions were formed, most likely due to the circulation of cooler surface waters. Other samples show Th far below well temperatures. No daugher minerals were seen, and no clathrates were recognized on freezing. Vapor-rich inclusions under pressure were found from a wide range of depths, suggesting that effervescence had occurred. Low-salinity fluids (1.2-4.0 weight-percent) were found as deep as 1,939 m. In summary, the data suggest a complex history of fluids surrounding these samples. A combination of processes—such as thermal metamorphism of evaporites and other sediments and mixing of water from metamorphic-dehydration reactions with partly evaporated Colorado River water—can explain the observed data.

10.3.3 Other Brine Studies

A number of other studies focused upon specialized properties of the brines produced from the flow tests; a complete review is beyond the scope of this report. Hammond et al. (1988) discussed the radioisotope-decay chains measured in the brines and the interaction of various radioisotopes with reservoir rocks. Laul and Smith (1987) discussed the "disequilibrium of natural radionuclides in the brines" and suggested analogies to nuclear waste in a breached salt repository. Campbell et al. (1987) discussed the composition of the SSSDP brines and compared them to ocean floor ridgecrest hydrothermal-vent waters and the Red Sea brines. Valette-Silver et al. (1987) discussed the occurrence of Be and trace-element chemistry in State 2-14 fluids. Janik and Truesdell (1987) investigated gas geothermometers applied to separated steam from the December 1985 flow test, but found the temperatures much too low (220°C compared to 300°C measured downhole) to be reliable.

Darnall (1988; Report LL, Appendix A) examined metal-ion concentrations in geothermal brines from the June 1988 (long-term) flow test. Samples were taken from the two-phase flow line near the wellhead and from the weir box. An attempt was made to obtain steam-free brine from flow line sampling. The analytical data, shown in Table 10.12, require interpretation and explanation. None of the flow line samples indicated silver above the detection limits which ranged from 140-540 ppb. On the other hand, the weir box sample showed the presence of nearly 1 ppm (890 ppb) silver. Other data indicates that the precipitate contained iron, silica, lead, arsenic, cadmium and copper. The severe loss of copper, arsenic and cadmium suggests losses due to sulfide formation, and hence silver and gold would be lost as sulfides. Gold concentrations in the flow line samples were uniformly low and ranged from 0.0325 to 0.120 ppb. Platinum was detected at the 5 ppb level in two of the flow line samples, but was below detection limits in four other samples.

McKibben et al. (1988) studied sulfur-isotope variations in minerals and fluids from State 2-14 and other Salton Sea-area geothermal wells. These isotope data demonstrate that H_2S in the Salton Sea Geothermal System (SSGS) brines is generated by partial hydrothermal reduction of minerals in the host sediments, and that no magmatic input of sulfur is indicated. SO_4^{2-} reduction is promoted by interaction of the sediments with an upwelling diapir of Fe^{2+}-rich hypersaline brine. Base metals are carried in the brines as chloride complexes, and vein-sulfide precipitation within the reservoir occurs during brine dilution and oxidation at an interface between the hypersaline brines

Table 10.12

Neutron-Activation Analysis of Precious Metals in Salton Sea Geothermal Water: Well State 2-14

(from Darnall, 1988; Report LL, Appendix A)

	Metal Concentration (PPB)*					
Sample	Ag	Au	Pt	Ir	Pd	Comments
DMA 05	ND<540.	0.0717±0.0122	ND<16 -	—	—	Sample from flowline; collected 6/3/88 after 500 mL passed through sampler.
DMA 08	ND<290.	—	—	—	—	Sample from flowline; collected in dilute nitric acid immediately after collection of DMA 05.
DMA 02	—	0.0586±0.0047	5.25±1.47	—	—	Sample from flowline (unacidified); collected immediately after DMA 08.
DMA 03	—	0.0683±0.0057	4.80±1.10	—	—	Sample from flowline (unacidified); collected 6/4/88 after 1000 mL passed through sampler.
DMA 06	ND<500.	—	—	—	—	Sample from flowline (acidified); collected immediately after DMA 03.
DMA 01	890.±134	0.0258±0.0054	ND<12	—	—	Sample collected 6/5/88 at Weir box after geothermal water exposed to atmosphere. Sample was filtered through 0.45µ filter prior to collection.
DMA 07	ND<140.	—	—	ND<0.8	—	Sample from flowline; collected 6/5/88 and acidified.
DMA 04	—	0.0325±0.0036	ND<4	—	ND>6.5	Sample from flowline (unacidified); collected immediately after DMA 07.
179	ND<140	0.120±0.008	ND<8.4	—	—	Sample from flowline (acidified); collected immediately after DMA 04.

*ND - Not Detected; below limit of detection and overlying, more oxidized, lower-salinity fluids.

Leslie et al. (Report NN, Appendix A) measured a wide range of isotopes in the ^{238}U, ^{235}U, and ^{232}Th decay chains in geothermal brines collected during the June 1988 (long-term) flow test. High concentrations of radium, radon and lead isotopes are generated and maintained by the input of these isotopes from solid phases into brine: by both recoil and leaching processes; by the high-chloride content of the brine, which complexes radium and lead; and by the apparent absence of suitable, unoccupied, adsorption sites. In contrast, uranium, thorium, actinium, bismuth and polonium isotopes all have low concentrations due to efficient sorption from brine to rock.

McKibben and Williams (Report MM, Appendix A) studied fluid and solid samples from the long-term flow test and found that significant levels of Pt group elements and Au were not being transported by the Salton Sea geothermal brines.

Michels (1987) discusses the "salinity stabilization for a non-convecting brine in a temperature gradient," based on observations of State 2-14 data.

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11.0 OTHER GEOSCIENCE STUDIES - STATE 2-14

11.1 INTRODUCTION

A variety of other studies were completed during the SSSDP that did not focus on temperature and heat flow, production testing, or fluid chemistry. These studies have also been reported in the literature or presented at technical meetings. A brief review is in order for this summary report.

11.2 GEOPHYSICAL STUDIES

11.2.1 Seismic Monitoring of the June 1988 Flow and Injection Test

As part of the SSSDP long-term flow and injection test, Lawrence Livermore National Laboratory (LLNL) deployed a network of recording stations to determine if any sources of seismic energy related to the test were measurable at the surface. The study is reported by Jarpe et al. (1988; Report KK, Appendix A). The network included seven three-component stations within a 3 km radius of the two wells (2-14 and 1-13), and three small groups of six- to nine-sensors (arrays) within a 1000 m-square area. The network of three-component stations, which primarily provide phase-arrival times, was used to detect and locate microearthquakes in the traditional manner. The network of three arrays, which can provide direction, velocity, and depth information for any incomming seismic energy, was used to monitor all possible low-frequency (3-25 Hz) sources of seismic energy originating from the flow and injection test.

The seismic network, sensitive enough to be triggered by magnitude 0.0 or larger events, measured no impulsive microearthquakes in the vicinity of the flow test in the 8-month period (September 1987- June 2, 1988) before the test and only one event during the flow test. This small (magnitude -0.5) seismic event occurred when well State 2-14 was first opened, and was followed by an air wave. The source of this event was not determined, but the event provided a useful opportunity to compare the various monitoring capabilities of the arrays deployed. The negative results of this experiment indicate that neither stress nor thermal effects were large enough to induce microearthquakes larger than the magnitude 0.0 threshold during (or before) the flow test.

11.2.2 Vertical Seismic Profile Study

As part of the SSSDP, a vertical seismic profile (VSP) survey was conducted by the Lawrence Berkely Laboratory (LBL) to obtain information on seismic velocity near the well; to identify reflective horizons within and beneath the well; to detect evidence of fracture zones surrounding the well; and to investigate seismic shear-wave velocity distributions (Daley et al., 1988). A three-component geophone was used to collect VSP data from P- and S-wave sources at two distances from the well. Survey results showed a reflection from the known fractured reservoir between 2,042 and 2,105 m (Daley et al. 1988), and two possible zones of transition in properties. Near 670 m, there were changes in P- and S-wave velocity and S-wave anisotropy which, combined with the appearance of anhydrite alteration, may indicate the "cap-rock" zone. The 1,190 to 1,280 m zone corresponds to an increase in epidote mineralization and large-scale hydrothermal alteration. Indications of fracturing were observed from a zone near 915 m. The area surrounding the well site appears to have a more complicated geometry of anisotropy, as indicated by shear-wave data.

11.2.3 Borehole Gravity Measurements

Borehole gravity measurements were completed over a depth range from 1,737 to 1,027 m in State 2-14 by EDCON, Inc. (1986), under contract to Lawrence Livermore National Laboratory (LLNL). The survey data and interpretation are reported by Kasameyer and Hearst (1988). The survey was conducted in March 1986 and measurements started at a depth of 1,737 m, near the bottom of the production casing, and were stopped at 1,027 m because of difficulties with the equipment. Forty-six readings were taken with the instrument clamped at 36 different depth stations, selected to encompass zones of uniform density determined from the density log.

A gravimetric-density log was obtained for the interval 1,027-1,737 m that in general is a good match to the gamma-gamma densities reported by Paillet (1986). The gamma-gamma density log and the borehole gravimeter data, coupled with surface gravity data, were used to infer lateral changes in density away from the borehole.

The borehole gravity measurments indicate that the dense rocks penetrated between 1 and 2 km depth must extend several kilometers from the well. There is no evidence from the data that the SSSDP well is near the edge of the high-density zone it penetrates. The densified zone coincides with much of a broad thermal anomaly that has been found to the northeast of the Salton Sea geothermal field (Kasameyer and Hearst, 1986).

11.3 PHYSICAL PROPERTY STUDIES

A number of physical property and petrophysical studies have been completed using core samples from State 2-14. Tarif et al.(1988), reported a detailed study of acoustic properties and their relation to microstructure and field measurements. Noblet and McDowell (1987) reported bulk density, sonic velocity, and porosity determinations on 111 core samples. Lin and Daily (1987) reported electrical-resistivity, ultrasonic-velocity, and brine-permeability determinations for a single siltstone core from a depth of 1,158 m. Readers are referred to these papers for detailed information.

11.4 TRANSPORT PROPERTIES AND STUDIES

The transport of heat and fluids within the SSGS has been addressed on two bases: through laboratory measurements of drill core from State 2-14, and from observations of non-advection within the SSGS.

Lin and Daily (1988) reported electrical-resistivity, ultrasonic-velocity, and brine-permeability measurements, at pressures and temperatures simulating borehole conditions, for two drill-core samples. Both samples were siltstone; the first sample from 1,158 m-depth, and the second from 919 m-depth. Both samples showed a strong anisotropy in resistivity and ultrasonic velocity, measured perpendicular and parallel to the sample axis. The brine permeability of the first sample decreased from about 5 microdarcies (μD) to about 1.6 μD during the experiment, as the samples were exposed to higher pressures and temperatures. The second sample (919 m) permeability had the same trend, but the permeability values were about three orders of magnitude larger.

Yearsley (1989) completed laboratory measurements of transport properties and coupled-flow phenomena on six "undisturbed" core samples from State 2-14. The samples varied from shale to siltstone to sandstone, with varying amounts of chlorite and epidote, and some pyrite, calcite and anhydrite. Sample depths were: 3,808 ft (2); 3,113 ft; 8,156 ft; 8,591 ft; and 6,037 ft. Yearsley determined hydraulic conductivity, thermal conductivity, electrical resistivty, and formation factors for all samples. He found that both chemico-osmosis and diffusion-osmosis can cause pore-fluid movement in cores from State 2-14; that chemico-osmosis tends to dominate for core samples saturated with dilute fluid (1 weight-percent TDS), but that diffusion-osmosis tends to dominate when the core samples are saturated with hypersaline brine (20-25 weight-percent TDS). Electro-osmosis and thermo-osmosis were thought not to be important in these rocks. Not surprisingly, hydraulic conductivity is overwhelmingly controlled by the presence or absence of fractures. This casts some doubt upon the importance of individual, small-sample measurements in estimating in-situ transport properties.

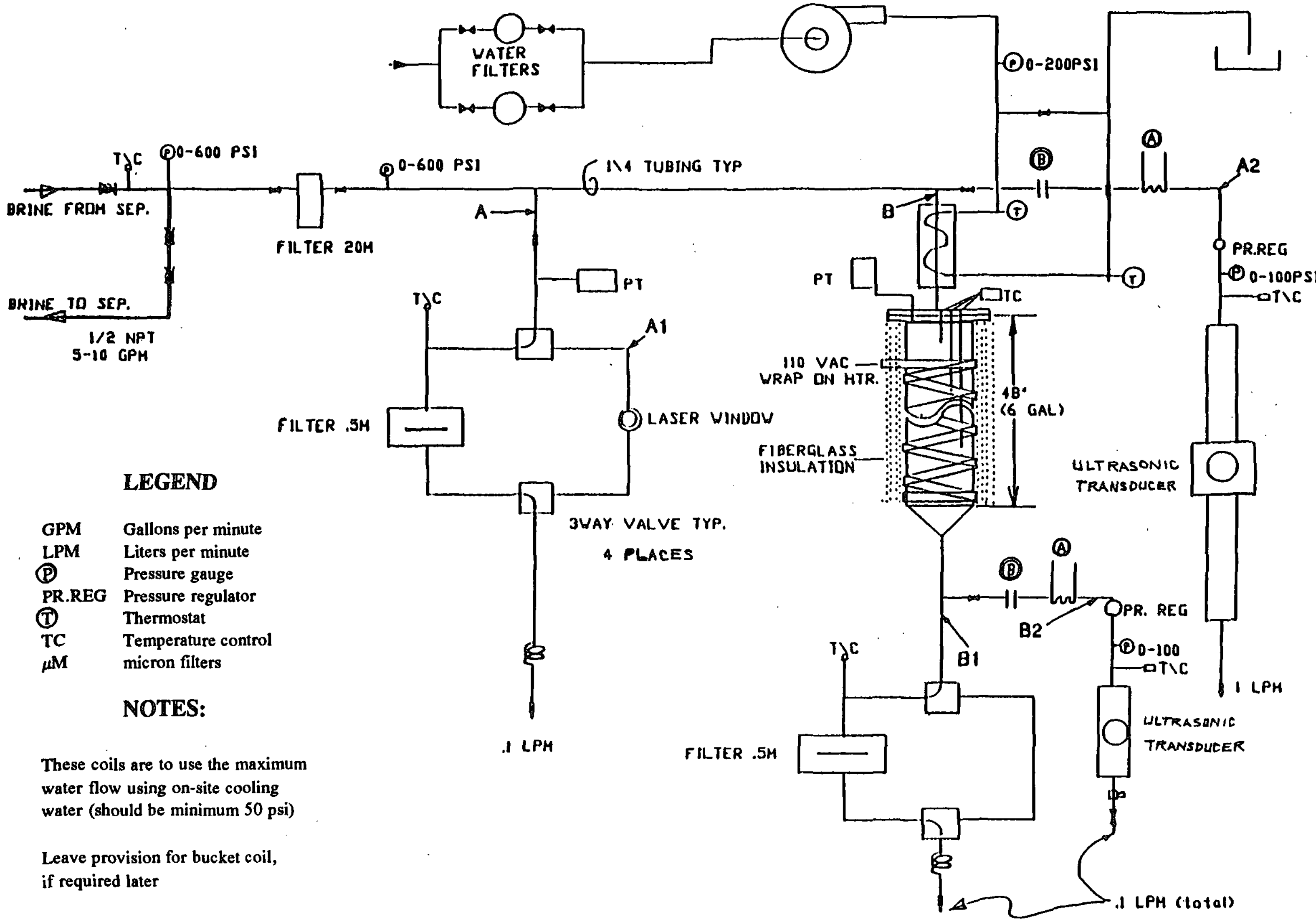
Michels (1988) has investigated the requirements for stabilizing brine-concentration gradients, and some of the consequences of these circumstances. Michels argues that, based on temperature gradients and fluid densities determined for State 2-14, salinity gradients may stabilize against vertical advection. He further concludes that non-advection of brine may be a general circumstance in the Salton Sea geothermal resource.

Williams (1988), however, notes that fluids of the Salton Sea Geothermal System (SSGS) cluster into two distinct populations in terms of salinity. The hot, hypersaline brine for which the SSGS is known, is overlain by a cooler (<260°C) fluid with distinctly lower salinity. He finds that both types of fluid are produced from closely spaced production intervals in geothermal wells, indicating that a sharp salinity interface exists over much of the field. The fluid interface occurs in parts of the reservoir where temperatures are about 260°C. The hypersaline brines have densities of approximately 1.0 gm/cm^3, while the low-TDS fluids have densities as low as 0.85 gm/cm^3. Williams believes the density-stratified interface implied by the data should act as a barrier to convective heat and mass transfer in the SSGS, thereby isolating the hypersaline reservoir from overlying dilute fluids.

11.5 PARTICLE-METER TESTING

Battelle Pacific Northwest Laboratories (PNL) used the opportunity presented by the June 1988 flow test to conduct tests of an experimental, on-stream particle meter for measurement of suspended-solids content. The equipment, shown in Figure 11.1, incorporates a laser-optical window, an ultrasonic detector, a weighed filter, and a heated precipitation tank. Results of the study are discussed in Report HH of Appendix A. The experiment demonstrated the value of using reflected ultrasonic impulses to count (and obtain some limited size information on) suspended particles for on-line application in a geothermal brine with strong scaling tendencies. Advantages of the instrumentation over other methods include improved high-temperature durability for the transducer and improved sizing information from the reflected signal. Principal conclusions from this study are:

- Counting and sizing particles using laser-light scattering requires constant maintenance in geothermal applications.
- Silica is the dominant scale species and appears in amounts orders of magnitude greater than other minor species, such as barium sulfate.
- The silica that formed at high temperatures and short residence times is very gelatinous and difficult to filter out of the brine.
- Correlation of instrument readings with particle collection data was difficult because conditions on the filter (i.e., temperature, flow rate, and pressure) could not be maintained constant for sufficiently long intervals to obtain comparable information.



LEGEND

GPM	Gallons per minute
LPM	Liters per minute
Ⓟ	Pressure gauge
PR.REG	Pressure regulator
Ⓣ	Thermostat
TC	Temperature control
μM	micron filters

NOTES:

Ⓐ These coils are to use the maximum water flow using on-site cooling water (should be minimum 50 psi)

Ⓑ Leave provision for bucket coil, if required later

Figure 11.1 Schematic Diagram of Particle-Meter Test Equipment
(from report HH, Appendix A)

11.6 GEOLOGICAL STUDIES

In addition to technical studies already cited, several additional studies have been presented at meetings and are reported in the literature. Many of these discuss alteration mineralogy or petrology (Cho et al., 1988; Shearer et al., 1988; Caruso et al., 1988; Bird et al., 1988; Charles et al.,1988; Hammond et al, 1988; Herzig and Elders, 1988; Anders and McKibben, 1987; Kramer and McDowell, 1987; Chou and Williams, 1987; Davis et al., 1987; Donaghe and Peacor, 1987; and Charles et al.,1987). The interested reader is referred to these papers for further information.

The significance of the SSSDP data base, in the broader scope of the Salton Sea Geothermal System (SSGS) and the geology of the Imperial Valley, is addressed by Sass and Elders (1986); Newmark et al., (1987, 1988); Elders (1987); McDowell (1987); and Williams (1987).

11.7 CHEMISTRY OF SCALE DEPOSITS

The Idaho National Engineering Laboratory (INEL) was responsible for a chemical and mineralogical study of scale deposits from State 2-14. Because of the possible economic importance of scale deposits in the future development of Imperial Valley geothermal resources, a substantial part of the INEL technical report (Report PP, Appendix A) is reproduced here.

Following the 19-day step-rate flow test of June 1988, 17 scale samples were taken from the flow line and the brine pond, as shown in Figure 11.2 and as described in Table 11.1.

Buden et al. (1991) described the chemistry of all 17 samples and more detailed analyses of five selected samples. Splits were made of the 17 samples and the University of Utah Research Institute (UURI) completed chemical analyses and x-ray diffractograms. Tables 11.2 and 11.3 give the bulk chemical analyses for major and minor elements, respectively.

A "C" was appended to the sample numbers to indicate the part of the sample taken for chemical analysis. On the basis of chemistry and sample locations, five representative samples were selected for more detailed analysis. Table 11.4 gives the mineral phases identified by x-ray diffraction.

Representative pieces of the five selected samples were examined, using a scanning electron microscope (SEM), with energy-dispersive spectroscopy capabilities. An "S" was appended to the sample numbers to indicate the part of the sample taken for SEM analysis. Complete descriptions of these samples are available in Buden et al. (1991).

Scale taken from the lines was high in amorphous material, containing primarily Fe and Si oxides. There were also crystalline phases with significant amounts of Na, Cl, K, Ca, S, Cu, Ag, Pb and Zn. The pond-scale samples were high in NaCl, with significant amounts of Fe, Si, Sr, Cu, Pb, Zn, Cd, As, Sb and Li.

The SEM analyses showed that: both the amorphous Fe-, O-, and Si-bearing scale and halite were nearly ubiquitous, and that composition of the amorphous phase varies; barite was common; magnetite precipitated at the high-temperature end of the line; sulfides appeared throughout the piping, with zinc and lead sulfides predominating at the hotter end and silver sulfide towards the cooler end; and that chlorides of potassium and silver were present, as well as halite. Textures and crystal form were illustrated by typical micrographs. In general, the scale in the lines and pond consisted of a large number of different crystalline phases and an amorphous phase of varying chemical composition; these phases changed significantly with run conditions.

Table 11.5 indicates the fluid compositions for three different line sample conditions, the weir box sample, and calculated, pre-flash concentrations based on these samples. Table 11.6 presents a

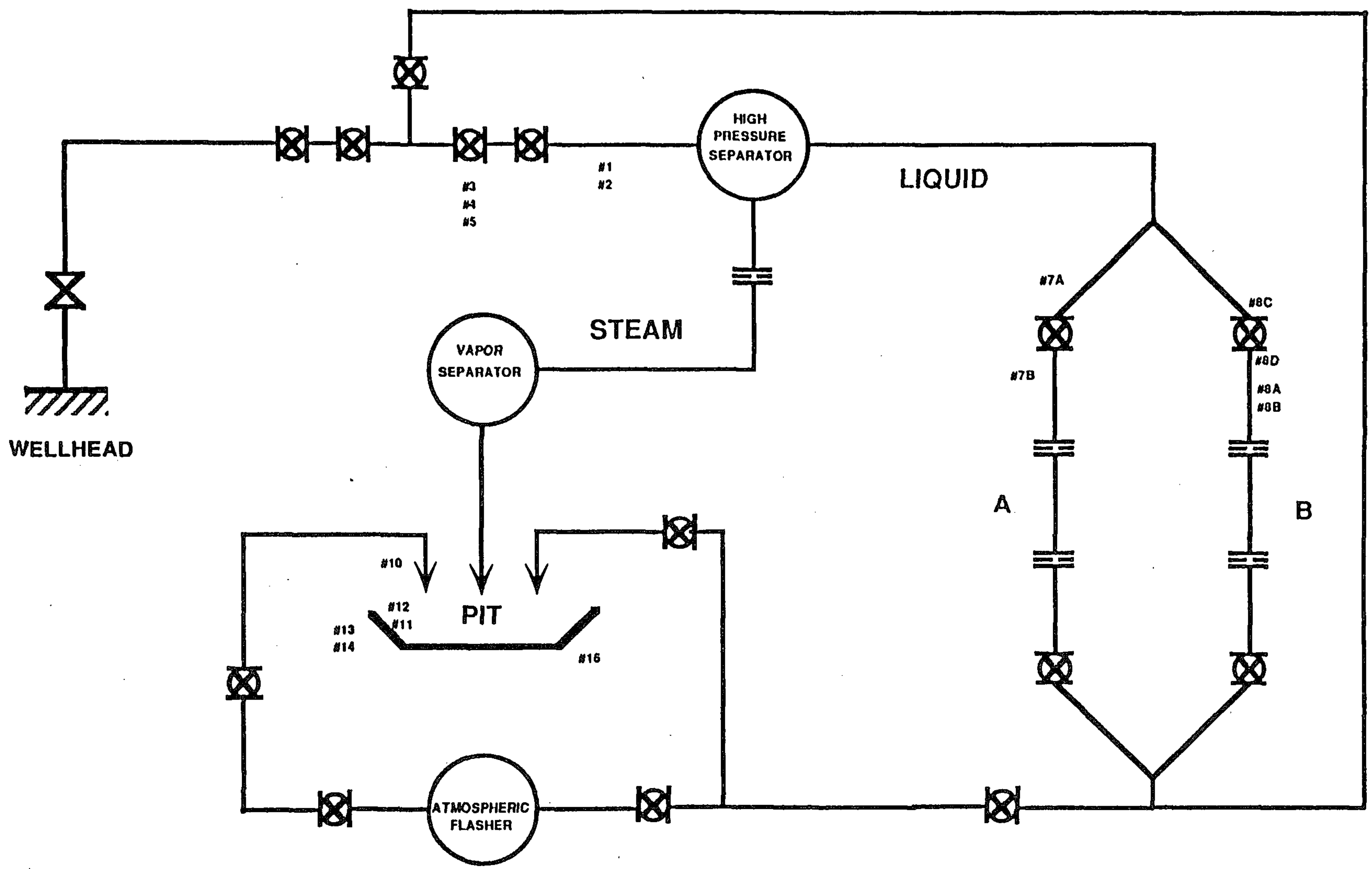


Figure 11.2 **Test Facility State 2-14 Showing Locations from Which Scale Samples Were Taken**
(report PP, Appendix A)

Table 11.1 Description of Scale Samples, June 1988.
Idaho National Engineering Laboratory (report PP, Appendix A)

Sample	Label Description	Additional Observations
1	Downstream HP separator-isolation valve; pipe coating.	Chunks of botryoidal, dull-black scale; brown coatings.
2	Downstream HP isolation; scale on bottom of pipe—loose crust on bottom.	Flat, black scale (2.0-cm square) with small reddish cubes intermingled in bag.
3	Isolation valve, HP separator valve seat.	Two pieces of flat, black scale; botryoidal forms; rusty coatings.
4	HP isolation valve; concave valve face.	Square chunks (1.5 cm) of dull-black scale with rusty coatings.
5	HP isolation valve; pipe on concave side of valve.	Chunks of scale from 2.5 cm to 3.0 cm in diameter; dull-black surface coated with red and yellow drusy material.
7A	Control valve, run A; pipe upstream	Crumbly, specular black scale coated with drusy 'rust'.
7B	Control valve, run A; pipe downstream.	Chips of dull-black scale with light-red coating.
8A	Control valve, run B; pipe downstream	Similar to 8C; chunks are coated with specular rind or small (<1 mm) cubic crystals.
8B	Control valve, run B; pipe downstream.	Similar to 8C with rusty coating on outside;curved surface against the pipe.
8C	Control valve, run B; gasket upstream.	Chunks of scale up to 2.5-cm long by 1-cm wide by 0.5-cm thick; some scales curve to reflect deposition on piping. Interlayered vitreous, black material and rusty, crystalline material.
8D	Control valve, run B; gasket downstream.	Chunks of scale from 1.5-cm long by 0.75-cm wide by 0.25-cm thick; similar to 8C in appearance.
10	Exit of weir box liquid stream.	Buff-colored clasts from 2.5 to 1.0 cm diameter; coatings of reddish cubes.
11	Salt scale below and to side of weir box; may be caused by mixing ditch waters; beneath sample 12.	Large (5-6 cm) chunk of green to clear scale with vitreous layer. Two layers visible.
12	Salt scale below and to side of weir box; may be mixed with ditch water; above sample 11.	Large (5-6 cm) chunks of stratified white and clear scale; cubes and possible rhombs up to 3-mm size.
13	Mud on pond bank by gauge, about 2 in. thick; is above salt scale samples 14 and 15.	Reddish, moist-appearing clay with occasional cubic crystals.
14	Salt scale;pond bank beneath sample 13 (mud) near pond gauge.	Large cubes (5 mm) of clear scale in tannish clay layer.
16	Scale on pond bank near southeast corner of pond.	Tan- to buff-colored crystals, approx. 1 mm in diameter. Cubic forms.

Table 11.2 Major Elements in Weight-Percent

INEL Scale Study (report PP, Appendix A)

Sample	Na	K	Ca	Mg	Fe	Al	Si	Ti	P	Ba	Mn	Cl	S	LOI
1C	1.52	1.39	0.91	0.09	12.43	2.59	19.02	0.00	0.00	0.01	0.82	0.61	4.19	9.53
2C	8.41	1.81	2.82	0.37	26.93	0.29	4.15	0.00	0.00	0.03	0.51	18.70	6.15	7.43
3C	2.16	1.79	1.67	0.15	17.43	2.32	21.46		0.00	0.04	1.06			5.96
4C	4.08	1.36	3.43	0.08	15.17	0.13	18.27	0.00	0.00	0.01	0.94	11.40	4.82	17.40
5C	1.74	1.34	1.35	0.08	15.13	1.86	19.07	0.00	0.00	0.05	1.04	2.70	2.75	10.20
7AC	3.97	1.98	3.93	0.18	18.97	0.05	15.10	0.00	0.00	0.01	1.11	13.50	1.80	20.70
7BC	0.45	0.25	0.94	0.12	26.45	0.06	20.42	0.00	0.00	0.01	1.42	0.85	0.17	16.30
8AC	2.21	1.11	1.58	0.21	21.31	0.47	17.81	0.00	0.00	0.02	1.30	4.88	0.83	19.70
8BC	1.14	0.61	0.65	0.24	22.57	0.36	20.47	0.00	0.00	0.01	1.55	1.63	0.45	15.10
8CC	4.04	1.49	2.30	0.22	20.60	0.29	16.03	0.01	0.01	0.10	0.87	9.80	0.37	19.90
8DC	1.30	0.71	0.88	0.20	22.07	0.56	19.21	0.00	0.00	0.02	1.50	1.88	1.10	13.20
10C	23.99	2.52	4.69	0.02	2.55	0.02	5.09	0.00	0.01	0.22	0.26	42.00	0.12	16.60
11C	39.10	0.06	0.10	0.01	0.03	0.02	1.50	0.00	0.00	0.04	0.01	59.60	0.00	0.67
12C	39.90	0.07	0.07	0.01	0.03	0.02	1.50	0.00	0.00	0.04	0.02	60.70	0.00	0.41
13C	17.86	3.12	6.54	0.03	1.71	0.07	3.81	0.00	0.01	0.19	0.34	40.40	0.08	25.40
14C	37.89	0.53	0.81	0.08	0.29	0.32	1.15	0.01	0.01	0.10	0.04	56.80	0.01	3.61
16C	39.41	0.09	0.15	0.01	0.02	0.02	1.50	0.00	0.00	0.02	0.01	60.10	0.00	0.92

The samples have been grouped by sampling location. The first were taken before the high pressure separator, the second from the lines beyond the separator, and the third from below the weir box. LOI = Loss on Ignition; is the weight-percent of water in the sample.

Table 11.3 Minor Elements in ppm

INEL Scale Study (report PP, Appendix A)

Sample #	Sr	Cr	Co	Ni	Cu	Pb	Zn	Cd	Ag	As	Sb	Sn	Li	Be	Zr	La	Ce	Hg
1C	131		20	18	102000	2349	530	14	34020	656	810	19	49	141	28	6		6
2C	358	89	34	37	13696	5814	4550	616	382	4387	268	23	165	11		13		4
3C	237	250		12	27228	983	2495	23	7412	351	244	21	116	157		9		
4C	356	5	18	15	5259	1744	559	10	643	922	1272	9	168	40		10		6
5C	200		5	18	113800	936	675	14	37590	1006	852	15	74	152	34	7		7
7AC	510		3	14	2120	125	523	11	485	324	76	10	263	101		16	13	5
7BC	66		3	15	1282	224	342	14	235	494	611	16	29	174		8		5
8AC	215		2	16	19900	182	436	12	4402	395	369	32	117	217		9		7
8BC	81			14	10578	116	265	11	2432	526	617	12	58	271		8		
8CC	329	18	3	25	3877	125	2627	13	981	379	227	12	160	150		13		5
8DC	112	10	69	22	25346	342	442	12	16078	1145	2829	13	63	281		6		5
10C	698	3	1	7	95	2446	615	16	23	289	162		225	5		19	20	
11C	38					723	16	76	16				6					4
12C	35						772	17	12				5					4
13C	923	2	2	6	106	355	1029	23	12	252	171	9	350	6		20	24	5
14C	185	2	2	4	17	241	145	50	10	63			47		19	9	17	4
16C	33					584	27	70	12				10					3

The samples have been grouped by sampling location. The first were taken before the high pressure separator, the second from the lines beyond the separator, and the third from below the weir box.

Table 11.4 Phases Identified by X-ray Diffraction Analyses
INEL Scale Study (report PP, Appendix A)

Sample Number	Phases Identified
2S	Halite (NaCl) Sphalerite (ZnS) Mangetite (Fe_3O_4) Possible Chalcopyrite ($CuFeS_2$)
7BS	No crystalline phases identified
8Cs	Halite (NaCl) Possible Sylvite (KCl)
8DS	Halite (NaCl) Possible Sylvite (KCl)
13S	Halite (NaCl) Possible Sylvite (KCl) Possible Silver metal

Table 11.5 Fluid Compositions, State 2-14 Flow Test, June 1988.
INEL Scale Study (report PP, Appendix A)

Sample #	180	182	173	254	173	254
Type	line sample 6/3/88	line sample 6/4/88	line sample 6/4/88	weir box sample 6/5/88	Calculated pre-flash concentrations based on above samples	
Temp. °F	494	492	492	225		
Analyses in Milligrams per kilogram (mg/kg)						
Sodium	56092	55830	55495	70702	52287	52750
Calcium	28387	28013	27795	35556	26188	26528
Potassium	17522	17387	17413	22096	16407	16485
Iron	1731	1730	1713	2185	1614	1630
Manganese	1528	1510	1526	1928	1437	1438
Zinc	527	522	526	665	496	496
Silica	496	492	496	626	467	467
Strontium	418	419	420	531	395	396
Boron	415	412	414	524	390	391
Lithium	221	220	219	279	207	208
Ammonium	405	415	404	518	381	386
Barium	111	116	132	152	124	113
Lead	99	102	101	127	95	95
Magnesium	46	44	45	57	43	43
Arsenic	16	15	16.3	20	15	15
Cadmium	3	2	2.3	2.9	2	2
Copper	2	2	2.1	2.4	2	2
Chloride	154796	155162	155042	196373	146080	146512
Bromide	100	103	105	130	99	97
TOTALS	262914	262496	261867	332474	246729	248054

Table 11.6 Summary of Analyses Showing Inferred Mineral Phases Present
INEL Scale Study, Well State 2-14 (from report PP, Appendix A)

Sample #	2	7B	8C	8D	13
Location	Downstream of the HP isolation valve	Downstream of control valve of line A	Upstream gasket of control valve of line B	Downstream gasket of control valve of line B	Mud on pond bank by gauge
Chemical Analyses	High Fe Moderate Na, Cl High Cu, Pb, Zn, As	High Fe, Si High Mn	High Fe, Si Moderate Na, Cl High Cu, Zn	High Fe, Si High Cu, Ag	High Na, Cl, K, Ca, Ba
XRD Analyses	Halite (NaCl) Sphalerite (ZnS) Magnetite (Fe3O4) ?Chalcopyrite (CuFeS2)	No crystalline material in sufficient quantity to identify by XRD	Halite (NaCl) ?Sylvite (KCl)	Halite (NaCl) ?Sylvite	Halite (NaCl) ?Sylvite.(KCl) ?Silver (Ag)
SEM Analyses	pipe side? ------------ Fe, O, Cl, Si, Ca matrix ------------ Sphalerite (ZnS) Galena (PbS) Fe, O, Cl, (Si), (Ca) ------------ Magnetite (Fe3O4) Fe, O, Cl, Si, Ca ------------ Halite (NaCl) ?Galena (PbS)	pipe side? ------------ Fe, O, Si, (Mn) ------------ Barite (BaSO4) Fe, O, Si, (Mn) ------------ Chalcopyrite (CuFeS2) Covellite (CuS) Fe, O, Si, (Mn)	Barite (BaSO4) Fe, O, Si ------------ Halite (NaCl) Barite (BaSO4) Cu-S-Ag mineral Zn-Fe-O-S mineral Cu-Fe-S mineral Sylvite (KCl) ------------ Covellite (CuS) Chlorargyrite (AgCl)	Barite (BaSO4) Chlorargyrite (AgCl) Covellite (CuS) Fe, O, Si, (Cl) ------------ ?Halite (NaCl) ?Barite (BaSO4) Acanthite (Ag2S) ?Gypsum (CaSO4.2H2O) Fe, O, Si, (Cl) ------------ Covellite (CuS) Chlorargyite (AgCl) Fe, O, Si, Cl	Halite (NaCl) Sylvite (KCl) Barite (BaSO4) ?Fluorite (CaF2) Ca, O, Si, Cl ------------ Halite (NaCl) Sylvite (KCl) ------------ Halite (NaCl) Sylvite (KCl) Gypsum (CaS O4.2H2O)

summary of the analytical results for the five samples studied in detail, with the inferred mineral phases present.

11.8 GEOTHERMAL WASTE-TREATMENT BIOTECHNOLOGY

Scientists at Brookhaven National Laboratory (BNL) have shown that acidiphilic microorganisms can be used as "active agents" in the detoxification of geothermal-brine residues (Premuzic and Lin, 1988). The successful development of this technology could have a major economic impact on geothermal power production in the Imperial Valley, where geothermal brines have dissoved-solids contents up to 350,000 ppm. BNL proposed to use well-characterized geothermal sludge, resulting from the 2-14 flow test, to conduct scaled-up biochemical testing.

Conclusions of the BNL study (Premuzic and Lin, 1988; Report II of Appendix A) include:

- Choice of microorganisms may well be predetemined by the composition of a particular sludge;
- The treatment cycle may be shortened from six to three days, if only few metals are to be considered;
- The supply of nutrients and air will dictate a particular basic-design concept for bioreactor design (batch or continuous).

The preliminary results indicate that mixed cultures of different strains of microorganisms, the relative concentration of the residual brine sludges, and the number of toxic metals present in concentrations exceeding the threshold limits, all play critical roles in scaled-up processes, and these require further research and development.

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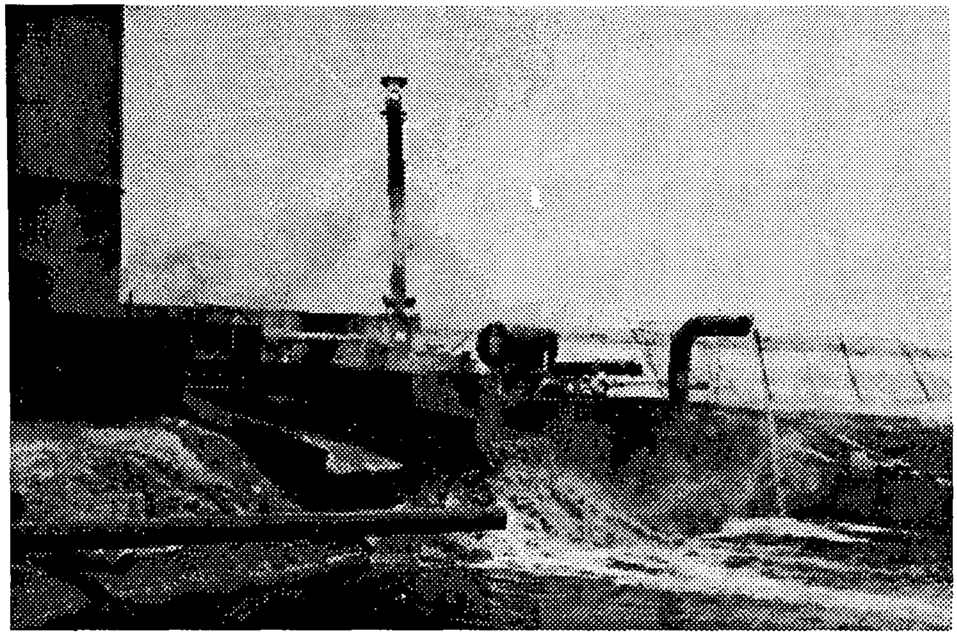
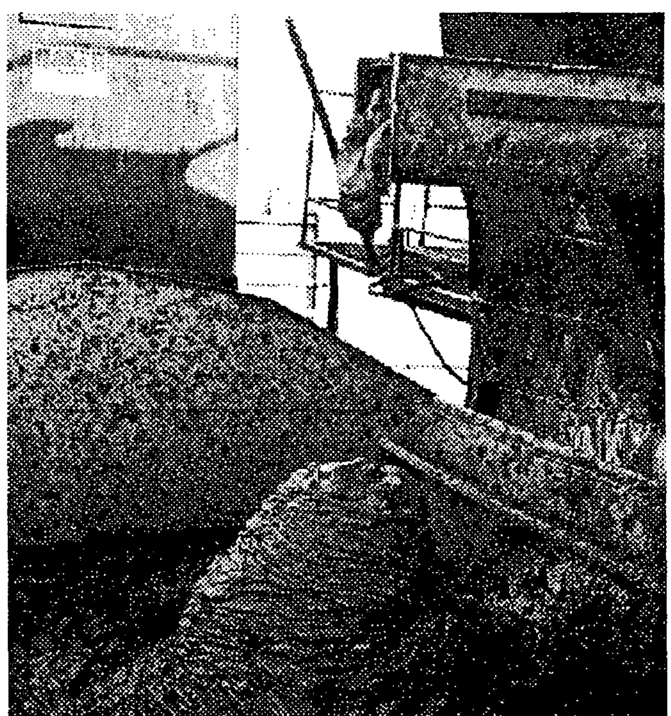


Brine discharge into the brine pond, showing Baker tank overflow (center) and brine fraction flow from weirboxes. Long term SSSDP flow test, June 13, 1988.



Centrifuged sludge being deposited in Baker tank at SSSDP site during cleanup, December 7,1988.

12.0 SITE RESTORATION AND BRINE POND CLEANUP

12. 1 INTRODUCTION

As a result of Salton Sea Scientific Drilling Project (SSSDP) drilling and testing activities, substantial disturbance had occurred to the natural ground surface. Waste materials, resulting from drilling and reservoir testing, included drilling muds and geothermal fluids (brines). Drilling muds were placed in a mud sump located near the State 2-14 wellhead (Figure 12.1).

Geothermal brines produced during two short-term flow tests (Phase-1), and from 12-hour and 19-day flow tests (Phase-2), were discharged into a holding pond located 300 feet east of the wellhead, across Davis Road (Figure 12.1). The chemistry of the geothermal fluids was described earlier (Chapters 9, 10, 11). The produced fluids are high in dissolved solids, including several heavy metals, and these precipitate and settle out as the fluids cool and evaporate. The resultant products within the brine pond included a salt cake or crust at the top, liquid brine, and a sludge of varying salt and water content at the bottom.

SSSDP Phase-2 included a task for site cleanup and restoration, as contracted between the leaseholder and Bechtel National, Inc., the DOE contractor, that would leave the brine pond and the mud sump ready for reuse as a condition of returning the site to the leaseholder.

The cleanup activities proved to be difficult and accounted for a significant part of the total cost of the SSSDP. Because of the potential value in project planning, technology, and cost reduction by the geothermal industry in future cleanup efforts, the environmental restoration activities are discussed here in some detail. This account is compiled from DOE memoranda, Bechtel periodic reports and letters, subcontractors reports, notes and invoices. Specific reference to many of these materials would not contribute to the discussion. Therefore, this description is in large part the editor's interpretation of available files.

12.1.1 Regulatory Requirements and Authority

As leaseholder of the SSSDP site, Kennecott was legally responsible for the drilling of State 2-14 well, production of brines, and removal of the resultant sludge deposits in the mud sump and brine pond. The discharge of any hazardous waste or hazardous wastes containing free liquids into surface impoundments is regulated by general provisions of the federal Resource Conservation and Recovery Act (RCRA) of 1976, and regulations adopted by the California Regional Water Quality Control Board (CRWQCB) and other state and county agencies. Cleanup of the mud sump and the brine pond, should the contents be found to contain hazardous wastes, are specifically provided for by the California Toxic Pits Cleanup Act (TPCA) of 1984, as amended in 1985 and 1986. Section 25206.4, which bears upon the SSSDP waste-disposal problem, states:

> "(a) Notwithstanding any other provision of law, unless granted an exemption pursuant to subdivision (b) or Section 25208.13, a person shall not discharge liquid hazardous wastes or hazardous wastes containing free liquids into a surface impoundment after June 30, 1988, if the surface impoundment, or the land immediately beneath it, contains hazardous wastes and is within one-half mile upgradient from a potential source of drinking water. A person who owns a surface impoundment which meets the conditions specified in this subdivision shall close the impoundment...."

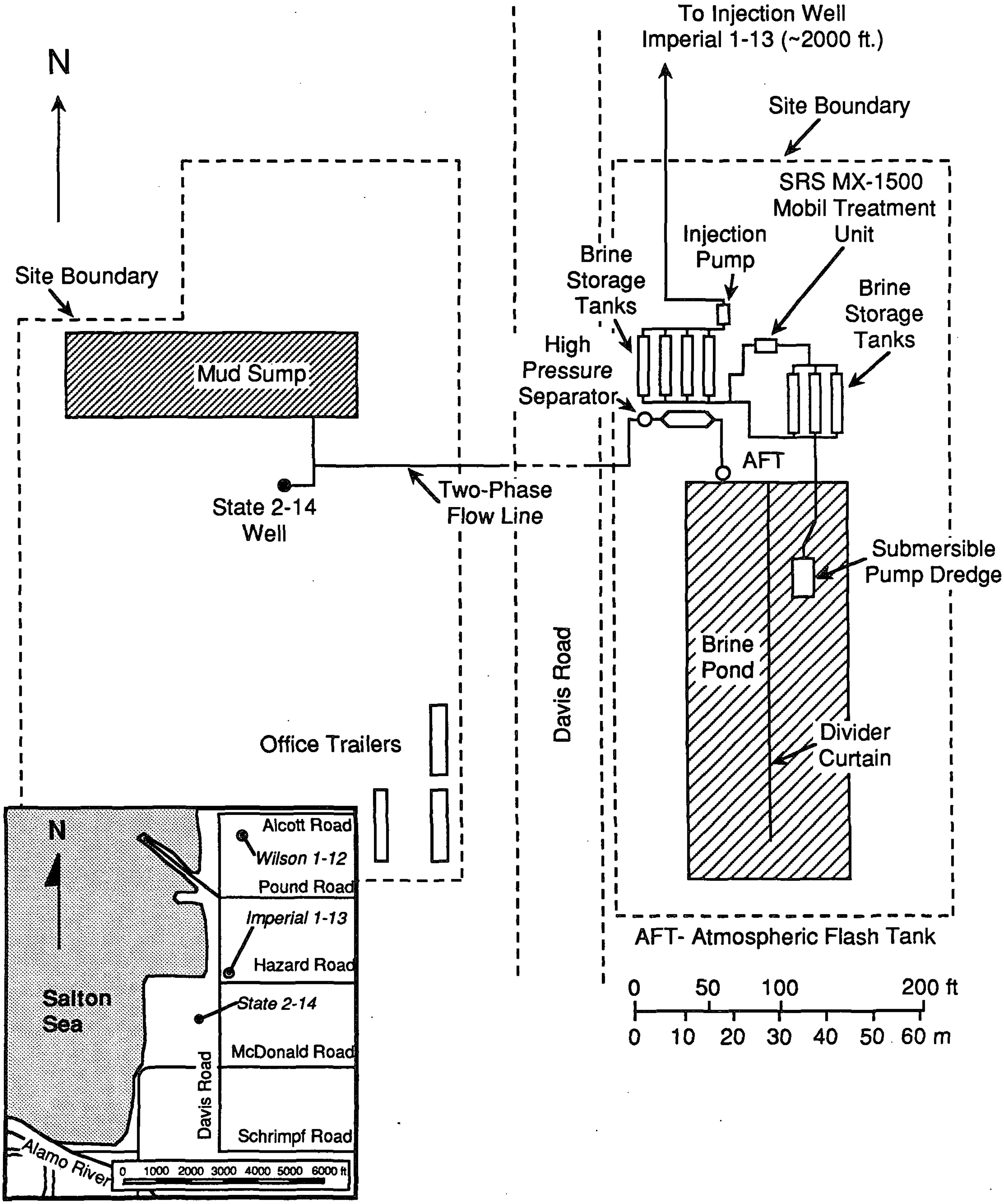


Figure 12.1 Location of brine pond and mud sump with schematic of cleanup units.

Other sections of the TCPA describe exemptions, provisions for construction of surface impoundments, liner requirements and other items. It was the intent of SSSDP management to complete all reservoir testing and cleanup operations prior to June 30, 1988, but this was not the case.

The CRWQCB was the cognizant regulatory agency, and CRWQCB Order No. 85-36 regulates use of the pond and disposition of wastes stored in the pond. CRWQCB required Kennecott to remove accumulated salt, mud and cuttings, to transport the wastes to an acceptable disposal site, and to leave the pond and sump in a condition ready for reuse. This differs from a requirement to restore the site to its original condition. The term "ready for reuse" was further defined to include the removal of all visible salt cake and sludge materials from the sides and bottom of the brine pond and mud sump.

Cleanup responsibilities were transferred from Kennecott to Bechtel National Inc., through the amended Kennecott/Bechtel contract, and included as "Task 6: Well abandonment and Site Cleanup" in the amended Bechtel/DOE contract.

The disposal of waste materials must be in accord with the California Department of Health Services List of Inorganic Persistent and Bioaccumulative Toxic Substances (Bechtel, Geothermal Brine Pond Sludge Removal Plan, 10/24/88). Of particular interest in the geothermal brines are the heavy-metal concentrations. Should heavy metals exceed the listed thresholds, the sludge waste would be deemed hazardous and would require disposal at a Class-I site. If the heavy-metal concentration should be below the threshold values, the sludge would be considered nonhazardous, and could be disposed at a Class-II site. Kennecott's permit from the CRWQCB provided that nonhazardous, liquid waste below an allowable threshold of 6,000 mg/L total dissolved solids (TDS), can be disposed at a Class-III waste-management unit approved by the Regional Board. Since extensive dilution and other treatment would be required, and might not be successful in reducing the TDS content from greater than 200,000 mg/L to less than 6,000 mg/L, this did not seem to be a reasonable option.

The International Technology Corporation (IT) operated a Waste Management Facility near Westmoreland, approximately ten miles from the SSSDP site, that was licensed to accept Class-I (Hazardous) and Class-II (Nonhazardous) materials. The site had been established primarily to service geothermal operators in the Imperial Valley. The IT Corporation issued a letter to Bechtel stating that, as of December 1, 1987, it would not accept liquid wastes. Two important issues for developing a brine-pond cleanup plan, therefore, were identified: the determination of hazardous or nonhazardous waste; and the need to solidify the sludge material, which was neither liquid suitable for injection, nor solid suitable for solid-waste disposal at the IT site.

12.2 MUD SUMP CLEANUP

The State 2-14 well mud sump was a rectangular pit approximately five ft deep with surface dimensions of 190 ft (east-west) by 60 ft (north-south), Figure 12.1. The southern edge of the pit was located 50 ft north of the wellhead. Mud-sump wastes, essentially drilling mud residues, were first hauled to the IT Waste Management Facility for disposal in June 1987, prior to beginning Phase-2 well-repair operations. These wastes totaled almost 600 tons, some 400 tons greater than estimated earlier (Bechtel Progress Report No. TP-20, June-August 1987). A second shipment of mud-sump wastes were similarly disposed in May 1988, prior to beginning the long-term flow test of the well. The mud sump was not used after this cleanup and was left in a condition acceptable to Kennecott (Bechtel, Geothermal Brine Pond Sludge Removal Plan, 10/24/88).

12.3 BRINE POND

12.3.1 Location and Size

Geothermal brines produced during flow tests of the State 2-14 well and the Wilson 1-12 well were discharged through a 10-inch flow line to the weir box at the north side of a large brine-holding pond located 300 ft east of the wellhead, across Davis Road (Figure 12.1) from the State 2-14 well. The dimensions of the rectangular pit are shown as 285 ft (north-south) x 110 ft (east-west) (Bechtel General Arrangement Plan-Preliminary, Drawing No.169377-P001-006). The pond was divided longitudinally in the middle with a divider curtain for increased brine retention time. Later measurements (DOE/SAN Memo, Sept. 20, 1988) verified surface dimensions of 285 ft x 110 ft. The pond was lined with a layer of compacted clay over native soil.

12.3.2 Deposits and Fluids

Geothermal fluids were discharged into the brine-holding pond during the following flow tests of State 2-14 well:

December 28-31, 1985	2 days	600,000 lb/hr
March 20-22, 1986	2 days	580,000 lb/hr
August 31,1987	12 hours	750,000 lb/hr
June 1-19, 1988	19 days	variable

Additional fluids resulted from a short (1-2 hr) flow test of the Kennecott Wilson 1-12 well in July 1988. Some drilling muds were also pumped into the pond during the Phase-l drilling operations. Precipitation from the brines formed a sludge layer of variable density and water content. Evaporation at the surface of the brine formed a salt crust one-to-two inches thick, which generally covered the brine pond. In the course of the cleanup, a second salt layer was discovered below the upper brine layer. This lower layer probably resulted from previous short-term tests during Phase-1 operations.

12.3.3 Sampling and Physical Properties

Sampling and analysis of the brine-pond sludge was required to determine if the sludge should be disposed of as hazardous (Class I) or nonhazardous (Class II) material. The resultant classification dictated the nature of disposal, as well as the cleanup cost ($95/ton versus $55/ton) at the time of cleanup planning.

A preliminary random sampling by Bechtel prior to the flow test had indicated that the sludge was nonhazardous, but post-test sampling indicated that the material might be hazardous (Bechtel Report No.TP-27, June 13-July 24, 1988). Based on these conflicting results, Bechtel proposed to classify the wastes as hazardous and recommended to plan the cleanup on that basis. DOE, however, noted the opportunity for reducing disposal costs by $40/ton, perhaps totaling $40,000, and proceeded with a new sampling program.

On September 14, 1988, a meeting was held to consider three sampling plans of 9-, 21-, and 39-sample sites. After conferring with the Chemfix representative, agreement was reached that the 9-site sampling program was adequate. Concerned about conflicting dimensions stated for the brine pond, a distance-measuring wheel was used to measure the pond on September 15, confirming surface dimensions of 285 x 110 ft. Considering the slope of the pond's banks, the bottom dimensions were estimated as 275 x 100 ft. The depth to the pond bottom was uncertain. After cleanup, the depth was estimated to be nine feet, somewhat greater than indicated earlier. Noting a significant buildup of sludge at the north end of the pond (where brines flowed into the pond from the weir box), the sampling plan was modified on-site to include 12 sampling stations (Figure 12.2).

On September 15, 1988, the U.S. Department of Energy, San Francisco Operations Office (DOE/SAN), assisted by Kennecott Corp. and Chemfix Corp. representatives, carried out a systematic sampling program of the sludge in the brine pond (DOE/SAN Memo, Sept. 16, 1988). The configuration of the brine pond, its deposits and sample sites, taken from that report, are shown as Figure 12.2. An abstracted description of the sampling procedure from that report follows.

A Rogue River core sampler with a 4-inch diameter, 30-inch long aluminum barrel, was used to sample the sludge. A 2-inch diameter steel pipe was used as a ram-probe to break through the salt crust to provide an opening for the corer. The corer was forced into the sludge manually, and at each station struck a hard layer, thought to be the compacted bottom liner of the pond. This suggested that the recovered core represented the full vertical depth of the sludge deposit. Subsequently, a buried salt layer discovered during the cleanup operations indicated that this was not necessarily the case. On lines "O" and "A", core samples were retrieved of the first layer of sludge, for a total of six samples. On lines "B" and "C", less than 12 inches of a very watery sludge was present, and the amount of solids recovered was so minimal that it was decided to discard the samples.

Each sample from lines "A" and "O" was blended thoroughly, and each sample was split four ways. A split of each sample was packaged, labeled and distributed as follows: Brookhaven National Lab.; Chemfix; and NET Pacific Labs. The fourth split of each sample on lines "A" and "O" was composited, blended, and in turn split into four parts, three of which were distributed as above. The two remaining composite splits for each line were then blended together for an overall composite sample, which was split three ways and distributed to the above-named organizations.

In the course of sampling, it was noted that the majority of the sludge was located at the north end of the pond (Figure 12.2). At the southern part of the pond, as much as 20 inches of brine was present below the salt crust and above the 12-inch thickness of mixed sludge and brine.

The total volume of material within the brine pit, (salt crust, brine and sludge), could be estimated fairly accurately, based on the measurements of Crawford et al. (1988). Assuming an average total depth of 33 inches (2.75 ft), the approximate volume was 78,670 cu ft, equal to 2,910 cu yd or 588,530 gallons liquid measure.

The estimation of sludge volume was not straightforward, and was subject to considerable error. The distribution of dense sludge within half of the pit was indicated from six sample sites, and the high-fluid nature of the remaining six samples prevented an accurate thickness determination and sample recovery. Bechtel estimated a sludge volume of 56,100 cu ft, equal to 2,080 cu yds or 420,000 gallons. Using the same basic data, DOE/SAN estimated a sludge volume of 33,000 cu ft (1,220 cu yd) or 247,000 gallons. These estimates did not include the surface salt cake, nor account for the deep salt layer discovered during cleanup. The physical properties of the sludge, determined from laboratory analyses and information provided by waste-management contractors, and summarized by Bechtel (1988), are shown in Table 12.1.

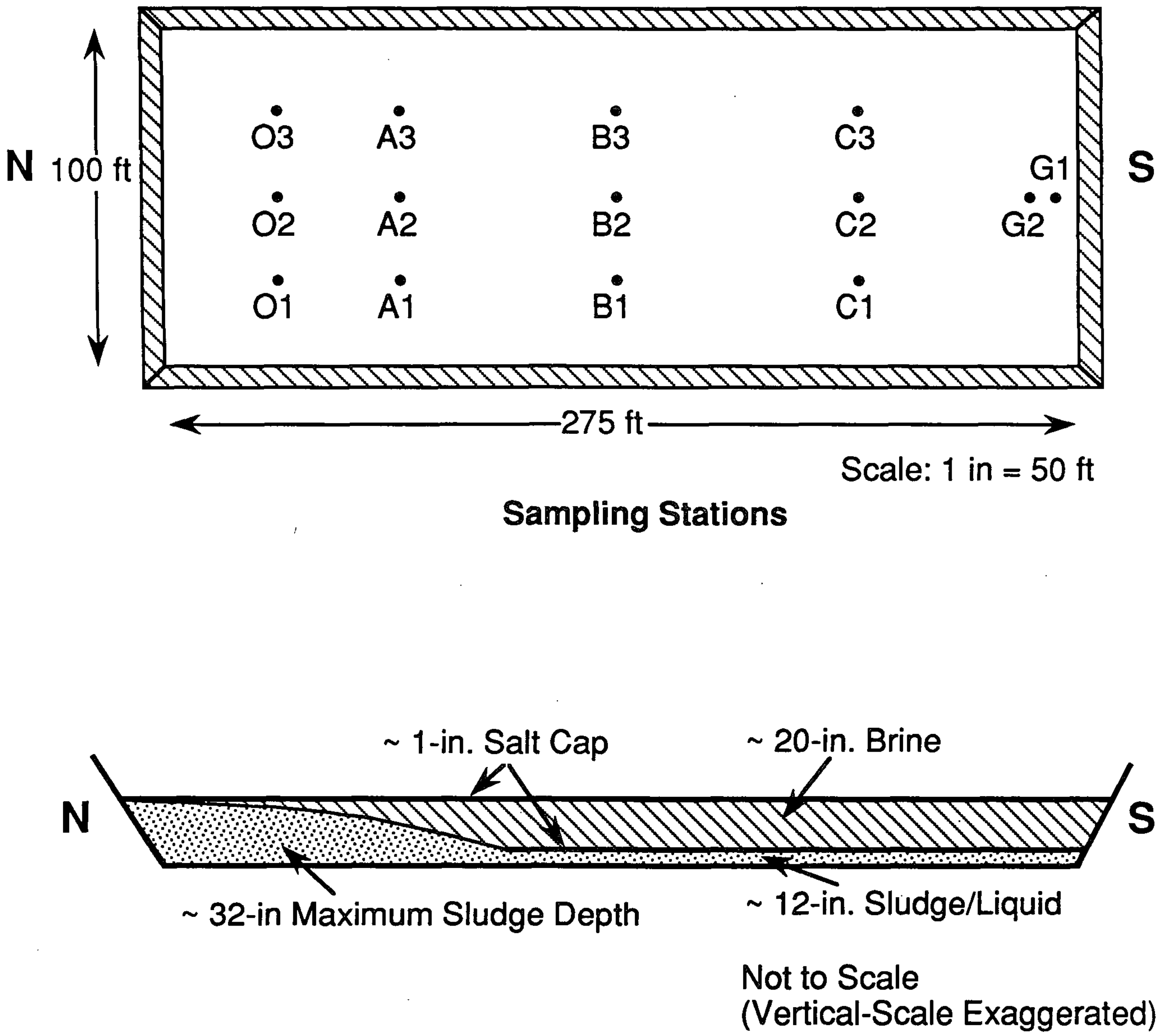


Figure 12.2. **Sampling Program - SSSDP Brine Pond**
Kennecott - State 2-14 Well, Sept. 15, 1988

Table 12.1
Sludge Physical Properties

Sludge Volume:	10,000 bbl (420,000 gal)
Sludge Density:	1.3 s.g. (wet sludge) 1.5 s.g. (dry solids)
Percent Solids in Wet Sludge:	30 percent
Sludge Weight:	10.3 lb/gal (wet) 4,326,000 lb (wet) 2,163 ton (wet)
	1,297,800 lb (dry) 649 ton (dry)
Allowable Water Content: (to pass paint filter test)	40-45 percent
Sludge Weight with 45-percent water: (after dewatering)	1,180 ton
Sludge Soluble Salt Content:	10-15 percent (wet)
Sludge Weight, After Fresh Water Rinse: 1,062 ton (assumes removal of 10% salts)	

12.3.4 Analytical Results

Brine-pond sludge was sampled and tested for chemical constituents and physical properties on several occasions between June 1987 and July 1988. The pertinent results from this initial sampling program are summarized in Table 12.2.

Sample 1 was obtained in June 1987, prior to well repair operations, and was analyzed by ATS Laboratory. Samples 2C, 24C, and 24G were taken in March 1988, after the 12-hour flow test and prior to the long-term flow test. These were also analyzed by ATS Laboratory. Samples 3, 4, and 5 were taken after the 25-day (19 days continuous flow) flow test and were analyzed by Quality Assurance Laboratory, ATS Laboratory, and BTC Environmental, Inc., respectively. Samples were analyzed for California Assessment Manual (CAM) metals and compared with the California Department of Health List of Inorganic Persistent and Bioaccumulative Toxic Substances and their threshold concentration values for heavy metals. If the metal concentrations exceeded these thresholds, the waste would be deemed hazardous and would require disposal at a Class-I site, unless treated. If the waste was nonhazardous, it could be disposed at a Class-II site.

Table 12.2 Brine-Pond Sludge, Analytical Results: June 1987 - July 1988

Sample	Date	Sampling Method	Analyses	Reference	Results
1	6/87	Scoop: top of sludge	CAM metals;	1	Nonhazardous; <TTLC; <STLC
2C	3/88	Pipe auger from boat	CAM metals; *	1	Nonhazardous; <TTLC; <STLC
24C	3/88	Pipe auger from boat	CAM metals; *	1	Nonhazardous; <TTLC; <STLC
24G	3/88	Pipe auger from boat	CAM metals; *	1	Nonhazardous <TTLC; <STLC
		FLOW TEST			
3	6/23/88	Scoop; top of sludge, 6 sites, blended	CAM metals; STLC	1	Cd, Pb>STLC
4	7/6/88	Scoop; top of sludge, 1 site	CAM metals; #	1	Pb>STLC
5	7/6/88	Scoop; top of sludge, 1 site	CAM metals; HCb	1	<TTLC; <STLC

STLC = Soluble Threshold Limit Concentration *CAM = California Assessment Manual*
TTLC = Total Threshold Limit Concentration *HCb = Hydrocarbons*
** = TDS, Moisture, ash, acid -insoluble ash, cations, anions; ATS Laboratory*
 # = pH, total Cl, soluable Cl, moisture, CAM metals on wash sample; ATS Laboratory

All samples taken from the brine pond prior to the 20-day flow test proved to be nonhazardous: all constituents were below the allowable limits for Total Threshold Limit Concentration (TTLC) and Soluble Threshold Limit Concentration (STLC) values. Analyses of Samples 3, 4 and 5, taken after the 20-day test, show considerable scatter. The heavy-metal concentrations are below the threshold for TTLC for all samples. The soluble cadmium concentration for Sample 3, and soluble lead concentration for Samples 3 and 4, exceeded the allowable STLC. Thus, the waste generated during the long-term flow test was regarded as potentially hazardous. The analytical results varied considerably among the three laboratories. Sample 3, run by Quality Assurance Laboratory (June 30 analysis) reports 2.0 mg/L for arsenic, 207 percent higher than the July 5 analysis of 0.965 mg/L run on the same sample. The July 5 analysis of cadmium (3.16 mg/L) is 178 percent higher than the June 30 analysis of 1.77 mg/L. The STLC lead analyses for Samples 1-5, including two duplicate analyses by different laboratories, were: 0.85; 3.35, 2.85, 2.54; 42.75 and 40.2; 13.0 and 12.7; and 2.44 mg/L, respectively.

These results led Bechtel to conclude that further sampling and analyses would be unlikely to provide better information. Bechtel proposed that, because sampling and analytical variations were so great, the waste should be treated conservatively as hazardous for processing and disposal purposes. IT Corporation agreed that it could adjust disposal costs, subject to amended waste manifests, should analyses of the processed waste show it to be nonhazardous. Subsequent sampling and analyses clarified the TTLC and STLC and led to negotiations which established the classiciation and disposal fees of the waste.

Two factors led to a decision by DOE to perform further chemical analyses. First, the chemical analysis results varied sufficiently to prevent a firm conclusion regarding heavy metal concentrations, and the earlier analytical samples may not have been sufficiently representative of the waste composition. Second, bids from waste-management contractors for removal, processing, and disposal differed substantially in cost for nonhazardous and hazardous waste. These considerations led to the sampling effort of September 15, 1988.

The analytical results of the September 15, 1988, sampling from only one certified laboratory, NET Pacific, were available by October 10, 1988. Seven samples were analyzed: A-1, A-2, A-3, 0-1, 0-2, 0-3 and A/O, a composite mix of the six other samples. The TTLC and STLC were determined for each sample and recorded with the reporting limits for each of 17 CAM metals. Comparison of the reported concentrations with California Department of Health Services limits for these elements are presented in Table 12.3.

No values exceeded the TTLC, although antimony, arsenic, barium, copper, silver and zinc showed elevated, and interesting, values. One constituent, arsenic, exceeded the STLC in all seven samples, by factors of 1.5 to 2.2. Cadmium and lead, of concern from initial sample results, were well below the STLC.

A Brookhaven National Laboratory chemist completed a detailed analysis of the sludge samples for the principal metals of concern, and reported these results to DOE/SAN (Brookhaven National Laboratory Informal Report, Nov. 15, 1988). The principal results of this work are summarized in Table 12.4. The Brookhaven report made several observations from these results:

1. Chemical variation in the samples due to mass distribution in the settling pond was significant;

2. Consistent methods of sampling and sample preparation for analysis were required to establish an undisputable analytical procedure for geothermal sludge;

3. Detailed studies were needed to determine the metal loss during solubilization, as well as interference from matrix and process materials;

4. The analyses should be performed on dry samples, with liquid separated and analyzed separately;

5. Analyses for "as received" samples were all below threshold concentration limits;

6. The metal concentrations of separated out liquid were above the STLC.

Table 12.4 shows metal concentrations in the liquid sample that are similar to the NET Pacific Laboratory results for arsenic and copper, but much higher for lead and zinc. These results indicate that arsenic, cadmium, lead and zinc, all exceed the STLC.

In November 1988, Kennecott negotiated a $55/ton disposal fee for either hazardous or nonhazardous material with the IT dump manager. Should waste be determined hazardous, a 10 percent county tax would be imposed. Since the Federal government was exempt from any State Franchise Board Tax, it was believed that a $55/ton rate was established for all wastes generated at the Salton Sea site.

Table 12.3 Comparison of Analytical Results with Threshold Limits
NET Pacific Laboratory Results, October 14, 1988

Solubles								
Substance	STLC (mg/l)	A-1 (mg/l)	A-2 (mg/l)	A-3 (mg/l)	O-1 (mg/l)	O-2 (mg/l)	O-3 (mg/l)	A/O Comp (mg/l)
Antimony	15	3	3	3	3	2	3	4
Arsenic	5.0	9.8	7.4	10	9.8	8.8	11	9.8
Barium	100	11	10	14	13	12	16	13
Beryllium	0.75	<0.05	0.05	<0.05	0.05	<0.05	<0.05	0.05
Cadmium	1.0	0.43	0.58	0.37	0.54	0.53	0.41	0.61
Chromium (VI)	5	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Chromium	560	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Cobalt	80	<0.05	0.09	0.06	<0.05	<0.05	<0.05	<0.05
Copper	25	3.0	2.3	2.9	4.0	3.6	4.9	4.1
Lead	5.0	0.9	0.4	0.5	0.4	0.4	0.6	0.3
Mercury	0.2	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Molybdenum	350	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Nickel	20	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Selenium	1.0	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Silver	5	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Thallium	7.0	0.7	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3
Vanadium	24	0.26	0.24	<0.05	0.22	0.13	<0.05	<0.05
Zinc	250	36	36	45	33	26	43	41

Totals								
Substance	TTLC (mg/kg)	A-1 (mg/kg)	A-2 (mg/kg)	A-3 (mg/kg)	O-1 (mg/kg)	O-2 (mg/kg)	O-3 (mg/kg)	A/O Comp (mg/kg)
Antimony	500	58	46	56	55	45	45	54
Arsenic	500	110	100	150	130	120	150	140
Barium	10,000	910	670	170	890	110	140	120
Beryllium	75	<5	<5	<5	<5	<5	<5	<5
Cadmium	100	8	8	6	5	8	5	10
Chromium (VI)	500	<5	<5	<5	<5	<5	<5	<5
Chromium	2,500	<5	<5	<5	<5	6	<5	<5
Cobalt	8,000	<5	<5	6	8	5	<5	9
Copper	2,500	55	38	51	80	48	59	57
Lead	1,000	<20	180	140	180	190	150	200
Mercury	20	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Molybdenum	3,500	<10	<10	<10	<10	<10	<10	<10
Nickel	2,000	<2	<2	<2	<2	<2	<2	<2
Selenium	100	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
Silver	500	5	3	5	6	3	3	5
Thallium	700	<30	<30	<30	<30	<30	<30	<30
Vanadium	2,400	5	<5	<5	6	<5	<5	<5
Zinc	5,000	430	400	530	410	390	490	460

Water was dripping from the composite sample during the paint-filter test.

Table 12.4 Analytical Results for Sludge, Brookhaven National Laboratory

Liquid Sample Substance \ Sample	STLC (mg/L)	A-1	A-2	A-3	0-1	0-2	0-3	A-comp	0-comp	A+0 comp	G-1
		Metals in ppm (μg/mL)									
Arsenic	5.0	8.8	5.7	5.0	0.5	6.8	7.0	8.5	7.4	8.0	2.7
Cadmium	1.0	2.0	1.4	0.5	3.8	3.9	1.3	1.5	2.6	2.1	1.2
Copper	25	1.7	3.0	5.0	1.3	1.9	1.8	2.8	1.4	1.4	13.3
Lead	5.0	190	193	170	210	230	170	180	190	200	68
Zinc	250	1010	1050	1190	834	983	1090	1020	1000	1100	2020
Dried Solids	TTLC (mg/Kg)										
Arsenic	500	290	230	350	230	170	300	240	240	230	---
Cadmium	100	33	29	27	35	35	29	29	33	32	---
Copper	2,500	255	152	223	253	198	315	195	246	234	---
Lead	1,000	470	580	400	580	480	470	430	510	480	---
Zinc	5,000	1050	730	1170	724	754	1180	932	919	883	---
Total*Sludge Sample		Metals in ppm (μg/g)									
Arsenic	---	250	82	64	83	60	65	63	72	64	---
Cadmium	---	10.6	10.6	5.0	13.2	13.5	6.7	7.8	10.5	9.3	---
Copper	---	77	54	42	88	70	66	49	71	63	---
Lead	---	209	270	157	263	242	180	184	220	180	---
Zinc	---	680	622	815	499	577	780	670	650	670	---

Sample Characterization	A-1	A-2	A-3	0-1	0-2	0-3	A-comp	0-comp	A+0 comp
Total Sludge (g)	1210.5	1207.9	1164.9	1239.4	1221.7	1214.7	1178.9	1203.6	1198.2
Liquid* (g)	537.1	525.9	745.8	460.0	482.7	744.7	636.6	576.2	593
Wet Solids*#(g)	673.4	682.0	419.1	779.4	739	470	542.3	627.4	605.2
Percent Solids (%)	55.6	56.5	36.0	62.9	60.5	38.7	46.0	52.1	50.5

* after Centrifuge at 10,000g for 15 min.

sample weight later reduced by 38 - 51% by oven drying at 100°C

12.4 BRINE POND CLEANUP

The process of the brine pond cleanup involved the use of new technology and consequently encountered unanticipated problems and costs. The experience gained may be applicable to future cleanup operations by geothermal operators in the Imperial Valley and elsewhere, and therefore is described here in considerable detail.

12.4.1 Subcontractor Proposals and Selection

Bechtel solicited quotations for waste disposal from seven firms identified from a bidders list prepared for a similar waste-management procurement for the Elk Hills Strategic Petroleum Reserve Project. Three firms declined to bid. Initial specifications were based on the assumption that the waste could be classified as nonhazardous. After the final sampling program and the identification of arsenic at hazardous levels, additional quotes were requested. Bidders made site visits and took samples. Four firms submitted bids. Following a designation based on analytical results that the waste would be hazardous, and addressing a final bid basis of 10,000 barrels of sludge, three final bids were received.

Bechtel recommended award of the cleanup subcontract to Separation and Recovery Systems (SRS). The proposed procedure was to dewater the sludge with the SRS centrifuge process, ship the processed solids to IT for disposal, and inject the process fluids into an existing well. This approach for disposal of the sludge was accepted by Kennecott (Bechtel Progress Report No. TP-30, Sept.19-Oct. 30, 1988).

12.4.2 Operational Plan

The initial operational plan developed by SRS and Bechtel included the following elements (Bechtel Scope of Work, Brine Pond Cleanup, November 2, 1988):

1. Removal by mechanical means of the salt crust above the sludge; break salt crust into pieces of a size acceptable for disposal.

2. Removal of the polyethylene pond curtain; prepare for disposal.

3. Dense sludge removal and pond dredging, using a pontoon-type dredge with an electric submersible pump system, pumping to two Baker temporary storage tanks. These tanks were to be used as feed storage for the MX-1500 Mobile Treatment Unit. The unused dredge sludge was to be recirculated to the pond, keeping the solids in suspension.

4. SRS would dewater the pumpable sludge at a rate of approximately 1,000 bbl per day, using the MX-1500 Mobile Treatment Unit. Solids would be conveyed into containers for later transport and disposal. The liquid phase would be pumped to a tank provided by Bechtel, and Bechtel would be responsible for subsequent disposition of the liquids. This was to be accomplished by injection to the Imperial 1-13 well, the disposal well used in the long-term flow test.

5. After all pumpable sludge had been removed from the pond and processed, SRS would scrape the sides and bottom of the pond of any remaining solids and load it into containers for disposal.

12.4.3 Cleanup Chronology and Discussion

Several problems encountered in the cleanup process prolonged the cleanup period and escalated costs. Because of this, the cleanup may be regarded as a two-part activity: Phase 2A, completed under the direction of Bechtel prior to December 25, 1988; and Phase 2B, completed under the direction of Kennecott, from December 25, 1988 to completion in February 1989. Table 12.5 presents a short-form chronology of significant activities and milestones for the project.

12.4.3.1 *Phase 2A, Bechtel-SRS Cleanup*

SRS mobilized to the site on November 14, and began pumping pond fluids to the Baker tanks for injection by Bechtel on November 17. On November 31, the first load of salt crust that had been draglined to the bank was loaded by backhoe, dressed with flyash to absorb free fluid, and shipped to the IT waste facility. Seven of eight tanks of brine, pumped from the holding pond, had been successfully injected into the Imperial well. A decision was made to add flyash to both salt crust and sludge, as required, to absorb fluids that would likely drip from the trucks, due to vibration, during transport to the dump. The addition of flyash addressed leakage from the trucks, an important criterion for acceptance at the IT waste facility, but impacted both total disposal weight and cost. The flyash itself was available for the cost of handling only.

By December 7, after nine days of regular operation, several problems were apparent. To this date, only 150 tons of salt crust, plus minor sludge, had been accepted at IT. An estimated 270 tons of sludge (700 bbl), had been pumped from the northeast part of the pond, revealing a submerged salt crust. Most of the sludge had been passing through the centrifuge unaffected to the site tanks. Second, forty to fifty percent of the material pumped to the site tanks was now bypassing the centrifuge. The centrifuged produced solids were wet, and flyash was being added. None of the processed sludge had yet been shipped.

On December 7, measurements indicated rapid plugging of the Imperial well. Wellhead pressure at approximately 1000 hours (10 a.m.) was about 220 psi at 120 gpm, and flow from the pump discharge showed extensive solids. It appeared that sludge buildup in the site tanks was being carried to the pump. To avoid further plugging, injection was stopped and, since the site tanks were full, pond pumping was also stopped. SRS suggested investigating the addition of a polymer to enable more solids to be separated by the centrifuge. The introduction of the polymer to the slurry being fed into the centrifuge would hopefully cause the fine-grained solids to agglomerate. These fine grains would then fall out with the larger particle-sized solids, leaving a relatively clean fluid to inject. An attempt was made to unplug the Imperial well by injecting fresh water for a few hours. This attempt proved unsuccessful because less than 100 gpm was injected at a pressure of 265 psi (Bechtel SSSDP Brine Pond Sludge Removal Status — Report No. 2, Dec. 8, 1988).

A DOE/SAN project review on December 12 reiterated the above problems, and several additional concerns:

1. There was a greater volume of fluid in the pond than anyone had anticipated. The fluid's source was unclear: shallow ground water could have seeped into the pond, or the sludge could have dewatered.

2. A second, and possibly a third, salt cake layer was present, possibly a product of the earlier short flow tests.

3. Centrifuging did not completely separate liquids from solids, leaving an estimated 30 percent (or more) solid with the liquid fraction, and rendering the liquid unfit for injection.

Table 12.5 Brine Pond Cleanup Chronology; Phase 2

Date	Activity
08/31/87	12-hour flow test
05/23/88	Mud pit cleaned
06/01 - 06/19	19-day flow test
06/20 - 06/22	44-hour pressure-buildup test
06/88 - 09/88	Bechtel cleanup plan developed
	Bechtel request for quotations, brine pond cleanup
06/23/88	First quotes from contractors to Bechtel (nonhazardous waste)
06/28 - 07/22	Second quotes from contractors to Bechtel (hazardous waste)
08/22/88	IT Corp. bid for disposal of geothermal waste
09/07/88	Kennecott letter to Bechtel about lack of progress
09/15/88	Detailed sampling of brine pond by DOE, Kennecott
09/30/88	Cleanup rebids due to Bechtel
10/10/88	Bechtel draft brine-pond sludge-removal plan to Kennecott
10/13/88	Analytical results submitted by NET Pacific to DOE/SAN
10/24/88	Bechtel submittal to Kennecott, DOE/SAN; SSSDP Geothermal Brine Pond Sludge Removal plan; recommendation to subcontract to SRS, Inc. for cleanup
10/26 - 11/09	DOE/SAN analysis of bids
10/28/88	Kennecott acceptance of Bechtel plan
11/09/88	Bechtel subcontract with SRS, Inc.
11/14/88	Begin on-site mobilization by SRS, Bechtel
11/15/88	Bechtel analyses to DOE/SAN
11/17/88	SRS began pumping pond fluids to site tanks
11/21/88	126,000 gallons pumped from pond to date; SRS using drag line on salt crust
11/22/88	IT rejects load of salt crust and sludge due to dripping fluid
11/22/88	Kennecott and Bechtel confirm IT rate of $55.00/ton for all wastes
11/29/88	8 Baker tanks of brine injected into Imperial 1-13 well
11/30/88	SRS began pumping sludge to centrifuge unit; first disposal of sludge at IT
12/06/88	SRS began bypass of centrifuge, injecting fluids into Imperial 1-13 well
12/07/88	Rapid plugging of Imperial well; shutdown to investigate adding polymer
12/08/88	Shutdown to evaluate polymer; began reprocessing with polymer
12/08 - 12/14	Reprocessing with polymer; direct removal, hauling, disposal
12/15 - 12/23	Processing with polymer; injection; direct removal, hauling, disposal
12/23/88	Shutdown at 1200 hrs; reached Bechtel cost ceiling
12/28/88	DOE/SAN - Bechtel Contract Mod. for cleanup; statement of work changes
12/30/88	Kennecott authorized Glenn Tinsley & Assoc. and SRS to resume cleanup
12/31/88	CRWQCB cleanup deadline; extended to Feb. 10, 1989
1/2 - 1/6/89	Heavy rains, wet surface; mud holidays
1/07/89	SRS pumping brine pond
1/08/89	Injection to Imperial well; pumping brine pond
1/09/89	Site inspection by David Mulliner, Waste Management Consultant
1/10 - 2/8/89	Pumping, processing with polymer, injection, direct removal by SRS
1/30/89	Finished pumping sludge from brine pond
2/04/89	Last sludge processed from Baker tanks
2/08/89	Inspection by CRWQCB; samples taken for analysis; SRS demobilization
2/15/89	Last load of sludge to IT
2/16/89	Sample analysis reported; miscellaneous cleanup completed
2/17/89	CRWQCB declares site acceptable
2/28/89	Turnover of site and equipment from Kennecott to Freeport - MacMoran

4. The solids fraction produced by centrifuging contained about 40 percent liquid that dripped, making it unacceptable at the IT dump.

5. The surface salt cake was dense, but could be selectively loaded by hand and backhoe. The underlying salt cake was wet and required the addition of flyash.

6. SRS determined that the introduction of a polymer into the slurry being fed to the centrifuge would result in the fine particle-sized solids agglomerating, then falling out with the larger-sized particles, leaving a relatively clean fluid to inject. Some polymer, perhaps 50 ppm, would be expected to remain in the processed liquid.

7. SRS proposed that the processed solids fraction, too wet to take to the dump, be taken from the Baker tank and laid on a tarp, on the ground, to facilitate drying before shipment.

Reprocessing of previously treated sludge with a polymer additive began on December 8 and continued to December 14. Shipping of salt cake and sludge resumed on December 12, with three loads accepted by IT. Injection to the Imperial well resumed, and it accepted fluid more readily (250 gpm at 160 psi) on December 12. Processing of untreated sludge by addition of the polymer began on December 15 and continued to December 23. Addition of the polymer substantially improved the centrifuge separation, resulting in a cleaner liquid fraction and a dryer solids fraction.

Removal of the salt crust by dragline continued and, by December 15, approximately 65 percent of the pond had been cleared. On this day, a bad bearing in the centrifuge forced a one-day shutdown for repair (Bechtel, 1988, SSSDP Brine Pond Sludge Removal Status- Report No. 6). The mechanical removal and drying of salt crust and dense sludge continued in a routine manner with shipment of dried waste to the IT dump site. The wet sludge was slurried with fresh water for pumping with a submersible pump, and then pumped to the two SRS Baker feed tanks at a rate of approximately 1,000 bbl per day. After an appropriate settling time, the fluids in the upper part of the tank were diluted with fresh water to slurry and dissolve maximum salt, then processed with polymer and centrifuged. The solid product was shipped to the IT site and the separated fluids were injected into the Imperial 1-13 well. On December 23, the prime contractor's cost ceiling was reached, and DOE was forced to issue a stop-work order.

At the time of the stop-work order, a total of 1,277 tons of material had been removed from the brine pond. This included 595 tons of salt crust and dense sludge removed by direct or mechanical means (no centrifuge processing), which was then hauled to the IT site for disposal. An estimated 1,600 tons of sludge remained to be processed. These quantities compare with earlier Bechtel estimates of 10,000 bbl sludge, 2,163 tons net weight, and 649 tons dry material, which were the bid bases for subcontractors.

12.4.3.2 *Phase 2B, Kennecott—SRS Cleanup*

Kennecott, facing a December 31 cleanup deadline issued by the California Regional Water Quality Control Board (CRWQCB), gave written notice to Bechtel to resume the cleanup within 24 hours, or Kennecott would contract directly with SRS, and then charge Bechtel for the costs. Because costs had consumed available funds, Bechtel could not comply and Kennecott executed a contract with SRS on a lump-sum basis for completion of the job. Kennecott received an extension from the CRWQCB until February 10,1989, after which date Kennecott would be subject to a $25,000/day fine.

The Kennecott-SRS agreement, patterned after the Bechtel-SRS contract, called for the mechanical removal of salt crust above the sludge and on the pond banks; breakage into pieces of a size acceptable for disposal; removal of the polyethylene pond curtain; removal of all possible dense sludge (that which would pass the EPA paint-filter test directly); the addition of flyash, if required; and transport and disposal of these materials to the IT dump. The pumpable sludge would be treated as before, with Kennecott disposing of the liquids by injection. All sludge was to be removed from the pond bottom, using all reasonable care to minimize removal of the native clay-soil pond bottom (about 2 inches).

SRS resumed the site cleanup on December 30. A second centrifuge unit that arrived on-site just prior to the December 23 shutdown was placed in operation to increase the throughput of sludge material. Two days of heavy rain the week of January 2 caused SRS to shutdown operations for a full week. Rain water was still present at the site on January 12. Processed sludge on the drying pads was too wet to haul to the dump, but high winds were quickly drying the material and the site as a whole. The high winds were strong enough to close the IT dump on January 11. The Unit 2 centrifuge went down January 12, was taken out of service and removed from the site. Work continued with a host of mechanical problems, including additional centrifuge failures, pump motor burnout, and interruption of fresh water supply. High winds forced closure of the disposal site on several days in late January and early February. The last of the sludge was processed February 4 and final shipment to the dump was completed on February 15, 1989. Final estimates of the volumes and tonnages of material processed are shown in Table 12.6.

After all sludge material had been removed from the brine pond, the pond was allowed to dry. Final cleanup activities included cleanup and grading of the bottom and sides of the pit by bulldozer and manual means, and general site cleanup outside of the pit.

Table 12.6 Summary of Materials Processed and Removed

Material	Phase 2-A Bechtel-SRS	Phase 2-B Kennecott-SRS	Total : 2A + 2B
Sludge sent to IT disposal site*	620.97 t	2,285.36 t	2,906.33 t
Total fluid injected	13,983 bbl	13,568 bbl	27,551 bbl
Total sludge processed	1,277 t	1,236 t	2,513 t

* includes top layer of salt, estimated at 300 tons

Volume Comparison: SRS vs Bectel (12/30/88 - 1/23/89)

SRS : (by tank gauge and weight tickets) Processed: 5,885 bbls x 0.21 ton/bbl = 1,236 tons

Bechtel : Processed volume = 1/2 slurried as 85% water and 15% solids;

Processed: 5,722 bbl x 0.21 ton/bbl = 1,212 tons

Volume Injected: 9,812 bbl
Solids Removed: 1,732 bbl
Volume Slurried: 11,544 bbl

12.4.4 Site Inspection

On February 8, Mr. Paul Sweeney, CRWQCB, conducted an inspection of the brine pond bottom and cleanup activities. Samples were taken from the bottom of the pit for analysis. The holding pond cleanup, though a painfully long and expensive process, had been thorough. The site appeared as though the pit was newly excavated. No visible evidence existed of sludge, salt cake or brine on the bottom, sides, or berm of the pit. The bottom had been bladed down an additional 2-4 inches, exposing fresh, native subsoil. There was no evidence of wetness from residual brine or ground water. The CRWQCB representative commented that this was one of the cleanest brine holding ponds he had seen in the Imperial Valley. Two soil samples were recovered with a spade to a depth of about 12 inches: one in the center of the pond, and another in the center toward the south end. Samples were split for analysis by CRWQCB and by Kennecott at a lab of their choosing (DOE/SAN Memo, Feb. 13, 1989). Analytical results for a fluid extract of the composite sample analyzed by Quality Assurance Laboratory (QAL, Feb. 15, 1989) for Kennecott are shown in Table 12.7. All metals reported were well below the TTLC. Following a final site inspection by CRWQCB in February, Kennecott was notified that the site cleanup met all CRWQCB requirements.

Table 12.7 Analytical Results; Post-Cleanup Brine Pond Sample

Analysis	Method	Units	Log Number: 1406-89	TTLC (mg/kg)
Conductivity*	STD 205	µmhos/cm	11,100	---
PH*	STD 423	units	7.47	---
TDS*	STD 209-B	mg/l	7,110/7,230**	---
Barium	6010	mg/kg	136	10,000
Lead	6010	mg/kg	25.0	1,000
Manganese	6010	mg/kg	375	---
Zinc	6010	mg/kg	95.8	5,000
Arsenic	6010	mg/kg	20.3	500

* Analysis performed on extract (20g Sample/200mL Nanopure Water)
** Duplicate analysis

Soil sample from center of brine-pond bottom, taken Feb. 8, 1989
Analysis by Quality Assurance Laboratory, San Diego, CA of Feb. 15, 1989

12.5 CLEANUP COSTS

Several factors combined to result in inaccurate estimates of the cleanup costs, and escalation in costs as the cleanup progressed. These included technical, contractual, and judgemental considerations, and the weather; they are discussed later. A general summary of cleanup costs follows in Table 12.8.

Table 12.8 Brine Pond Cleanup Costs (Thousands)

	Bechtel	SRS	Kennecott	
Precleanup: To 9/18/88	$56.*	---	---	
Phase 2A - 9/19/88 - 12/29/88	$43.4	$257.3	---	
Phase 2B -12/30/88 - 2/24/89	---	$240.0	$64.2	
Totals (estimated)	$99.4	$497.3	$64.2	$660.9

* *Includes May 1988 mud-pit cleanup for $36,550.*

The final, total direct cost of $660,900 is a significant part of the total $9,332,187 prime contract to Bechtel (about 7 percent).

Bechtel costs include minor subcontractor efforts associated with the mud sump and brine pond cleanup, design, travel, supervision, management, overhead and fee costs. SRS costs included fluid processing by centrifuge, mechanical removal, hauling, disposal fees, labor, supervisory and personnel expenses and related costs. Kennecott costs included a $24,000 management fee, $27,300 for Glen E. Tinsley & Associates for on-site project management and direct cleanup activities, $10,000 for equipment rental and services, and miscellaneous costs. Direct cleanup costs (SRS and Kennecott), therefore, totaled about $540,000, more than double the original $250,000 estimate. Internal DOE costs for active project management, travel, contracts accounting and legal activities were also significant.

12.6 CLEANUP SUMMARY EVALUATION

Environmental restoration and remediation is now recognized as a basic element of most resource development activities, and the drilling, testing and development of geothermal resources is no exception. The SSSDP brine pond cleanup was one of the most thorough efforts in this regard, and, as such, encountered a number of problems and unexpected costs.

12.6.1 Problems

Although some of the problems identified during the course of the cleanup could be attributed to use of untried technology on difficult geothermal brines and sludges, other basic causes have been identified in retrospect.

1. There was considerable confusion, well into the cleanup operation, as to what constituted an acceptable cleanup restoration to a natural site, or a "condition ready for reuse," as required by the CRWQCB permit and as stipulated by the Kennecott/Bechtel agreement.

2. The prime contractor underestimated the cleanup problem and failed to properly scope the problem. No substantial effort had been made to systematically sample the sludge and salt deposits, or to determine the volume and tonnages.

3. The subsequent sampling effort by DOE provided the first, and only, estimates of volumes of material. This effort was conducted under difficult field conditions present in the brine pond (breakable salt crust, gooey sludge, etc.) and determined that the material must be treated as hazardous. Nevertheless, the volume of material was underestimated by a factor of two, the presence of second and third layers of salt crust was not detected, and the true depth of the brine pond and sludge deposits was not known until the sludge had been removed. Clearly, an expanded effort to determine salt crust and sludge volumes, without taking additional samples for chemical analyses, would have permitted a closer estimate of the magnitude of the job.

4. A better subcontracting effort may have been possible. A request for an "expression of interest" to determine a broader list of potential subcontractors could have been issued prior to completion of the 20-day flow test, and before final tonnage estimates were available. The subcontract should have stipulated a firm, fixed price and placed the added costs for failures of any unproven technology (i.e., the centrifuge processing) upon the subcontractor.

5. The contractor consistently underestimated and under-bid the cleanup tasks. The estimates were based on a quantity of material calculated from measurements made by DOE, with an added margin. The resulting cost overruns caused delays while contract amendments were processed. Better scoping of the problem at the beginning may have resulted in adequate funding for the entire cleanup, before startup, thereby avoiding shutdowns caused by overruns.

6. The deadline for completing pond cleanup, imposed on Kennecott by the CRWQCB, may have precluded a better planned and more efficient cleanup.

7. The federal procurement system, with its built-in safeguards to avoid misuse of public monies, is not well suited for projects with substantial unanticipated costs and fixed deadlines. Delays in adding new monies for cleanup activities resulted in down-time charges and additional weather-related expenses. The monies, ultimately, had to come from other high-priority research projects.

12.6.2 Discussion—Technology Used

Several observations can be made about the technology used during the cleanup. The centrifuge process used by SRS had been successful in earlier projects in separating oil wastes from water, but had not been used for dewatering geothermal sludge. A laboratory test apparently reassured SRS that it would be effective, but initial processing at the site produced fluids with too high solids content to be acceptable for injection, and too much liquid in the solids for disposal. The addition of a polymer (about 50 ppm) to the slurried sludge resulted in fluid that was acceptable for injection, but produced a solid product that still required drying in the sun before disposal at the IT waste site. The centrifuge units broke down several times during the project, and were unable to process sludge at the projected rate.

Attempts to bypass the centrifuge with about 50 percent of the slurried sludge, and centrifuge processing without addition of a polymer, resulted in fluids that quickly reduced the injectivity of the Imperial 1-13 well, and threatened to damage the well. The well recovered after fluids were treated with the polymer, but long-term effects of injecting the treated fluids with polymer are not known.

Low-cost, low-technology, mechanical removal of the salt crust and dense sludge was effective and accounted for more than half the material shipped to the IT waste site. Use of a clamshell dredge caused mixing of salt and sludge and threatened rupture of the compacted pond bottom. Removal by backhoe and dragline proved more effective. Drying of the sludge, salt crust and processed sludge was accomplished on tarps in the sun. Lining the truck beds with flyash and adding flyash to the sludge prevented dripping on county roads and made a solid waste acceptable to IT. The tonnage of the disposed material was substantially increased by this process, however. The processed sludge was found to be highly hygroscopic because of the high calcium-chloride content, and readily absorbed moisture from humid air.

12.6.3 Recommendations

Cleanup of the mud pit and brine pond was successfully accomplished after considerable difficulty at a cost estimated at $661,000, or about 7 percent of the prime Bechtel contract for the SSSDP. The cleanup was judged acceptable to the CRWQCB without modification.

Future cleanup efforts may benefit from some of the lessons learned in this project. The depths of mud and brine pits should be accurately recorded. The depths of deposits could readily be determined, if several simple depth gauges (marked posts) are placed within the pits after excavation and lining. Cleanup operations should be more accurately scoped in advance by carefully sampling the thicknesses of the deposits present.

Mechanical removal of salt crust and sludge, and drying in the sun, proved to be an effective and low-cost means for removing much of the deposits. Careful use of a backhoe and other equipment may prove cost-effective in separating nonhazardous salt crust from hazardous sludge materials, thereby reducing future disposal costs.

The use of polymers in treating geothermal brines, and the long-term effects of injecting brines with polymers into subsurface reservoirs, may well be topics worthy of future research. Future cleanup operations may be reduced in scope by injection of geothermal brines during production testing, if suitable injection wells and horizons are available. Innovative contracting, which separates low- and high-tech efforts, as attempted by DOE in this effort, may result in substantial cost savings.

Potential waste-management contractors should be informed of cleanup histories such as this, prior to designing and bidding on similar jobs. DOE should solicit other well-documented cleanup histories from industry and make the information available to geothermal industry developers and waste-management contractors.

12.7 REFERENCES

Bechtel National, Inc., 1988, Progress Report No., TP-30, Sept. 19-Oct. 30, 5 p.

Bechtel National, Inc., 1988, Geothermal Brine Sludge Pond Removal Plan, Oct. 24, 18 p.

Bechtel National, Inc., 1987, Progress Report No. TP-20, June-August 1987, 5 p.

Bechtel National, Inc., 1988, Report No. TP-27, June 13-July 24, 5 p.

DOE/SAN, 1988, Memorandum, Sept. 20

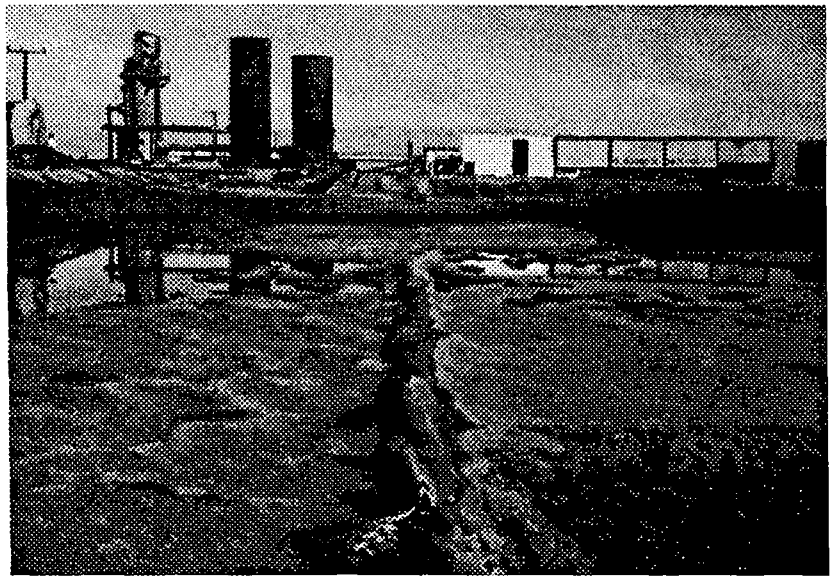
DOE/SAN, 1988, Memorandum, Sept. 16

DOE/SAN, 1989, Memorandum, Feb. 13

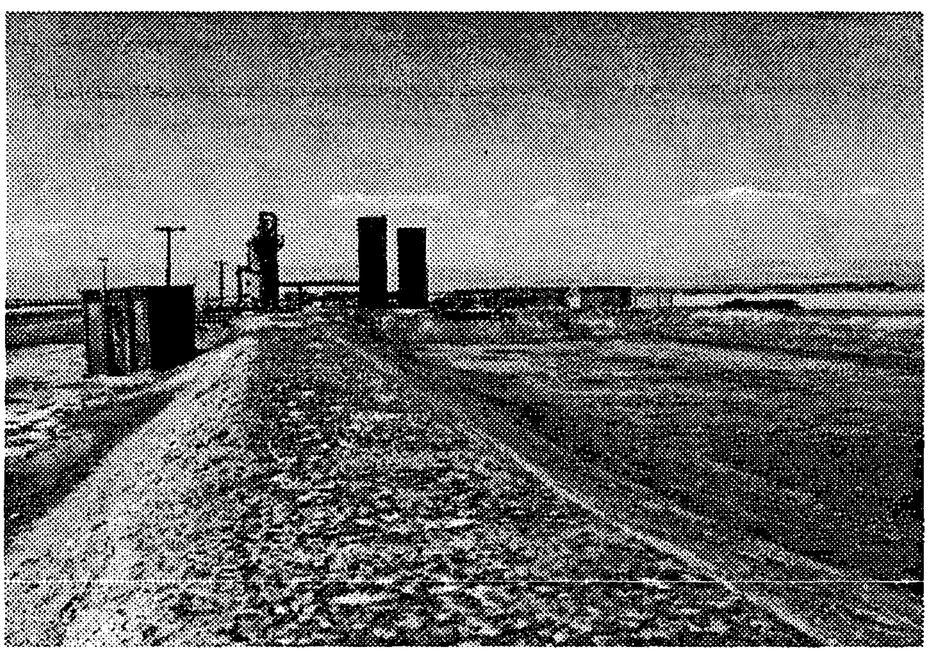
Brookhaven National Laboratory, 1988, Informal Report, Nov. 15, 10 p.

Bechtel National, Inc., 1988, SSSDP Brine Pond Sludge Removal Status-Report No. 2, Dec. 8

Bechtel National, Inc., 1988, SSSDP Brine Pond Sludge Removal Status-Report No. 6, Dec 20



Looking north across SSSDP brine pond during cleanup, November 22, 1988. Note salt crust that remains and dragline teeth marks at right front.



Looking north across SSSDP brine pond after cleanup, April 1991.

13.0 COST SUMMARY

The total contract value for the prime contractor, Bechtel National, Inc., for Phase-1 and Phase-2 activities is estimated at $9,488,000. Federal overhead adjustments may still be in progress. Additional project expenses were offset by cost-shares borne by Kennecott ($40,000) and by Bechtel ($55,000).

13.1 BECHTEL PROJECT COST SUMMARY

Table 13.1 presents an estimated SSSDP project cost summary, compiled from available records, by phase and task.

The estimated costs incurred in completing major blocks of work, and corresponding periods of performance, are shown in Table 13.2. Note that these costs do not include the scientific experiments costs, nor overhead adjustments, nor some project-management costs.

The largest expenditures were for drilling, coring, and remedial work associated with maintaining the drill hole. Table 13.3, compiled from Bechtel periodic reports, examines drilling and coring performance trends in terms of cost and footage, as a function of depth interval. Drilling cost increased dramatically as depth increased. The major factors in higher drilling costs with increased depth were related to directional drilling; lost-circulation control; stuck pipe; and well control.

An additional cost breakdown for subcontractor costs relating to specific subcontractors, tasks, and/or equipment and supply items is presented in Appendix C.

13.2 ASSOCIATED SCIENCE COSTS

A detailed accounting of the associated science costs of the SSSDP would be difficult to reconstruct, and would be subject to major inaccuracies, in part because of the variable funding sources. More than 50 scientists have participated in this project, and several major science organizations. Among these are: Brookhaven National Laboratory; Lawerence Livermore National Laboratory: Sandia National Laboratory; Los Alamos National Laboratory; Lawrence Berkeley Laboratory; Idaho National Engineering Laboratory; the U.S. Geological Survey; the University of Utah Research Institute; and a number of other academic institutions and investigators funded by the National Science Foundation. Their scientific experiments' costs are not included in the foregoing tables. A very conservative estimate, cognizant of the cost of well logging, borehole-gravity surveys, chemical analyses, etc., would be in excess of $1,000,000.

Thus, the total costs associated with the SSSDP (including science) certainly exceeded $10,500,000.

Table 13.1

SSSDP PROJECT COST SUMMARY

(THOUSANDS)

PHASE I

TASK 1. Site & Well Design, etc.	$ 1,201	
2. Site & Procurement Preparation	946	
3. Well Drilling & Coring Program	3,275	
4. Flow Test	838	
5. Standby Operations	580	
6. Well & Site Cleanup	155	
7. 1985 AIC Overhead Adjustment (1984-85)	150	
8. 1989 AIC Overhead Adjustment (1984-86)	156	
PHASE-1 TOTAL		$7,301

PHASE II

TASK 1. Repair Well Bore	$ 482	
2. Construct Flow-Test Facility	474	
3. Flow Test	167	
4. Cleanup and Draft Final Report	419	
5. Utilities	34	
6. Project Management	443	
7. Other Cleanup and Cleanup Management	168	
8. 1987-88,-89 AIC Overhead Adjustment	(*)	
PHASE-2 TOTAL		$2,187

BECHTEL NATIONAL, INC.-Prime Contract	$9,488
Cost Share	
Kennecott Cost Share	40
Bechtel Cost Share	55
PROJECT TOTAL COST - (excluding most science)	$9,583

* To be determined

Table 13.2

SUMMARY OF SALTON SEA SCIENTIFIC DRILLING PROGRAM COSTS [1,2]

Activity	Period of Performance	Estimated Cost ($1,000s)
Phase I		
Tasks 1 and 2 Prespud	Sept. 1984 through Oct. 1985	1,720
Task 3 Drilling and completion	Oct. 1985 through March 1986	2,974
Coring and logging	Oct. 1985 through March 1986	930
Task 4 Flow test facility and two flow tests	Dec. 1985 and March 1986	680
Task 5 and 6 Standby and restoration	April 1986 through Nov. 1986	400
Task 5a Remedial operation	July 1986 through August 1986	290
	Phase-1 Sub-Total	$ 6,994
Phase II		
Tasks 1 Repair well bore	January 1988 through April 1988	482
Tasks 2 and 3 Construct Flow-Test Facility	April 1988 through June 1988	641
Tasks 4 Cleanup, draft final report	July 1988 through February 1989	660
	Phase-2 Sub-Total	$ 1,783

(1) *Excludes the scientific experiments budget.*

(2) *Includes some project management (est.) Excludes AIC overhead adjustments.*

Table 13.3

DRILLING AND CORING PERFORMANCE TRENDS [(a)]

Depth Intervals (ft)	*Days to Complete*	*Average Cost/Day*	*Average Ft/Day*	*Average Cost/Ft*	*Delays*
Surface to 3,500	21	$ 15,500	165	$ 95	One day: setting conductor; one-day: fishing
3,500 to 6,000	23	17,000	110	155	Two days: fishing; two days: fishing
6,000 to 7,000	20	19,500	50	390	Six days: directional drilling; two days: fishing
7,000 to 8,000	10	19,500	100	195	Two days: directional drilling; two days: lost circulation control
8,000 to 9,000	11	26,000	90	290	Five days: lost circulation control
9,000 to 10,000	27	24,500	35	660	Damaged core bits; seven days: lost circulation control and cementing; two days: stuck pipe; two days: well control
10,000 to 10,564	5	23,000	90	250	Two days: well control; one day: stuck pipe

(a) Excludes casing, flow tests, and logging activities.

14.0 SUMMARY AND RECOMMENDATIONS

A review and discussion of selected parts of the engineering and drilling aspects of the SSSDP is presented in this section, with recommendations for conducting future scientific drilling in high-temperature geothermal systems. A detailed discussion and recommendations relating to all the various geoscience studies would unduly lengthen this report and is better left to the technical reports and papers cited earlier. However, section 14.7 does note many scientific accomplishments of the program.

14.1 DRILLING

14.1.1 Summary

Drilling provides access for all the science conducted from a borehole and is, of course, the major engineering and cost element. Drilling in high-temperature geothermal systems is notoriously unpredictible and expensive, and the SSSDP was no exception. No one involved in the management of this program from the Department of Energy, Bechtel National Corporation, or the subcontractor drilling engineer had experience in drilling geothermal wells. The direct drilling costs of the SSSDP, approximately $6.4 million, was well above costs reported for hydrothermal wells completed by industry, when drilling depth and inflation were considered (Chappel et al., 1979; Rowley, 1985; Tester and Herzog, 1990).

Drilling progress slowed and costs escalated at depths greater than 6,000 ft, due to hole deviation and lost-circulation problems, which in turn can be attributed to fracturing and alteration effects. These are common to many geothermal wells and are not unusual. The major drilling problem for well State 2-14 resulted from the separation of the collar of the 7 in. hanging liner at 6,195 ft, after total depth had been reached. Detailed metallurgical studies by Brookhaven National Laboratories on the recovered collars and liner (Report G in Appendix A) suggested that failure resulted from embrittlement, due to the presence of H_2S and O_2 in the brine, and perhaps due to additional stress caused by the 5-degree dogleg at about 6,200 ft. Separation of the liner resulted in the need for remedial work in Phase-1 and the well rework effort in Phase-2. When these proved unsucessful, significant data were lost.

14.1.2 Recommendations

While it is uncertain that the drilling problems encountered in State 2-14 could have been avoided, the following recommendations for drilling in high-temperature geothermal environments should be restated.

- At a minimum, the responsible drilling engineer should be experienced in all phases of geothermal drilling operations and should be familiar with normal geothermal drilling practices in the area of investigation.
- Cost constraints during drilling operations should not be used to justify the choice of cheaper, high-risk procedures since most do not work and result in much higher costs over time to repair the damage.
- Further development of advanced lost-circulation materials (LCM) is warranted and should continue to be supported by DOE;
- Drilling techniques should be modified to the extent possible to avoid or minimize unplanned doglegs in the borehole (i.e., regulation of weight on bit, rigid drill-string

assembly, more frequent directional surveys, etc.)

- All components of the geothermal drill string must be geothermally hardened, anticipating H_2S, O_2 and H_2 embrittlement and corrosion.

14.2 REMEDIAL DRILLING AND REWORK

14.2.1 Summary

Both the August 1986 and the August 1987 efforts to regain access to the bottom of the drill hole were unsuccessful. Attempts to sidetrack the hole failed when the positive-displacement mud motors did not operate because excessive heat caused the elastomer stators to disintegrate. Failure of the turbine mud motors was caused by insufficient fluid flow to operate and cool the motors. The drilling supervisor should have calibrated the flow from the mud pumps before deployment of a mud motor, not after the failure of four mud motors. Drilling with a whipstock achieved some kick-off, as indicated by some formation cuttings in the returns, but the bit may never have completely exited the original hole.

Loss of circulation during the rework was not a problem, because the mud weight was low; however, the under-balanced system allowed the well to flow on numerous occassions. Well flow was controlled by bullheading brine down the hole to kill it.

14.2.2 Recommendations

If similar sidetracking efforts are to be undertaken in geothermal wells under similar hot conditions, it is recommended that mud motors be used only with adequate, calibrated mud flow, and with improved high-temperature models. Experienced, expert drilling supervision is essential.

Because sidetrackingwith mud motors was unsuccessful, improved designs for mud motors to resist high temperatures are needed to increase the chances for success in hot geothermal wells.

14.3 CONSTRUCTION OF FLOW TEST FACILITY

14.3.1 Summary

Previously used flow-test equipment from the DOE Geothermal Test Facility at East Mesa was reconditioned for the long-term flow test. The high-pressure separator, atmospheric flash tank and the vent silencer were coated with rust from previous use and storage. The major piping was badly rusted and corroded. None of the valves were operational, and the instrumentation was in poor condition. It proved less expensive to rent replacement flow and level recorders than to recondition existing ones. In net, however, construction of the flow-test facility with the available previously-used equipment was successful and probably less costly than all new construction.

14.3.2 Recommendations

A number of recommendations concerning facility construction arose because of adverse test conditions and incidents experienced during the test period in June:

- The pressure taps for the wellhead pressure gauge and for one of the brine orifice meters plugged during the flow test. When this happened, a rodding tool was used for cleaning the ports, without shutting down the line; this allowed the test to proceed with essentially no interruption.

Use of a rodding tool is recommended as an appropriate remedy for plugged pressure taps. The piping and valve for the tap must be straight and short enough to permit use of the rodding tool.

- A nylon-reinforced, polyethylene diverter curtain accumulated so much salt and sludge that brine flowed over the top of the curtain near the brine pond inlet, short-circuiting the longer path to the opposite end of the brine pond and back. This allowed brine from the pond inlet to flow directly to the brine pump inlet.

  Recommendations to avoid this adverse condition include: 1) a different design for the diverter curtain, possibly using floats instead of a tensioned cable to support the curtain; or 2) a permanent baffle, such as an earthen dike, to serve the same function as the diverter curtain; 3) using irrigation water from the beginning of the flow test to dilute the brine and limit accumulation of salt and sludge; and 4) a second water pump should be on site for backup in case the first pump fails.

- Cavitation occurred at the intake of the brine and the booster pumps, at one time or another, during the flow test. It was most severe for the brine pumps, especially when hot brine began to flow over the diverter curtain directly from the brine pond inlet.

  Recommendations to mitigate this condition, although none is a complete cure, are: 1) pump inlets should be large, short, and free of unnecessary valves, elbows, tees, and other pipe fittings; 2) the brine pump inlet line should be imbedded in the brine pond berm rather than passing over the top of it; 3) a second brine pump should be on site and available for backup if the first pump fails; 4) pumps should be kept as low as feasible — in this regard, skid mounting is better than trailer mounting; and 5) brine should be allowed to cool before arriving at the pump inlet.

- After the flow test was completed, the steam flow meter (orifice plate) was found to be obstructed by some debris, pieces of metal or scale apparently dislodged upstream. This caused all the steam flow-rate readings to be erroneously high.

  Recommendations to avoid such flow meter obstruction include: 1) the upstream piping should be completely disassembled (if used equipment is installed) and cleaned, and corroded or scaled components should be replaced, if they cannot be thoroughly cleaned; 2) the indicated flash fraction should be compared with theoretical values early in the test period, and discrepancies should be traced and remedied to within the expected accuracy of the flow meters; and 3) provisions should be made to isolate and disassemble flow meters without affecting well flow.

14.4 JUNE 1988 FLOW TEST

14.4.1 Summary

At typical commercial operating wellhead pressure of 250 psig (1,724 kPa), about 840,000 lbm/hr (381,000 kg/hr) could be produced from the State 2-14 well. This could generate about 12 MWe in a two-stage flash plant.

Increased well deliverability during the flow test suggests that the well improved during the course of the test. It is likely that flowing the well at higher rates may have cleaned drilling solids from the reservoir rock, or the damaged well bore, and may have opened additional flow paths unavailable at the start of the test. Pressure recovery following drawdown (when additional pressure decrease should be expected) was recorded after flow rate changes. This is further evidence of well productivity improvement during the flow test. Unfortunately, it makes the drawdown curves impossible to analyze accurately for quantitative reservoir parameters. It is also possible that increasing flow was the result of formation damage in a single permeable zone, and continued enlargement of the sand face would cause major problems.

The average productivity index for the State 2-14 well during the flow test was 1,527 lbm/hr per psi (100 kg/hr per kPa). The productivity curve is a straight line, which would be expected from matrix permeability alone. However, reservoirs in the Salton Sea area, typically, are extensively fractured, but also have significant matrix storage capacity. Because well improvement was noted from other data during the flow test, the straight-line productivity curve does not necessarily imply matrix-only permeability. The permeability is probably affected by fracturing in addition to matrix permeability.

Horner-plot analysis of the pressure buildup data yielded a calculated skin factor of +23.1. Positive values indicate large pressure losses as fluid enters the wellbore. These can be caused by wellbore damage, pressure drop across liners or through perforations, partial-penetration completions, wellbore-storage effects, closing of fractures as pressure decreases, and turbulent flow, as fluid enters the wellbore at high rates. For the State 2-14 well, it is concluded that the well sustained damage during drilling and rework activities; however, high flow rates into the wellbore probably contributed to the apparent skin effect also.

The Imperial 1-13 well was used as an injection well during the flow test, with total injected brine of 72.6 million lbm (32.9 million kg). From the start of injection, injectivity (flow rate per unit of wellhead pressure) began to decline. At the end of the test, injectivity was only about 20 percent of the initial value. This progressive decrease is typical of a well undergoing formation plugging by suspended solids. Because injection throughout the test consisted of unfiltered fluid containing some suspended solids, it is concluded that this condition caused most of the reduced injectivity.

A constriction in the State 2-14 well casing, discovered after the June 1988 flow test, probably developed sometime during the flow test. The precise time of development and the reasons thereof, cannot be determined with the information presently available. It is concluded that the effects of the constriction were minimal, because flow was not choked and downhole pressure profiles suggest that the actual pressure drop through the constriction was small.

14.4.2 Recommendations

Two recommendations are offered with respect to flow test procedures. First, reservoir engineers and drilling supervisors should jointly evaluate the benefits and risks of flowing the well early in a long-term flow test, at the highest sustainable rate, to clean out the well and producing formations. Also, for highly saline brines, injected brine should be filtered to protect the injection well from plugging by suspended solids.

14.5 BRINE CHEMISTRY

14.5.1 Summary

Total dissolved solids varied little during the flow test in June 1988, even though the well flow rate varied over a range of 7:1. For flow rates slightly greater than 100,000 lbm/hr (45,359 kg/hr), the TDS concentration was about 232,000 mg/kg, increasing to about 249,000 mg/kg as the flow rate was increased to 400,000 lbm/hr (181,400 kg/hr).

Noncondensible gas content was rather high. Concentrations measured during the June 1988 flow test were approximately one-half of one percent (3,928 to 5,731 mg/kg). Hydrogen sulfide is reported as 22, 2.2, and 6 mg/kg for the three rate-steps in the June 1988 flow test.

As well-flow rate was changed in the June 1988 flow test, changes in the geothermometer-cation ratios — Na/K, Na/Ca, and Ca/K— lead to the following conclusions:

- More than one zone was producing a significant part of the total well flow.

- The various zones were producing different proportions of total flow as the well flow increased.

The sodium, potassium and calcium concentrations for fluids produced during the December 1985 test of the State 2-14 well and those from the Hudson No. 1 well, about one-half mile away, are strikingly similar. An interval between 6,000 and 6,200 ft (1,829 to 1,890 m) of the State 2-14 well was tested, and the production zone in the Hudson No. 1 well was at about 6,000 ft (1,829 m). Therefore, geothermal fluid produced from the zone between 6,000 to 6,200 ft (1,890 m) depth in the State 2-14 well and the fluid produced from the Hudson No. 1 well probably came from the same source.

Temperatures in the State 2-14 well are comparable to those in the nearby River Ranch No. 1 well from 3,000 to 5,000 ft (914 to 1,524 m). At 6,000 and 7,000 ft (1,829 and 2,134 m), the temperatures are 23 and 20 °F (13 and 11 °C) higher, respectively, in the River Ranch No. 1 well. Temperatures in the State 2-14 well are 120 to 130 °F (67 to 72 °C) lower than those in the Elmore No. 1 well for all depths from 3,000 to 7,000 ft (914 to 2,134 m). Likewise, temperatures in the State 2-14 well are 80 to 120 °F (44 to 67 °C) lower than those in the IID Nos. 1 and 2 wells, from 3,000 ft (914 m) to total depths for the IID wells: 5,213 ft (1,589 m) for IID No. 1, and almost 6,000 ft (1,829 m) for IID No. 2. These temperature data indicate that the State 2-14 well is on the southeast flank of the northeast-trending, highest-temperature area of the Salton Sea geothermal system. Comparisons with nearby wells show that temperatures at a given depth decrease rapidly on the flanks of a geothermal system.

14.5.2 Recommendations

Additional testing should be done to confirm the high noncondensible-gas content before designing a power plant to use brine from this well. Additional testing should quantify the hydrogen-sulfide content to determine what hydrogen-sulfide abatement may be needed for power production.

14.6 SITE CLEANUP

14.6.1 Summary

Cleanup of the mud pit and the brine pond were accomplished after considerable difficulty at a cost estimated at $661,000, about 7 percent of the prime Bechtel contract for the SSSDP. The cleanup was judged acceptable to the CRWQCB without modifications. The amount of material to be removed and the cost to complete the project were consistently underestimated during the project.

Several observations can be made about the technology used during the cleanup. The centrifuge process used by a subcontractor, SRS, for dewatering the geothermal sludge, initially produced fluids with too much solids for injection, and too much liquid in the solid for disposal. The addition of a polymer to the slurried sludge resulted in fluid acceptable for injection, but solids still required drying before disposal. Low-cost, low-technology mechanical removal of the salt crust and dense sludge was effective and accounted for more than half the material shipped to the IT waste site. Lining the truck beds with flyash and adding flyash to the sludge prevented dripping on county roads and made a solid waste acceptable to IT. The processed sludge was found to be highly hygroscopic because of the high $CaCl_2$ content, and readily absorbed moisture from humid air.

14.6.2 Recommendations

The depths of mud and brine pits should be accurately recorded. The depths of deposits could readily be determined, if several simple depth gauges (marked posts) are placed within the pits after excavation and lining. Cleanup operations should be more accurately scoped in advance by carefully sampling the thicknesses of the deposits present.

Mechanical removal of salt crust and sludge, and drying in the sun, proved to be an effective and low-cost means for removing much of the deposits. Careful use of a backhoe and other equipment may prove cost effective in separating nonhazardous salt crust from hazardous sludge materials, thereby reducing future disposal costs.

The use of polymers in treating geothermal brines, and the long-term effects of injecting brines with polymers into subsurface reservoirs, may well be topics worthy of future research. Future cleanup operations may be reduced in scope by injection of geothermal brines during production testing, if suitable injection wells and horizons are available. Innovative contracting, which separates low- and high-tech efforts, may result in substantial cost savings.

Potential waste-management contractors should be informed of cleanup histories such as this, prior to designing and bidding of similar jobs. DOE should solicit other well-documented cleanup histories from industry and make the information available to geothermal-industry developers and waste-management contractors.

14.7 SCIENTIFIC ACCOMPLISHMENTS FROM THE SALTON SEA SCIENTIFIC DRILLING PROJECT

Because of the site selection and the inexperience of those involved in drilling the State 2-14 well, many original SSSDP research objectives could not be met. Original research objectives focused on probing the roots of a hot (355° ± 10°C), near-surface, magmatically driven, hypersaline geothermal system, to increase basic scientific understanding of the development of geothermal resources, and to advance technology of drilling and testing to achieve those objectives (Sass and Elders, 1986; Elders and Sass, 1988). The location of State 2-14 well (on the southeast flank of the Salton Sea high-temperature hydrothermal anomaly) and the budget limitations eliminated the possibility of drilling the roots of the system. However, the collection of detailed temperature profiles, petrologic profiles, samples from fluid inclusions, and geophysical data from the edge of an active system has provided strong clues about the evolution and age of this active hydrothermal system.

Few advances were made in drilling technology, and some equipment was not even at the state of normal practice. Well testing and chemical sampling were inferior to common industry practice because of funding limitations, and the results of these tests are of limited usefulness.

Forty-one science and technology-development projects were funded by the USGS, DOE Office of Basic Energy Sciences, DOE Geothermal Technology Division, and National Science Foundation (Adduci et al., 1986). New data were collected in a geotectonic environment of active continental rifting, metamorphism and ore genesis (Lachenbruch et al., 1985; Charles et al., 1988; McKibben and Elders, 1985). Inexperience of drilling personnel in working within the Salton Sea hydrothermal system contributed to poor designs and equipment failures. Nonetheless, considerable new data were acquired that help to understand this complex hydrothermal system.

A key finding with implications for commercial resource evaluation and development throughout the Salton Sea geothermal system (SSGS) is that, although porosity decreases and rock induration increases with depth, permeability-controlling fractures increase with depth (Paillet and Morin, 1988; Daley et al., 1988). High flow-rate tests were completed successfully through multiple flow zones from depths of 6,120 to 10,564 ft (1,865 to 3,220 m). These results suggest strong merit in evaluating both shallow and deep resource potential in the SSGS (Harper and Rabb, 1986; Michels, 1986). Unprecedented recovery of 725 ft (220 m) of rock core from a geothermal well made possible pioneering studies of petrophysical properties (Lin and Daily, 1988; Tarif et al., 1988), sedimentary and evaporitic facies analysis (Herzig et al., 1988; McKibben et al., 1988a; McKibben et al., 1988b; McKibben et al., 1987), resolution of the source of salts in the SSGS brines (McKibben et al., 1988a), evaluation of structural relationships (Herzig et al., 1988; Daley et al., 1988), identification of igneous-intrusive units (Herzig and Elders, 1988), the resolution of mineral-paragenesis and vein-deposition sequences related to ore-body emplacement (Charles et al., 1988; Caruso et al., 1988; McKibben and Elders, 1985), and detailed petrography, whole rock chemistry, and isotope analysis that permitted identification of sulfur sources in ore mineralization (McKibben and Eldridge, 1988; Herzig et al., 1988). Earlier work based on studies of drilling chips recovered from geothermal wells in the SSGS identified progressive metamorphism of up to greenschist facies (Muffler and White, 1969; McKibben and Elders, 1985), implying metamorphism under low-temperature conditions; drill core from the State 2-14 well demonstrated the presence of higher-grade metamorphism (low amphibolite) at temperatures and pressures that presently are lower than expected for that metamorphic grade (Sass et al., 1988; Cho et al., 1988; Shearer et al., 1988).

Geophysically, laboratory petrophysical measurements of porosity, density and P-wave velocity correlated well with downhole well-logging values (Lin and Daily, 1988; Tarif et al., 1988), and vertical seismic profiling showed strong reflectance and scattering effects that agreed well with fracture zones encountered by the borehole (Daley et al., 1988). Despite disappointing performance of wireline tools at depths greater than 5,900 ft (1,800 m) — which speaks directly to the need for upgrading high-temperature performance and reliability — significant advances in logging technology were demonstrated. In particular, rapid-response time, heat-shielded, electronic memory temperature and pressure tools, and downhole samplers that proved capable of withstanding 660°F (350°C), offer innovations for future downhole-tool development (Carson, 1986; Solbau et al., 1986; Wolfenbarger, 1986; Sass et al., 1988; Grigsby et al., 1987).

As a part of the SSSDP program, gravity and magnetic data were combined with conductive heat-flow data to: 1) refine the boundaries of the local, intense thermal anomalies responsible for the rate of heat flux for the entire Salton Trough (Newmark et al., 1988; Elders and Sass, 1988); and 2) confirm earlier work that inferred that the SSGS is about 10,000 years old (Sass et al., 1988). The new evidence suggesting that the system has cooled in the vicinity of State 2-14 may indicate that there was an older system in the same area (or to the east of the present system). This result may place new constraints on future models of the SSGS.

Remaining fundamental geologic work includes the following:

- Geologic and geophysical correlations between the State 2-14 well and other geothermal wells in the SSGS.

- Comparisons between the SSGS and other geothermal systems, such as lithologically similar Cerro Prieto, which has a strikingly lower occurrence of hydrothermal-vein mineralization.

- Some scientists (Sass et al., 1988; Newmark et al., 1988) have proposed a future, deep geothermal research well drilled on the axis of the thermal anomaly. Such a well could extend the understanding of continental rifting and geothermal system genesis being formulated from data from off axis State 2-14 well. The valuable information to be gained from an on-axis hole would be the temperature profile, and, if it went above 360°C, the corresponding alteration of the rocks. The State 2-14 well, however, provided limited new information about the region and the expense was great, so the approach of deep scientific drilling for this area should be carefully evaluated before future wells are proposed.

Time provides a useful filter for evaluating the scientific value of major drilling projects. Provision should be made for a systematic assessment of the scientific value of future expensive multi-agency projects three to five years after drilling is completed.

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APPENDIX A

REPORTS SUBMITTED TO BECHTEL NATIONAL, INC.

Technical data obtained during the course of the SSSDP and reports completed by numerous subcontractors were submitted to Bechtel National, Inc. (Bechtel), the prime contractor. This appendix identifies the various reports, many of which have been cited in this final report, identifies authors or organizations of origin, and indicates page length as an indicator of reproduction cost and level-of-detail. All materials are held by the SSSDP Archivist, the University of Utah Research Institute. Copies of these reports are available at cost and may be ordered from:

SSSDP Archivist
University of Utah Research Institute
391 Chipeta Way, Suite C
Salt Lake City, UT 84108

PHASE-1 REPORTS

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A	CONTINUOUS SLIM-HOLE WIRELINE CORING STUDY Jack D. Powers, P.E.	29
B	DRILLING SUPERVISOR'S DAILY REPORTS Cleveland Drilling Co. - Rig #6	147
C	DRILLING CONTRACTOR'S DAILY DRILLING REPORTS Cleveland Drilling Co. - Rig #6	161
D	WELL DESIGN PLAN Bechtel National, Inc.; Berkeley Group, Inc.	26
E	DRILLING AND COMPLETION PROGRAM PLAN Bechtel National, Inc.; Berkeley Group, Inc.	20
F	NORTON-CHRISTENSEN - CORING ENGINEER'S REPORTS Norton-Christensen, Petroleum Diamond Products Div.	32
G	METALLURGICAL REPORT - LINER FAILURE D. van Rooyen and J. R. Weeks, Brookhaven National Laboratory	31
H	SINGLE SHOT SURVEYS AND TEMPERATURE MEASUREMENTS	2
I	EASTMAN-WHIPSTOCK - DIRECTIONAL SURVEY REPORT Eastman-Whipstock Co. Data list plus map	6

Report		Length (pages)
J	BIT RECORD Smith Tool Company	15
K	PROFCO - PRODUCT USAGE RECAP Profco Co., Ventura, CA	18
L	PROFCO - MUD ENGINEERS' DAILY REPORT Profco Co., Ventura, CA	114
M	REMEDIAL PROGRAM SUPPORT DATA G. W. Reich, Profoco Co., Ventura, CA	18
N	GEOTHERMEX - GEOLOGIC INTERPRETATION REPORT GeothermEx, Inc., Richmond, CA	156
O	EXLOG SMITH - MUD LOG R.F. Smith Corp, Geothermal Division Geothermal Data Log	28
P	INJECTIVITY TEST RESULTS Well Test Decision Committee	6
Q	FLOW TEST PROCEDURES Well Test Committee - D. T. Raab et al.	30
R	GEOTHEMEX - FIRST FLOW TEST REPORT GeothermEx, Inc., Richmond, CA	42
S	FIRST FLOW TEST - RAW FIELD DATA Anonymous Time summary of activities, events	12
T	GEOTHERMEX - SECOND FLOW TEST REPORT GeothermEx, Inc., Richmond, CA	102
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V	SITE PROCEDURES MANUAL Bechtel National Inc.	25
W	SITE SAFETY MANUAL Bechtel National Inc.	16
X	VISITOR SAFETY MANUAL Bechtel National Inc.	2
Y	WELL PRODUCTION TESTING REPORT- OPERATIONAL AND TECHNICAL ANALYSIS Robert W. Nicholson, WPT, Inc.	93

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BB	BIT RECORD Anonymous	2
CC	MUD ENGINEER'S REPORT Milpark Drilling Fluids	4
DD	REPORT OF SHORT FLOW TEST August 31, 1987 David K. Mulliner, Consultant	9
EE	WELL TEST PLAN Bechtel National, Inc. (with Addendum "Detailed Flow Test Procedure") by Mesquite Group, Inc.	12 24
FF	WELL TEST RESULTS (with addendum A-F) Mesquite Group, Inc.	53 97
GG	BRINE CHEMISTRY RESULTS David K. Mulliner, Consultant (with Addendum A-C: analytical data)	36 16
HH	PARTICLE METER TESTING Battelle Pacific Northwest Laboratories	5
II	GEOTHERMAL WASTE TREATMENT BIOTECHNOLOGY Brookhaven National Laboratory (Eugene T. Premuzic and Mow Lin)	7
JJ	CHEMICAL SAMPLING AND ANALYSIS TO CHARACTERIZE THE BRINE Electric Power Research Institute (Mark Petersen)	34
KK	SEISMIC MONITORING Lawrence Livermore National Laboratory (S.P. Jarpe, P.W. Kasameyer, L.J. Hutchings, and T.F. Hauk)	10
LL	METAL ION CONCENTRATIONS IN GEOTHERMAL BRINES New Mexico State University (Dennis W. Darnall)	6

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MM	TRANSPORT OF PLATINUM GROUP ELEMENTS, GOLD, AND SULFUR IN THE SALTON SEA GEOTHERMAL BRINES University of California at Riverside (Michael A. McKibben and Alan E. Williams)	4
NN	URANIUM SERIES ISOTOPE MEASUREMENTS University of Southern California (Bret W. Leslie, Douglas E. Hammond, and Teh-Lung Ku)	14
OO	LIQUID AND GAS SAMPLING University of Utah Research Institute (Michael Adams and Michelle Lemieux)	5
PP	CHEMISTRY OF SCALE FROM THE JUNE 1988 WELL TEST Idaho National Engineering Laboratory (R. Buden, K. McCormick, S. Rawson, J. Renner, and D. Faulder)	21

APPENDIX B

SUMMARY OF DAILY DRILLING ACTIVITY

PHASE I

DRILLING OPERATIONS

The drilling and flow test operations took 160 working days, starting on October 23, 1985, and concluding on April 1, 1986. The depth progress chart for this period is shown in Figure 5.1. A brief summary of each day's activities is presented below. For brevity, the daily summaries use acronyms common to the drilling industry. These acronyms are explained in Table B.1. This appendix is taken from material reported in Bechtel (1987).

Table B.1

DRILLING INDUSTRY ACRONYMS

Acronym	Meaning	Acronym	Meaning
ABOP	Annular Blowout Preventer	LD	Lay Down
BHA	Bottom-Hole Assembly	MU	Make Up
BHC	Borehole-Compensated Sonic Log	NU	Nipple Up
BOPE	Blowout Prevention Equipment	POH	Pull Out of Hole
CDOG	California Department of Oil and Gas	PU	Pick Up
CIP	Cement in Place	RD	Rig Down
CNL	Compensated Neutron Log	RIH	Run In Hole
DIL	Dual Induction Log	RU	Rig Up
DS	Deviation Survey	S	Spectrum Log
GR	Gamma Ray Log	WO	Wait On
KB	Kelly Bushing	WOC	Wait on Cement

APPENDIX B

SUMMARY OF DAILY DRILLING ACTIVITY

PHASE I

[*NOTE:* The pound sign (#) has two different uses in the daily summaries below: 1) when it precedes the number, it indicates the core "number"; 2) when it follows the number, it is short notation for "pounds per foot (lb/ft)."]

Date	Activity
10/23/85	Rigged up (RU) and drilled rat hole.
10/24/85	Made up (MU) 17-1/2 in. bit and 26 in. hole opener and drilled to 150 ft, Kelly Bushing (KB). Picked up (PU) 42 in. hole opener and opened 26 in. hole to 42 in. from surface to 150 ft. Ran and welded 30 in., 0.5 in. wall casing (conductor pipe) to 150 ft.
10/25/85	Cemented 30 in. conductor pipe through two strings of 2-7/8 in. tubing run in annulus. Cemented with 26 cu. yds of Redi-mix concrete (eight sacks of cement and sand mix) using a concrete pump truck. Nippled up (NU) 30 in. blow-out prevention equipment (BOPE).
10/26/85	Drilled 17-1/2 in. hole from 150 ft to 727 ft. Deviation survey (DS): 485 ft-1/4°.
10/27/85	Drilled 17-1/2 in. hole to 1,000 ft. Pulled out of hole (POH) and PU 26 in. hole opener. Opened 17-1/2 in. hole to 26 in. from 150 ft to 949 ft. DS: 1,000 ft-1/4°.
10/28/85	Opened 17-1/2 in. hole to 26 in. from 949 ft to 1,032 ft. Circulated hole 3/4 hour and wiped hole back to 150 ft. Ran in hole (RIH) to bottom and ran survey. DS: 1,032 ft-1/4, S73E. POH and RU to run casing. Ran 25 joints of 20 in., 94 lb/ft and 133 lb/ft, K-55 casing to 1,032 ft, KB. Ran 11 joints of 133 lb/ft on bottom (460.09 ft) and 14 joints to 94 lb/ft on top (529.97 ft) for a total of 1,032.49 ft. Set casing at 1,032 ft, KB. Centralizers installed as follows:

Date	Activity

Centralizer No.	Location
1	1,020 ft, at 10 ft above shoe
2	999 ft, at 10 ft below first collar
3	776 ft, at Collar #6
4	569 ft, at Collar #11
5	361 ft, at Collar #16
6	162 ft, at Collar #22
7	123 ft, at Collar #23

RU Halliburton and pumped pre-flush and cement. Displaced cement with 1936 ft^3 of mud. Pump rate was 14 bbls/min. mixing and displacing. Last 100 ft^3 of cement was staged in. Circulated 536 ft^3 of cement.

10/29/85 Wait on cement (WOC) 4 hours. Cut off 20 in. casing (29.44 ft) and removed 30 in. annular blowout preventer (ABOP). Cut off 30 in. flange and 20 in. casing. Welded on 20 in. flange and NU 20 in. BOPE. Installed rotary table.

10/30/85 Tested BOPE to 1,000 psi (witnessed and approved by R. Oquito, California Department of Oil and Gas [CDOG]). RIH with drilling assembly and hit top of cement at 982 ft (43 ft of cement in casing). Drilled out cement and drilled to first core point at 1,553 ft. Conditioned hole and POH for core barrel. DS: 1,336 ft-1/4°, N51E.

10/31/85 PU core bbl., RIH. Cut 5-1/4 in. core (#1) from 1,553 ft to 1,576 ft with a 9-5/8 in. x 5-1/4 in. core bit. POH and recovered 24 ft of core. RIH with new 17-1/2 in. bit and reamed from 1,553 ft to 1,576 ft. Drilled from 1,576 ft to 1,908 ft. DS: 1,646 ft-1/4°, N15E.

11/01/85 Drilled from 1,908 ft to 1,983 ft. POH and PU core barrel. RIH and cored (#2) from 1,983 ft to 2,013 ft (100 percent recovery). POH with core barrel, laid down (LD) core, PU drilling assembly, RIH. Reamed core hole from 1,983 ft to 2,013 ft. Drilled from 2,013 ft to 2,238 ft. DS: 2,012 ft-1°, N41E.

11/02/85 Drilled from 2,238 ft to 2,447 ft. POH and PU core barrel. RIH and cored (#3) from 2,447 ft to 2,477 ft. Recovered 30 ft (100 percent) of core. MU bottom-hole assembly (BHA) and RIH. DS: 2,279 ft-1-3/4°, N30E; 2,447 ft-1-1/2°, N18E.

11/03/85 Reamed core hole from 2,447 ft to 2,477 ft. Drilled from 2,477 ft to 2,970 ft and POH for core barrel. DS: 2,771 ft-1-1/4°, N22E; 2,949 ft-2-1/4°, N18E.

Date	Activity
11/04/85	PU core barrel and RIH. Cored (#4) from 2,970 ft to 3,030 ft. POH and recovered 60 ft of core with core barrel. RIH and reamed core hole from 2,970 ft to 3,030 ft with 17-1/2 in. bit. POH and RU Schlumberger. Ran Tandem Dual Induction (DIL), Compensated Density Neutron (CNL), Borehole-Compensated Sonic (BHC) and Gamma Ray (GR) followed by 4-Arm Caliper log.
11/05/85	Finished running Caliper log. Rigged down (RD) Schlumberger. RU USGS to log. USGS ran Temperature and Caliper logs. RD USGS. RIH and conditioned hole. POH and RU USGS to log. USGS ran GR and Spectrum (S) logs.
11/06/85	USGS ran GR, S, Temperature, Acoustic, Caliper, Televiewer and Sonic logs. Maximum temperature 369°F (187°C).
11/07/85	USGS ran Sonic, Temperature and Caliper logs. RD USGS, PU BHA and RIH. Circulated and conditioned mud. Mud flashed on bottoms up. Reamed core hole from 2,970 ft to 3,030 ft and drilled from 3,030 ft to 3,078 ft.
11/08/85	Bit quit drilling. POH and found two bit cones missing. Wait on (WO) fishing tools. USGS ran temperature log while WO tools. PU 11-3/4 in. magnet and RIH to 3,078 ft and tag junk. POH. No junk recovery. WO fishing tools.
11/09/85	WO tools. MU 17-1/2 in. concave mill and RIH. Reamed hole from 3,038 ft to 3,079 ft. Milled on junk from 3,078 ft to 3,080 ft. POH and LD mill. PU junk sub and junk basket and RIH. Work over junk from 3,080 ft to 3,083 ft. POH and recovered half of one cone and a quarter of the second cone, some bearings and 1 ft of formation. Redressed junk basket.
11/10/85	RIH with junk basket. Work over junk from 3,083 ft to 3,084 ft. POH and recovered 2 ft of formation and no junk. (Note: 1 ft core from junk basket was considered core #5.) LD junk basket and PU 17-1/2 in. bit. Reamed hole from 3,080 ft to 3,087 ft and drilled from 3,087 ft to 3,107 ft. Circulated bottoms up and POH for core #6. PU core bbl. and RIH. Cut core (#6) from 3,107 ft to 3,167 ft and jammed bbl. POH and recovered 54.7 ft of core (91 percent). RU USGS and ran temperature log. Temperature 355°F (179°C) at 3,470 ft.
11/11/85	USGS finished running temperature log. MU drilling assembly and RIH. Reamed from 3,107 ft to 3,167 ft. Drilled from 3,167 ft to 3,431 ft and POH for bit change. DS: 3,192 ft-3°, N15E; 3,358 ft-3-1/2°, N28E.
11/12/85	MU bit #6, RIH. Reamed from 3,400 ft to 3,431 ft. Drilled from 3,431 ft to 3,470 ft. POH for core barrel. RIH with core barrel and cored (#7) from 3,470 ft to 3,505 ft. POH and recovered 34 ft of core (97 percent). RU USGS and ran temperature survey. DS: 3,470 ft-3-3/4°, N33E.

Date	Activity
11/13/85	MU 17-1/2 in. drilling assembly and RIH to 3,470 ft. Reamed from 3,470 ft to 3,505 ft and drilled from 3,505 ft to 3,515 ft. Conditioned hole for logs and POH. Ran Schlumberger DIL, FDC, CNL, GR and Caliper logs. RD Schlumberger. Max. temperature 235°F (113°C). DS: 3,515 ft-4-1/4°, N31E. Final temperature 276°F (136°C).
11/14/85	RU USGS wireline unit and ran temperature survey. RD USGS, PU drilling assembly and RIH. Conditioned mud to run casing. Ran multi-shot survey on POH. RU, ran 12 jts. of 13-3/8 in., 72#, N-80, R-3, BT&C casing (472.66 ft) and 70 jts. of 13-3/8 in., 68#, C-95, R03, BT&C casing (3,041.33 ft) with Howco super-seal float shoe at 3,515 ft KB and super-seal float collar at 3,474 ft. Ran 25 centralizers. RD casing crew, RU cementing head and conditioned hole for cementing.
11/15/85	Cemented casing. Dropped top plug and displaced with 2,950 ft^3 of mud. Bumped plug with 1,400 psi. Lost returns at 2,200 ft^3 of displacement. Cement in place (CIP) 6 a.m., WOC 4-1/2 hours. LD 20 in. BOPE and cut off 13-3/8 in. casing. Cemented top job through 1 in. tubing at 150 ft with 200 ft^3 class "G" cement, plus 1:1 perlite, plus 40 percent silica flour, plus 3 percent gel, plus 0.65 percent CFT-2. Got cement returns to surface, CIP 7:00 p.m. WOC two hours. Cut off 20 in. casing flange and welded on 13-3/8 in. casing head.
11/16/85	Welded on 13-3/8 in. casing head and NU 13-5/8 in. BOPE.
11/17/85	Installed rotary table, MU 12-1/4 in. bit and RIH to 3,474 ft. Circulated and cooled mud. Tested BOPE to 1,500 psi, witnessed and approved by CDOG. Drilled out float collar at 3,474 ft and cement and float shoe at 3,515 ft. Drilled from 3,515 ft to 3,530 ft and conditioned mud. POH and made an end inspection of hevi-wate drill pipe, drill collars and subs. RU Schlumberger and ran cement bond log. MU 12-1/4 in. bit and drilling assembly and RIH. Drilled from 3,530 ft to 3,547 ft.
11/18/85	Drilled from 3,547 ft to 3,790 ft. POH, RU USGS wireline unit and ran temperature survey. DS: 3,663 ft-3-1/2°, N33E; 3,740 ft-3-1/2°, N38E.
11/19/85	Finished running 12-hour temperature survey, RD USGS. Maximum temperature 400°F (204°C). RIH with core barrel and cored from 3,790 ft to 3,850 ft. POH with core #8. Recovered 56.6 ft of core for 94 percent recovery. RIH and reamed core hole from 3,790 ft to 3,850 ft. Drilled from 3,850 ft to 3,921 ft. DS: 3,921 ft-3-3/4°, N31E.

Date	Activity
11/20/85	Drilled from 3,921 ft to 4,007 ft and conditioned hole for core #9. POH and MU up core barrel. RIH with core barrel and cut core #9 from 4,007 ft to 4,067 ft. POH with core barrel and recovered 60 ft of core (100 percent recovery). MU drilling assembly and RIH. Reamed from 4,007 ft to 4,067 ft and drilled from 4,067 ft to 4,070 ft.
11/21/85	Drilled from 4,070 ft to 4,241 ft. POH for core. RIH with core barrel and cut core #10 from 4,241 ft to 4,301 ft. POH and serviced core barrel. Recovered 58.6 ft of core. RIH and cut core #11 from 4,301 ft to 4,306 ft. DS: 4,067 ft-3-3/4°, N26E; 4,162 ft-3-3/4°, N30E.
11/22/85	Continued core #11 from 4,306 ft to 4,334 ft. POH and recovered 33 ft of core. RIH with drilling assembly and reamed core hole from 4,301 ft to 4,334 ft. Drilled from 4,334 ft to 4,511 ft. DS: 4,221 ft-4°, N28E.
11/23/85	Drilled from 4,511 ft to 4,641 ft. POH for temperature log. RU USGS wireline unit and ran temperature log. Installed Kelly spinner while logging. RD USGS and RIH with drilling assembly. DS: 4,561 ft-4°, N9E.
11/24/85	Reamed tight hole from 4,276 ft to 4,641 ft and drilled from 4,641 ft to 4,643 ft. POH for core barrel. RIH with core barrel and cut core #12 from 4,643 ft to 4,676 ft. POH and recovered 33 ft of core. RU USGS wireline unit and ran temperature survey.
11/25/85	Finished running temperature survey, RD USGS wireline unit. RIH with core barrel and cut core #13 from 4,676 ft to 4,686 ft, where barrel jammed. POH and recovered 3 ft of core. RIH with drilling assembly and reamed core hole from 4,676 ft to 4,686 ft. Drilled from 4,686 ft to 4,697 ft.
11/26/85	Drilled from 4,697 ft to 4,710 ft. Had excessive torque and POH. Left four blades from welded-blade stabilizer in hole. RIH and spotted KCL water for mini-injection test and pulled back into shoe at 3,515 ft. Ran injectivity test with negative results. RIH from 3,515 ft to 4,707 ft and circulated out KCL water. POH and WO fishing tools. RIH with Globe junk basket and worked over junk at 4,710 ft.
11/27/85	Worked over junk at 4,710 ft and POH with no junk recovery. RIH with junk mill and mill on junk at 4,710 ft. POH with mill #1 and RIH with mill #2. Milled junk from 4,710 ft to 4,718 ft. POH with mill and MU junk basket.

Date	Activity
11/28/85	RIH with junk basket and worked over junk at 4,718 ft. POH, LD junk basket. Recovered 6 in. core and no junk. (Note: core from junk basket considered core #14.) RIH with mill #3 and milled from 4,718 ft to 4,722 ft. POH with mill #3 and RIH with drilling assembly. Reamed tight hole or bridges from 4,175 ft to 4,237 ft then RIH to 4,722 ft. Drilled from 4,722 ft to 4,789 ft. DS: 4,764 ft-4-1/2°, N13E.
11/29/85	Drilled from 4,789 ft to 4,943 ft. POH to check bit. Bit worn out. Changed bit and RIH. Reamed from 4,890 ft to 4,943 ft and drilled from 4,943 ft to 4,973 ft. DS: 4,899 ft-4-1/4°, N23E.
11/30/85	Drilled from 4,973 ft to 5,007 ft. POH due to severe torquing problems. Found severe wear on bottom 1 ft of near-bit stabilizer wear pads. LD short collar, near-bit stabilizer, junk sub and stabilizer. RIH and ream from 4,970 ft to 5,007 ft and drilled from 5,007 ft to 5,167 ft. Torque problems cleared up. DS: 4,972 ft-4-1/4°, N28E; 5,056 ft-4°, N37E.
12/01/85	Drilled from 5,167 ft to 5,188 ft. DS: 5,138 ft-3-3/4°, N45E. POH for core barrel. RIH with core barrel and cored from 5,188 ft to 5,218 ft. POH with core #15 and recovered 30 ft (100 percent). RIH with bit #16 to 5,146 ft. Reamed from 5,146 ft to 5,194 ft.
12/02/85	Reamed from 5,194 ft to 5,218 ft. POH hole and MU bit #15 rerun (RR). RIH and drilled from 5,218 ft to 5,381 ft; POH and changed BHA and bit. RIH. DS: 5,228 ft-4-3/4°, N58E, 5,336 ft-6-1/4°, N73E.
12/03/85	RIH and reamed from 5,326 ft to 5,381 ft. Drilled from 5,381 ft to 5,422 ft. POH and RU for mini-injection test. Ran mini-injection test with 80 barrels of mud. RIH hole and tagged bottom at 5,422 ft (no fill). POH and MU bit #17 RR. RIH with drill pipe to 5,422 ft. Mixed 1,500 barrels of 2 percent KCL water and displaced mud in hole with KCL water and POH. DS: 5,410 ft-7-1/2°, N75E.
12/04/85	RU to run maxi-injection test. Injected 1,000 barrels of 2 percent KCL water at 85 GPM. Maximum pressure 1,500 psi without temperature buildup. RU USGS wireline unit and ran continuous temperature survey. Injection test and temperature log indicated poor prognosis for flow test. RD USGS wireline unit and RIH with bit #17 RR to 5,422 ft. No fill. Displace KCL water with mud. POH, MU bit #18, changed BHA and RIH to 5,029 ft. Reamed from 5,029 ft to 5,099 ft.

Date	Activity
12/05/85	Reamed from 5,099 ft to 5,422 ft and drilled from 5,422 ft to 5,424 ft where pipe twisted off. POH and LD one joint of heavy-weight. MU 11-3/4 in. overshot with a 6-1/4 in. grapple and RIH. Top of fish at 5,107.89 ft, length of fish 316.86 ft., Left bit, N.B. stabilizer, monel, stabilizer, shock-sub, 1 x 9 in. DC, stabilizer, 2 x 9 in. DC, XO, 1 x 8 in. DC, D-Jar, U-Jar, 2 x 8 in. DC, XO and 1 x 5 in. hevi-wate drill pipe in hole. Recovered fish on first run. Tool joint on top of first joint of hevi-wate above collars had washed out, causing string to part. Made a magnetic particle inspection of BHA, subs, jars, and hevi-wate drill pipe. Changed out monel, D-jars, and bit #17 which was pinched. [Note: "hevi-wate" = "heavy-weight"]
12/06/85	Completed inspection of heavy-weight. Made up BHA and RIH to 5,422 ft. Drilled from 5,422 ft to 5,574 ft. Circulated bottoms up and POH for core #16. MU core barrel and RIH. Cored from 5,574 ft to 5,580 ft. DS: 5,471 ft-7-1/4°, N77E.
12/07/85	Cored from 5,580 ft to 5,591 ft where core barrel jammed. POH and recovered 17 ft of core. Made up BHA and RIH to 5,542 ft. Reamed from 5,542 ft to 5,591 ft. Drilled from 5,591 ft to 5,642 ft. POH, LD D-Jars and changed bit. RIH and drilled from 5,642 ft to 5,658 ft. DS: 5,564 ft-7°, N76E.
12/08/85	Drilled from 5,658 ft to 6,000 ft. DS: 5,642 ft-7-3/4°, N76E; 5,767 ft-8°, N78E; 5,861 ft-8°, N78E.
12/09/85	Conditioned hole for logs and POH. RU Schlumberger and ran DIL, FDC, CNL and GR logs. On last run with sonic log, Schlumberger pulled into sheave with tool and broke their rope socket, dropping tool to rig floor. Welder had to cut section of the floor loose from the tool. RD Schlumberger and rigged up USGS wireline unit to run temperature log.
12/10/85	Finished running temperature log. RIH to circulate and cool hole. POH and RU USGS wireline unit. USGS ran temperature/caliper and televiewer log. Installed 20 in. x 13-3/8 in. casing pack-off element while logging.
12/11/85	USGS ran Natural Gamma, Gamma Spectral, Sonic, Acoustic Velocity, Temperature and Caliper logs. Attempts at running televiewer log failed due to tool malfunction.
12/12/85	RD USGS and RIH. Circulated to cool hole and condition mud. POH and RU USGS wireline unit. Ran caliper and neutron logs. RD USGS and RIH with drill pipe. Circulated hole to cool and condition mud for running 9-5/8 in. casing.

Date	Activity
12/13/85	Finished circulating hole and conditioning mud. POH and took multi-shot survey on trip out from 6,000 ft to 3,515 ft. LD 8 in. and 9 in. drill collars with laydown machine. RU and started running 9-5/8 in. casing in hole.
12/14/85	Ran 137 joints (5,995.99 ft) of 9-5/8 in., 47lb/ft., C-95, Range 3 casing. Shoe set at 6,000 ft, float at 5,905 ft, cement basket at 3,446 ft, and stage collar at 3,315 ft. Centralizer installed at 5,976 ft, 5,954 ft, 5,932 ft, 5,883 ft, 5,861 ft, 5,816 ft, 5,771 ft, 5,724 ft, 5,677 ft, 3,536 ft, 3,514 ft, 3,270 ft, 3,230 ft, 3,193 ft, 220 ft, 178 ft, 133 ft, 87 ft and 42 ft. Cemented first stage. Dropped dart and displaced with 467 barrels of mud. Displacement was 35 barrels over, due to aeration of mud. Did not bump plug. Dropped opening bomb and opened stage tool with 1,400 psi. CIP 0900 hours. Circulated through stage tool for 4-1/2 hours. Cemented second stage through stage collar. Displaced closing plug with 1,474 ft^3 of mud. Bumped plug with 2,000 psi to close stage tool. CIP 4:00 p.m. Unbolted BOPE at casing head and raised BOPE with BOP jacks. Installed casing centralizer, cutoff casing (32.43 ft) and installed expansion spool packoff and expansion spool. Started NU master valve and BOPE.
12/15/85	Finished NU BOPE. Tested blind rams to 1,500 psi. MU 8-1/2 in. bit, 12-6 1/4 in. drill collars and RIH.
12/16/85	Tagged cement plug at 3,200 ft and pushed it to 3,315 ft. Drilled out stage tool and pressure tested stage tool to 1,500 psi. RIH and tagged bottom plug at 5,758 ft (147 ft high). Circulated and cooled casing. POH laying down drill pipe for inspection. Inspected drill pipe. Measured and PU drill pipe.
12/17/85	Finished PU drill pipe. Tagged plug at 5,758 ft. Drilled out cement, float collar and shoe from 5,758 ft to 6,000 ft. Drilled 8-1/2 in. hole from 6,000 ft to 6,026 ft. POH for core. PU core barrel and RIH. Cut core (#17) from 6,026 ft to 6,036 ft.
12/18/85	Continued coring from 6,036 ft to 6,043 ft, where 6-1/4 in. drill collars twisted off. POH and recovered drill pipe, hevi-wate drill pipe, and two drill collars. RU Schlumberger and ran cement bond log. RD Schlumberger and RIH with overshot to top of fish at 5,703 ft. Screwed onto fish and POH. Recovered all of fish.
12/19/85	Broke down fishing tools. Serviced core barrel and recovered 7 ft of core. Inspected drill collars, PU Turbo-Drill and RIH. Oriented turbo-drill and drilled from 6,043 ft to 6,045 ft. POH, LD mud motor and PU new mud motor and bit. RIH and oriented Turbo-Drill. Directionally drilled from 6,045 ft to 6,056 ft.

Date	Activity
12/20/85	Drilled with Turbo-Drill from 6,056 ft to 6,079 ft. POH and changed bits. RIH and reamed from 6,009 ft to 6,079 ft. Oriented Turbo-Drill and drilled from 6,079 ft to 6,112 ft. POH and left bit and 3 ft of Turbo-Drill drive shaft in hole. WO fishing tools. MU fishing tools and RIH. Fished for lost tools. DS: 6,060 ft-8°, N77E.
12/21/85	Recovered fish. LD fishing tools and PU drilling assembly. RIH and reamed from 6,040 ft to 6,112 ft. POH for Turbo-Drill. RIH, oriented Turbo-Drill and drilled from 6,112 ft to 6,151 ft. POH to change bit. RIH and oriented Turbo-Drill. Lost 40 bbls mud/hr at 6,119 ft. DS: 6,086 ft-6-1/4°, S89E; 6,121 ft-7-1/4°, S87E.
12/22/85	Turbo-drilled from 6,151 ft to 6,166 ft and POH. PU drilling assembly, RIH and reamed from 6,112 ft to 6,166 ft. POH with drilling assembly and PU Turbo-Drill. RIH, oriented Turbo-Drill and drilled from 6,166 ft to 6,227 ft. Losing from 34 to 66 bbl/hr between 6,119 ft and 6,160 ft. DS: 6,153 ft-4-1/2°, S86E; 6,187 ft-3-1/2°, S64E.
12/23/85	POH and PU drilling assembly. RIH and reamed from 6,166 ft to 6,227 ft. Displaced mud with water in hole. ND BOP and NU wellhead for flow test.
12/24/85	USGS ran temperature log. Put rig on standby secured at 4:00 a.m. for holidays.
12/25/85	Standby secured.
12/26/85	Standby secured.
12/27/85	Standby secured.
12/28/85	RU USGS and ran temperature survey. RD USGS and RU Otis wireline unit to run temperature survey. RD Otis and started flow test of well.
12/29/85	Flow-tested well. Shut in well and tightened leaking wellhead flanges. Opened well up and started flow test again.
12/30/85	Flow-tested well. RU Otis and ran temperature and pressure surveys while flowing well.
12/31/85	Flow-tested well. RD Otis and RU USGS wireline unit to run downhole fluid sampler. Sampler did not work. RD USGS and RU Otis to run battery-pack fluid sampler. Sampler did not work. RD Otis and RU to reinject brine.
01/01/86	Finished reinjecting brine followed by 220 bbls of fresh water and 420 bbls of mud. Removed test tree and NU BOPE.

Date	Activity
01/02/86	Finished NU BOPE. RIH with drilling assembly and hit fill at 6,105 ft. Cleaned out fill from 6,105 ft to 6,227 ft (62 ft fill). POH and PU Turbo-Drill. RIH, oriented Turbo-Drill and drilled from 6,227 ft to 6,316 ft. POH and LD Turbo-Drill. DS: 6,205 ft-3-1/2°, S64E; 6,223 ft-3-1/4°, S44E; 6,255 ft-3°, S18E.
01/03/86	PU drilling assembly, RIH and reamed from 6,227 ft to 6,316 ft and drilled from 6,316 ft to 6,506 ft. POH for core. RIH with core barrel. DS: 6,324 ft-4-1/2°, S31W; 6,387 ft-4-1/2°, S39W; 6,466 ft-5°, S38W.
01/04/86	Cored (#18) from 6,506 ft to 6,517 ft,where core barrel jammed. POH and recovered 11 ft of core. RIH and reamed from 6,457 ft to 6,517 ft. Drilled from 6,517 ft to 6,637 ft and lost complete circulation. Mixed and spotted four lost-circulation material (LCM) pills without getting returns. DS: 6,513 ft-5°, S38W; 6,577 ft-5-1/2°, S40W.
01/05/86	Spotted one more LCM pill without getting returns. Drilled ahead with water and no returns from 6,637 ft to 6,758 ft. POH and PU core bbl. RIH and cored (#19) without returns from 6,758 ft to 6,771 ft where core bbl jammed. POH and recovered 13 ft of core.
01/06/86	RIH open ended to 6,742 ft. Pumped 148 ft^3 of class "G", plus 40 percent silica flour, plus 3 percent gel, plus 1:1 perlite, plus 46 lbs flocele, plus CFR-2, plus HR-7. Displaced cement plug with 633 ft^3 of water. POH to 6,185 ft and spotted an LCM pill of cotton-seed pellets, gel, Fibertek, Kwik seal and wellpac. POH and shut well in. Rig on "standby secured" at 4:00 p.m. WOC.
01/07/86	Standby secured.
01/08/86	Standby secured.
01/09/86	Standby secured.
01/10/86	Started up rig. Had 125 psi on wellhead. Attempted to set test plug. Well flowing too much. Started strapping in hole with drill pipe through ABOP. RIH to 1,000 ft and circulated hole. RIH and tagged cement at 6,510 ft. Circulated and cooled hole. POH and set test plug. ND BOP, changed out master valve and NU BOP.
01/11/86	Finished NU BOP. Made up BHA, RIH and drilled out cement stringers from 6,329 ft to 6,410 ft. Drilled to 6,818 ft. Lost returns at 6,803 ft. POH to shoe and mixed LCM pill. Spotted 3 separate LCM pills.

Date	Activity
01/12/86	Mixed and pumped LCM pill. RIH and broke circulation at 6,403 ft, 6,778 ft and 6,818 ft. Drilled from 6,818 ft to 6,850 ft. Spotted LCM pill at 6,850 ft. RU Halliburton and pumped first cement plug of 119 ft^3 "G" cement, plus 40 percent silica flour, plus 1:1 perlite, plus 3 percent gel, plus 0.65 percent CFR-2, plus 0.3 percent HR-7, plus 1/4 lb/sk flocele. Displaced with 636 ft^3 water. POH and LD nine joints of cemented up drill pipe. RIH to 6,322 ft, pumped 158 ft^3 of same cement and POH.
01/13/86	Continued POH. MU BHA and RIH. Tagged cement at 5,749 ft. Cleaned out cement from 5,749 ft to 6,324 ft. POH looking for washout and found cement chunks plugging heavy-weight drill pipe. RIH and break circulation. Bit plugged. POH and unplug bit.
01/14/86	LD 6-1/4 in. monel collar plugged with cement. PU new monel and RIH. Drilled out cement from 6,324 ft to 6,850 ft. Drilled to 6,880 ft and POH for core barrel. RIH and cored from 6,880 ft to 6,889 ft where barrel jammed. POH with core #20 and recovered 9 ft of core.
01/15/86	LD core barrel. RIH open-ended to 6,773 ft. Mixed and pumped 50 bbl LCM pill containing cotton-seed hulls, plus cedar fiber, plus Kwik seal, plus 35 sacks of cement, plus 3 percent gel plus 1 sack lime, plus 0.5 percent retarder. Displaced with 451 ft^3 of water. Pull up to shoe, circulated and WOC. Squeezed cement in 10 bbl increments every two hours for 3 squeezes. Final squeeze pressure 500 psi. POH and made up BHA. RIH and cleaned out cement from 6,640 ft to 6,670 ft. RIH and reamed from 6,880 ft to 6,889 ft. Drilled from 6,889 ft to 6,973 ft.
01/16/86	Drilled from 6,973 ft to 7,000 ft with 20 to 80 BPH fluid losses. POH for core. RIH with core barrel and cored from 7,100 ft to 7,109 ft. POH and recovered 6 ft of core (#21). MU BHA and RIH to 7,100 ft. Reamed from 7,100 ft to 7,109 ft and drilled from 7,109 ft to 7,163 ft. DS: 7,156 ft-5°, S18W.
01/17/86	Drilled from 7,163 ft to 7,300 ft and POH for core barrel. RIH with core barrel and cored from 7,300 ft to 7,313 ft. POH with core #22 and recovered 11 ft. LD core barrel and RIH with drilling assembly. DS: 7,196 ft-4-3/4°, S10W.
01/18/86	RIH to 7,300 ft and reamed from 7,300 ft to 7,313 ft. Drilled from 7,313 ft to 7,356 ft and POH. Changed bit and RIH. Drilled from 7,356 ft to 7,432 ft. POH to look for washout and found none. RIH. DS: 7,341 ft-5°, S02E.
01/19/86	RIH and drilled from 7,432 ft to 7,547 ft. POH and PU core barrel. RIH and cored from 7,547 ft to 7,570 ft. POH with core #23 (92 percent recovery). PU BHA and RIH. DS: 7,414 ft-5°, S03W; 7,478 ft-5°, S07E.

Date	Activity
01/20/86	Reamed from 7,547 ft to 7,577 ft and drilled from 7,577 ft to 7,704 ft. POH hole for core barrel. RIH and cored from 7,704 ft to 7,734 ft. POH with core #24 (92 percent recovery). PU Turbo-Drill and RIH. DS: 7,549 ft-5°, S17E; 7,609 ft-4-3/4°, S26E; 7,654 ft-6-1/4°, S47E.
01/21/86	RIH with Turbo-Drill to 7,700 ft and reamed from 7,704 ft to 7,734 ft. Pulled up into shoe and worked on #1 pump. RIH, oriented Turbo-Drill, and drilled from 7,734 ft to 7,759 ft. POH and PU new bit. RIH and reamed from 7,722 ft to 7,759 ft. Oriented Turbo-Drill and drilled from 7,759 ft to 7,789 ft.
01/22/86	Turbo-drilled from 7,789 ft to 7,794 ft. POH and PU new Turbo-Drill and bit. RIH and reamed from 7,760 ft to 7,794 ft. Oriented Turbo-Drill and drilled from 7,794 ft to 7,860 ft. POH for bit change. RIH and reamed from 7,380 ft to 7,860 ft. Oriented Turbo-Drill and drilled from 7,860 ft to 7,907 ft. DS: 7,754 ft-5-1/4°, S47E; 7,785 ft-4-1/2°, S38E; 7,849 ft-2-1/4°, S02E.
01/23/86	POH to change bit. RIH and reamed tight hole from 7,849 ft to 7,907 ft. Oriented Turbo-Drill and drilled from 7,907 ft to 7,935 ft. POH and LD Turbo-Drill. PU new bit and BHA. RIH and reamed from 7,690 ft to 7,935 ft and drilled from 7,935 ft to 7,972 ft. DS: 7,880 ft-3-1/4°. S5W; 7,932 ft-4-3/4°, S13W.
01/24/86	POH and LD stabilizer and reamer and PU Turbo-Drill. RIH and reamed from 7,940 ft to 7,962 ft. Oriented Turbo-Drill and drilled from 7,972 ft to 8,017 ft. POH to change bits. RIH with bit #43 and reamed from 7,950 ft to 8,017 ft. Oriented Turbo-Drill and drilled from 8,017 ft to 8,027 ft. POH and LD Turbo-Drill. DS: 7,987 ft-4-1/4°, S23W.
01/25/86	PU new Turbo-Drill and RIH. Reamed from 8,000 ft to 8,027 ft and drilled from 8,027 ft to 8,070 ft. POH and LD Turbo-Drill. MU BHA and RIH with bit #41RR.
01/26/86	RIH and reamed from 7,964 ft to 8,070 ft. Drilled from 8,070 ft to 8,094 ft losing 100 BPH of mud. Lost total returns at 8,094 ft. Drilled blind from 8,094 ft to 8,126 ft. Spotted LCM pill and POH to inspect BHA. DS: 8,086 ft-5°, S33W.
01/27/86	Inspected subs and core barrel. PU Turbo-Drill and RIH with bit #45. Slip and cut drilling line and replaced brake band. Oriented Turbo-Drill. Well flowing. Turbo-drilled from 8,126 ft to 8,133 ft. Well still flowing. Mixed and pumped LCM pill until well static. POH and well started flowing on trip out. LD Turbo-Drill, MU bit on drill pipe, and RIH to 1,500 ft. Circulated and conditioned mud until hole static at 1,500 ft. POH for core barrel. RIH with core barrel to shoe and broke circulation.

Date	Activity
01/28/86	Mixed mud to increase mud volume. Spotted LCM pill at shoe and continued in hole with core barrel. Reamed from 8,111 ft to 8,133 ft and cored from 8,133 ft to 8,161 ft. POH with core #25 (100 percent recovery). LD core barrel and RIH with drill pipe and hevi-wate to 8,131 ft. Mixed and pumped LCM/gel/cement pill and pulled up into shoe, WOC.
01/29/86	Continued WOC. Filled hole with 200 bbls of mud and WOC two hours. Filled hole with 14 bbls of mud. RIH to 8,128 ft without tagging plug. Mixed and pumped a 50 bbl LCM/cement plug and pulled up into shoe. WOC six hours. Circulated at shoe with full returns. RIH to 8,128 ft and spotted a 50 bbl LCM pill. POH and PU BHA with bit #46. RIH and broke circulation at shoe. RIH and reamed from 8,106 ft to 8,161 ft. Drilled from 8,161 ft to 8,166 ft. Discontinued directional drilling.
01/30/86	Drilled from 8,166 ft to 8,395 ft and POH hole to PU core barrel. RIH with core barrel. DS: 8,190 ft-4-1/2°, S38W; 8,248 ft-4-1/4°, S31W; 8,311 ft-4-1/4°, S27W; 8,342 ft-4-1/4°, S23W.
01/31/86	Broke circulation at shoe and continued in hole to 8,395 ft. Cored from 8,395 ft to 8,402 ft, where core barrel jammed. POH with core #26 and recovered 7 ft of core. MU BHA, RIH to shoe and broke circulation. RIH and reamed from 8,342 ft to 8,402 ft. Drilled from 8,402 ft to 8,585 ft. DS: 8,388 ft-4°, S11W; 8,450 ft-3-3/4°, S11W; 8,532 ft-4-1/4°, S13W.
02/01/86	POH, PU core barrel. RIH to shoe and broke circulation. Well flowing. RIH to 8,585 ft and broke circulation. No returns. Cut core #27 from 8,585 ft to 8,604 ft without returns. Barrel jammed. POH and recovered 15 ft of core. PU BHA and RIH to shoe and broke circulation. No returns. RIH to 8,574 ft and reamed from 8,574 ft to 8,604 ft. Drilled from 8,604 ft to 8,630 ft. Mixed and spotted LCM pill. Drilled from 8,630 ft to 8,635 ft without returns.
02/02/86	Drilled from 8,635 ft to 8,660 ft without returns. Mixed and spotted LCM pill at 8,660 ft and POH to shoe. WO LCM pill two hours. RIH and spotted second LCM pill at 8,660 ft. Drilled from 8,660 ft to 8,692 ft without returns. Mixed and spotted 50 bbl. LCM/cement pill and POH to shoe. WOC six hours. Circulated at shoe with 80 percent returns. RIH and reamed from 8,652 ft to 8,692 ft. Drilled from 8,692 ft to 8,723 ft. Lost returns at 8,693 ft. DS: 8,660 ft-3-3/4°, S8W.
02/03/86	Drilled from 8,723 ft to 8,800 ft without returns. Mixed and spotted an LCM pill at 8,800 ft and POH for core barrel. RIH with core barrel and cored from 8,800 ft to 8,807 ft with full returns. POH with core #28 and recovered 7 ft of core. PU BHA and RIH to shoe. DS: 8,723 ft-3-3/4°, S2W; 8,786 ft-3-3/2°, S7E.

Date	Activity
02/04/86	Broke circulation at shoe with full returns. RIH to 8,780 ft and reamed from 8,780 ft to 8,807 ft. Drilled from 8,807 ft to 8,948 ft and lost returns. Drilled blind from 8,911 ft to 9,004 ft. Spotted 2 LCM pills at 9,004 ft and POH for core barrel. RIH with core barrel to shoe and break circulation then RIH to 9,004 ft. Started coring and lost circulation. Cored blind from 9,004 ft to 9,015 ft. DS: 8,818 ft-3-3/4°, S2E; 8,881 ft-3-3/4°, S12E; 8,954 ft-3-1/2°, S16E.
02/05/86	Cored from 9,015 ft to 9,027 ft. POH with core #29 and recovered 23 ft. RIH with drilling assembly and broke circulation at shoe. Continued RIH and reamed from 9,004 ft to 9,027 ft. Mixed and spotted 35 bbl. LCM/cement pill and POH to shoe. WOC four hours. Attempted to circulate and found pipe plugged. POH and LD plugged collar. Cleaned out and re-ran collar. RIH to shoe, mixed mud and WOC at shoe.
02/06/86	Mixed mud and RIH to 9,004 ft. Reamed from 9,004 ft to 9,027 ft and drilled from 9,027 ft to 9,070 ft and lost 50 percent returns at 9,070 ft. Mixed and spotted LCM pill at 9,070 ft and POH to 8,120 ft. Mixed mud while waiting on LCM pill. RIH to 9,070 ft and spotted another LCM pill. Drilled from 9,070 ft to 9,095 ft. Spotted another LCM pill on bottom and POH for core barrel. RIH to shoe with core barrel and broke circulation. RIH to 9,095 ft and cored from 9,095 ft to 9,098 ft, where core barrel jammed. DS: 9,002 ft-2-3/4°, S14E.
02/07/86	POH with core #30 and recovered 3 ft. RIH with BHA to shoe and broke circulation. Continued RIH to 9,098 ft and lost returns. Spotted an LCM pill and POH to 8,338 ft. Mixed mud while waiting on LCM pill. RIH to 9,098 ft and did not get returns. Mixed and spotted a 50 bbl LCM/cement pill. POH to shoe and WOC six hours. Pumped 10 bbls of mud and squeezed cement to 400 psi. RIH and could not get circulation. POH in stages and attempted to get circulation without success.
02/08/86	Continued staging out of the hole in five-stand increments and attempted circulation. Regained circulation at 5,048 ft. Staged back in hole and cleaned out cement from 8,700 ft to 9,098 ft. Drilled from 9,098 ft to 9,248 ft and POH for core. RIH to shoe with core barrel and broke circulation with full returns. Continued to RIH to 9,248 ft. DS: 9,198 ft-4°, S27E.
02/09/86	Broke circulation at 9,248 ft and stuck pipe. Worked stuck pipe and spotted diesel. Pipe came free. Cored from 9,248 ft to 9,254 ft where barrel jammed. POH and well started flowing. Circulated and cooled well at shoe. POH and well started flowing again. Circulated and killed well with a 9 lb/gal pill. POH with core #31 (58 percent recovery). RIH to shoe with drilling assembly and broke circulation. Continued in hole to 9,254 ft.

Date	Activity
02/10/86	Drilled from 9,254 ft to 9,450 ft. POH to shoe and well started flowing. Mixed and spotted a pill, then continued out of hole. DS: 9,400 ft-2-3/4°, S22E.
02/11/86	Slipped drilling line. RIH to shoe with new bit and broke circulation at shoe. RIH and reamed from 9,420 ft to 9,450 ft and lost circulation. Drilled to 9,453 ft and spotted an LCM pill. POH to shoe and attempted circulation. No circulation. POH and serviced junk sub. RIH to shoe and attempted to break circulation. Well flowing. Mixed and spotted LCM/cement pill and POH to shoe. WOC five hours. Filled annulus and circulated. Closed BOP and pressured up to 200 psi. Pressure dropped to zero.
02/12/86	WOC 2-1/2 hours. Closed BOP and pumped into formation at zero pressure. RIH to 8,500 ft and circulated with full returns. RIH to 9,350 ft and reamed from 9,360 ft to 9,453 ft. Circulated and conditioned mud. POH for core barrel. RIH with core barrel to 9,453 ft and cored from 9,453 ft to 9,458 ft.
02/13/86	POH with core #32 and recovered 2.4 ft of core. Core bit cracked on shank. PU new core bit and RIH to shoe. Mixed and spotted LCM pill with full returns. RIH and cut core #33 from 9,458 ft to 9,473 ft. POH with core barrel and recovered 6-1/2 ft of core. Magna-glowed BHA and grade-E drill pipe.
02/14/86	Continued Magna-glowing drill-pipe tool joints; RIH. LD 28 joints of bent drill pipe. Pumped 350 bbls of water at shoe before getting returns. POH and well started to flow.
02/15/86	RIH to shoe and circulated and killed well. RIH and hit bridge at 9,315 ft. Reamed from 9,315 ft to 9,473 ft and POH. RU USGS wireline unit and ran temperature survey. Ran spinner survey and tool malfunctioned. RD loggers. Well started flowing. Injected 300 bbls of mud and killed well. Changed out BHA and well started flowing again. Mixed mud and killed well.
02/16/86	Mixed mud and RIH to shoe. Filled drill pipe and mixed LCM pill. RIH to 9,200 ft and pumped a 50 bbl LCM/cement pill. POH to 8,500 ft and pumped another 50 bbl LCM/cement pill. POH to 7,400 ft and pumped a 50 bbl. LCM/cement pill. WOC six hours. RIH to 8,500 ft and could not get circulation. Staged out of hole and regained circulation at 4,700 ft.
02/17/86	POH and changed BHA. RIH to 5,800 ft and found bit plugged. POH and found cement in float sub. Staged in hole and broke circulation at 5,000 ft, 6,000 ft, 6,400 ft, 6,700 ft and 7,100 ft. Well flowing. Circulated and conditioned mud. RIH and broke circulation at 7,500 ft, 8,400 ft, 8,800 ft and 9,360 ft. Reamed from 9,360 ft to 9,473 ft and circulated bottoms-up.

Date	Activity
02/18/86	Strapped out of hole and found 18 ft error in previous measurements. Depth should be 9,455 ft instead of 9,473 ft. RIH with core barrel to shoe and circulated while building mud volume. RIH to 9,400 ft and attempted to break circulation without success. Staged out of hole to shoe without getting returns. POH, LD core barrel. RU USGS to run temperature survey.
02/19/86	Temperature survey stopped at 6,124 ft. RD wireline unit and RIH with bit to shoe and regained circulation. RIH to 9,230 ft and circulated to cement. RU Halliburton and cemented with 136 sx (35 bbls) of class "G," plus 3 percent gel, plus 2.3 percent HR-12, plus 0.65 percent CFR-2 with full returns and stuck drill pipe. Worked stuck pipe and tried to circulate cement out. Lost returns. Pumped down annulus and pipe came free. POH 10 stands. RIH and re-cemented at 9,230 ft. POH to 8,000 ft and WOC. Squeezed cement with 10 bbls to 200 psi. RIH to 8,750 ft and spotted 35 bbls of same cement. POH to 8,293 ft and spotted another 35 bbl cement plug. POH to 7,359 ft and WOC. Squeezed cement with 10 bbls to 200 psi.
02/20/86	RIH and tagged cement at 8,105 ft. Re-cement at 8,105 ft with 35 bbls of cement. POH to 7,390 ft and WOC. Squeezed cement with 10 bbls to 250 psi. Cemented with 35 bbls of cement at 7,390 ft and POH to shoe and WOC. Squeezed cement with 10 bbls to 250 psi. RIH to 6,292 ft and cemented with 35 bbls of cement. POH to 5,500 ft and WOC. Squeezed cement with 10 bbls to 250 psi. POH for drilling assembly. RIH with drilling assembly to 6,170 ft and tagged cement plug. Tested cement with 400 psi. Cleaned out cement from 6,170 ft to 6,270 ft and cement stringers from 6,270 ft to 6,485 ft. Lost returns at 6,485 ft. POH and stand back drilling assembly. RIH open-ended to 6,300 ft and broke circulation. No returns. RIH to 6,500 ft and RU Halliburton.
02/21/86	Cemented at 6,500 ft with 35 bbls class "G" cement, plus 3 percent gel, plus 2 percent HR-7, plus 0.75 percent CFR-2 without returns. POH to 5,900 ft and circulated with full returns. Squeezed cement with 2 bbls to 600 psi and POH. RIH with bit and heavy-weight pipe and tagged cement at 6,165 ft. Cleaned out cement plugs at 6,165 ft-6,332 ft, 6,525 ft-6,711 ft, 7,245 ft-7,490 ft, 7,857 ft-8,303 ft with full returns. Pressure tested plugs to 300 psi.
02/22/86	Drilled out cement from 8,308 ft to 8,759 ft, 9,002 ft to 9,331 ft and 9,395 ft to 9,473 ft. Circulated bottoms-up and made steel line measurement (SLM) of drill string while POH. Had tight hole from 6,230 ft to 6,170 ft. PU core bbl and RIH to 6,000 ft. Slipped and cut drilling line. RIH to 9,440 ft, broke circulation and got differentially stuck. Worked stuck drill pipe.

Date	Activity
02/23/86	Spotted 2,920 gals of diesel plus N10 (5 gals/20 bbls diesel) and worked pipe free. Cleaned out fill from 9,440 ft to 9,473 ft and cored from 9,473 ft to 9,477 ft where core bbl jammed. POH and LD core #34. Recovered 3 ft of core. RIH with drilling assembly and broke circulation at 6,000 ft, 7,200 ft, and 8,200 ft. Gained 200 bbls of fluid at 8,200 ft. Built mud weight from 8.2 pounds per gallon (ppg) to 8.5 ppg and dumped brine water. RIH to 9,447 ft and reamed from 9,447 ft to 9,477 ft. Drilled from 9,477 ft to 9,517 ft.
02/24/86	Circulated bottoms-up and POH for core. RIH with core bbl to shoe and broke circulation. Well flowing. RIH to 9,458 ft and stuck drill pipe. Spotted 75 bbls of diesel plus N10 and worked drill pipe free. Reamed from 9,458 ft to 9,488 ft. Spotted an LCM pill and POH.
02/25/86	LD core bbl and PU BHA. RIH to 6,000 ft and broke circulation with full returns. RIH to 9,417 ft and broke circulation without returns. Staged out of hole attempting circulation at 7,800 ft and 6,800 ft without success. Got full returns at casing shoe at 6,000 ft. Staged back in hole getting 75 percent returns at 6,994 ft, 7,615 ft, 8,549 ft and 9,419 ft. Reamed from 9,419 ft to 9,517 ft and drilled from 9,517 ft to 9,556 ft with full returns.
02/26/86	Drilled from 9,556 ft to 9,696 ft. POH for bit change. RIH slowly to casing shoe and broke circulation.
02/27/86	Staged in hole and broke circulation at 6,900 ft, 7,800 ft, 8,700 ft and 9,606 ft. Reamed from 9,606 ft to 9,694 ft and circulated hole. Made a wiper trip from 8,794 ft to 9,694 ft and circulated bottoms-up. POH for core bbl and well started flowing on trip out. Spotted a heavy-weight gel pill and continued trip out of hole. RIH with core bbl to 3,500 ft. Slipped and cut drilling line. Continued in hole, breaking circulation at 6,000 ft, 6,893 ft, 7,835 ft and 8,771 ft. Stuck core barrel in tight hole at 9,605 ft. Tripped jars twice before core bbl came loose. Reamed tight hole from 9,605 ft to 9,615 ft.
02/28/86	Reamed from 9,615 ft to 9,694 ft and cored from 9,694 ft to 9,698 ft. POH to 8,978 ft and well started flowing. Mixed and pumped an LCM pill. POH with core #35 and recovered 3.5 ft of core. Well started flowing. Shut well in and pumped a 70 bbl slug of 10 ppg mud through the kill line to make well static. RIH to shoe and circulated. Changed out drilling line. Staged in hole breaking circulation at 6,900 ft, 7,800 ft, 8,700 ft and 9,641 ft. Reamed from 9,641 ft to 9,698 ft.
03/01/86	Drilled from 9,698 ft to 9,907 ft. Circulated bottoms-up and POH for core barrel.

Date	Activity
03/02/86	RIH with core barrel breaking circulation at 6,000 ft, 8,327 ft and 9,907 ft. Cored from 9,907 ft to 9,912 ft and POH with core #36.
03/03/86	Recovered 9 in. of core. RIH with drilling assembly, breaking circulation at 6,000 ft, 8,150 ft and 9,824 ft. Reamed from 9,824 ft to 9,912 ft and drilled from 9,912 ft to 10,009 ft.
03/04/86	Drilled from 10,009 ft to 10,061 ft and circulated bottoms-up. POH to shoe and circulated to cool well and spot pill. Continued out of hole and changed bits. RIH to shoe and broke circulation. Repaired pitcher nipple and continued in hole. Drilled from 10,061 ft to 10,076 ft.
03/05/86	Drilled from 10,076 ft to 10,212 ft; spotted pill and POH. Changed BHA and RIH. Welded break in pitcher nipple.
03/06/86	RIH and reamed from 10,120 ft to 10,170 ft and stuck pipe. Worked stuck pipe and spotted 80 bbls of diesel. Well started flowing. Closed pipe rams and circulated through choke line. Pipe came free. Reamed hole from 10,170 ft to 10,212 ft and drilled from 10,212 ft to 10,306 ft.
03/07/86	Drilled from 10,306 ft to 10,350 ft; pumped a water pill and dropped multi-shot survey tool. Ran multi-shot survey back to 6000 ft. Well started flowing. Circulated and killed well. Retrieved multi-shot tool. Film was burned up. POH and LD monel collar and stabilizers. RIH to shoe and circulated. Continued in hole to 10,286 ft. Reamed from 10,286 ft to 10,350 ft and drilled from 10,350 ft to 10,374 ft.
03/08/86	Drilled from 10,374 ft to 10,475 ft, where 200 bbl/hr loss of circulation occurred. Mixed and spotted an LCM pill on bottom, then POH to shoe to build mud volume. Continued out of hole, RU USGS to run temperature and caliper logs.
03/09/86	Finished running caliper and temperature logs. RD USGS. RIH open ended with drill pipe to spot sand plug. Well started flowing. Staged in hole at 5,800, 6,850 ft, and 9,190 ft. Tagged fill at 10,382 ft and pulled back to 10,319 ft. RU Halliburton and pumped 86 sacks of #20 silica sand. Pulled three stands, broke circulation, and lost returns. RIH to 10,350 ft and spotted an LCM pill. POH to shoe and mixed mud.
03/10/86	Mixed mud and pumped 120 bbls down annulus in 40 bbl/hr increments. Pumped 120 bbls down drill pipe and got returns. RIH to 10,425 ft and circulated with only partial returns. Spotted another LCM pill on bottom, POH to shoe and built mud volume. Continued out of hole for logs. RU Schlumberger; ran electric log to 8,819 ft, where tool stopped. Ran log from 8,819 ft back to 6,000 ft and RD Schlumberger. RIH with well flowing. Circulated and killed well at 3,246 ft. RIH to 600 ft and circulated

Date	Activity
	bottoms-up. Continued in hole and hit bridge at 6,850 ft. Cleaned out bridge from 6,850 ft to 6,950 ft then RIH to 10,331 ft. Circulated and conditioned mud.
03/11/86	Continued circulating and conditioning mud. POH with bit and RIH open-ended to spot cement. Spotted 118 ft^3 cement plug from 10,414 ft to 10,114 ft consisting of class "G", 1:1 perlite, 40 percent silica flour, 3 percent gel, 0.65 percent CFR-2 and 2.5 percent HR-12. Cement was preceded by 25 ft^3 of water and followed by 10 ft^3 of water. Displaced cement with 995 ft^3 of mud. POH to 9,946 ft and circulated and conditioned mud while WOC. RIH after six hours and went to 10,414 ft without tagging cement. Circulated at 10,414 ft while waiting for additional cement. Recemented at 10,414 ft as in previous stage.
03/12/86	POH to 9,885 ft and circulated while WOC. RIH to 10,414 ft again without tagging cement plug. Attempted to circulate and found pipe plugged. POH with wet string. LD 42 joints of cemented-up drill pipe. RU USGS wireline truck and ran temperature and caliper logs to 8,700 ft, where they stopped. Caliper and televiewer tools did not work. RD USGS and RIH to shoe and circulated.
03/13/86	RIH and tagged plug at 10,266 ft with 20,000 lbs. Spotted an LCM pill on bottom and lost circulation while displacing. POH to 9,200 ft and pumped 60 bbls in annulus without getting returns. POH to 8,000 ft and pumped 50 bbls without returns. Mixed and spotted an LCM pill at 8,000 ft. POH to shoe and filled annulus with 215 bbls of water. Circulated at shoe. RIH to 10,200 ft and spotted an LCM pill. POH wet to shoe. Spotted another pill at the shoe and continued out of hole. RU USGS wireline unit and ran acoustic log. Well started flowing. Bullheaded 100 bbls of fluid down well while logging.
03/14/86	Finished logging and RD USGS. Bullheaded another 100 bbls of mud followed by 50 bbls of 11 lb/gal mud to kill well. RIH to shoe and circulated. Well flowing. Continued circulating and conditioning mud. Staged in hole to 8,000 ft and 10,000 ft circulating and conditioning mud. Weighted up mud to kill well and lost circulation. Mixed and spotted an LCM pill at 10,000 ft.
03/15/86	POH to shoe and spotted an LCM pill. Attempted to fill annulus with 200 bbls of water without success. Pumped another 214 bbls and filled annulus. RIH and spotted an LCM pill at 10,000 ft and got returns. Spotted another LCM pill at shoe. Well tried to flow. Mixed and pumped 70 bbls of 11.5 lb/gal mud. Well static. POH to run 7 in. liner. RU casing crew and started running liner.
03/16/86	Ran 102 joints of 7 in., 29#, N-80, LT&C casing for a total of 4,362 ft. Installed safety collar one joint below liner-hanger. MU and installed Brown type CPH liner-hanger and 20-ft polished bore receptacle (PBR). Thread-locked and tack-welded first ten joints. Length of liner-hanger with PBR was 38 ft. Hung liner

Date	Activity
	hanger and set seal assembly. Top of PBR at 5,735 ft with guide shoe set at 10,136 ft. POH, LD setting tool. RIH with well flowing. Circulated and killed well. POH laying down drill pipe. LD 132 joints of 5 in. drill pipe and BHA. PU 6-1/8 in. bit, 3 4-3/4 in. drill collars, 20 joints of 3-1/2 in. heavy-weight and 150 joints of 3-1/2 in. drill pipe and cross-over back to 5 in. drill pipe.
03/17/86	RIH to 7 in. casing shoe. Drilled out casing shoe and lost circulation. RIH and tagged fill at 10,245 ft. Cleaned out fill from 10,245 ft to 10,475 ft without returns. Pulled up hole to 7 in. casing shoe and spotted an LCM pill at 10,136 ft. WO pill two hours. Filled annulus with 217 bbls of water and got returns. RIH to 10,475 ft and drilled a 6-1/8 in. hole from 10,475 ft to 10,564 ft without returns. RU laydown machine and started out of hole, LD drill pipe.
03/18/86	Pumped a 250 bbl 11 lb/gal pill to kill well and continued out of hole, LD pipe. Well started flowing again. Pumped a 300 bbl pill to kill well. Continued spotting pills to kill well while POH. RD lay equipment and LD Kelly, Kelly spinner, rathole and mousehole. Tore out rig floor and started ND BOPE.
03/19/86	Finished ND BOPE and started NU wellhead and flowline.
03/20/86	ND 6 in. hydraulic gate valve and NU 4 in. gate valve on top of wellhead. Opened 10 in. master valve at 10:00 a.m. and flowed well to reserve pit for initial cleanup. Diverted flow through sample loop to brine pond.
03/21/86	Ran Kuster pressure and spinner survey on Otis wireline while flowing well. Shut well in at 10:00 p.m. when brine pond became full. Started running temperature/pressure surveys on Otis wireline.
03/22/86	Finished running pressure/temperature surveys. Made first run with Los Alamos fluid sampler.
03/23/86	Los Alamos sampler did not work. Ran fluid sampler one more time without success. RD Otis and RU Agnew and Sweet to run Leutert fluid sampler. Ran Leutert sampler three times without success. RU Otis and ran Bethke fluid-inclusion sampler to 10,200 ft.
03/24/86	POH with Bethke fluid-inclusion sampler after 24 hours. Wireline broke at rope socket on way out and dropped tool. RIH with wireline fishing tools and hit fill at 10,446 ft. Jarred tools down to 10,558 ft without finding fish. Abandoned fishing job. RU to run LANL sampler.
03/25/86	Ran LANL sampler three times to 10,200 ft. Sampler worked on second run only. Ran LBL sampler and recovered one liter of unpressurized fluid. RD Otis. Started reinjecting brine from brine pond into well.

Date	Activity
03/26/86	Reinjected brine.
03/27/86	Finished reinjecting brine. RU USGS wireline unit and ran temperature and velocity logs.
03/28/86	Finished running velocity logs. Installed 6 in. hydraulic gate valve and started running the LBL Vertical Seismic Profile (VSP).
03/29/86	Continued running VSP.
03/30/86	Finished running VSP. Removed 6 in. hydraulic gate valve and RU Dia-Log to run casing caliper log on 13-3/8 in. casing. RD Dia-Log, installed 4 in. gate valve, and RU LLNL to run downhole gravimeter.
03/31/86	LLNL finished running downhole gravimeter. Pumped 500 bbls of fresh water treated with 5 gals per 100 bbls of Hib-A corrosion inhibitor into well.
04/01/86	USGS ran final temperature log for beginning of shut-in period. Released rig at 4:00 p.m.

The drilling supervisor's and drilling contractor's daily reports are listed in Appendix A as Reports B and C, respectively.

APPENDIX C

ESTIMATED DRILLING PROGRAM SUBCONTRACTOR COSTS
(from Bechtel, 1987)

Predrilling Activities	Cost $1,000's
1.0 Well Design (Berkeley Group, Inc.)	49.4
2.0 Resource Evaluation Plan (GeothermEx)	32.0
3.0 Other Drilling Consultants	11.3
4.0 Site Preparation	
4.1 Permits	1.5
4.2 Civil Engineering/Soils Survey	43.5
4.3 Dike Closure/Dewatering	28.6
4.4 Site Construction	282.5
4.5 Electrical Contractor	17.0
4.6 Core Ramada	4.1
4.7 Septic Tank	3.3
4.8 Telephone Installation	3.2
Subtotal	383.7
Total	**476.4**

Drilling and Flow-Test Activities	
1.0 Drilling Contractor (Cleveland Drilling Company)	
1.1 Move In and Move Out	227.0
1.2 Daywork (Drilling and Coring)	757.6
1.3 Daywork (Flow Test)	255.0
Subtotal	1,239.6
2.0 Drilling Supervisor (Gerald Reich)	104.0
3.0 Drilling Fluids (Profco)	
3.1 Mud and Chemicals	382.2
3.2 Diesel	43.3
Subtotal	425.5

Drilling and Flow-Test Activities (Cont'd)		Cost $1,000's
4.0	Bits and Hole Openers	
	4.1 Bit Services	195.6
	4.2 Security	20.3
	Subtotal	215.9
5.0	Wellhead Equipment	
	5.1 Wellhead	89.3
	5.2 20" x 13-3/8" Pack-Off	5.3
	5.3 30" x 20" Pack-Off	3.8
	Subtotal	98.4
6.0	Rental Drilling Equipment	
	6.1 30" and 20" BOPE	27.5
	6.2 Stabilizer	110.4
	6.3 Jars	12.5
	6.4 3-1/2" Drill Pipe	16.0
	6.5 Miscellaneous Items	7.8
	6.6 Forklift	27.9
	Subtotal	202.1
7.0	Fishing Tools	36.2
8.0	Coring Services	124.2
9.0	Mud Logging	94.3
10.0	Commercial Geology	70.7
11.0	Cementing and Float Equipment	
	11.1 30" Conductor	2.4
	11.2 20" Casing (Cement = $27,100; Float equipment = $3,200)	30.3
	11.3 13-3/8" Casing (Cement = 56,000; Float equipment = $4,400)	60.4
	11.4 9-5/8" Casing (Cement = $45,300; Float equipment = $8,400)	53.7
	11.5 Cement and Sand Plugs	59.1
	Subtotal	205.9
12.0	Casing	
	12.1 30" Conductor	10.7
	12.2 20" Surface	79.0
	12.3 13-3/8" Intermediate	163.4
	12.4 9-5/8" Production	188.4
	12.5 7" Liner	73.0
	Subtotal	514.5

Drilling and Flow-Test Activities (Cont'd)	Cost $1,000's
13.0 Casing Crew	
13.1 20" Casing	5.9
13.2 13-3/8" Casing	4.7
13.3 9-3/4" Casing	7.7
13.4 7" Casing	4.8
13.5 Pickup/Laydown Drill Pipe	15.8
13.6 Pipe Spinners	11.7
13.7 Hauling	3.3
Subtotal	53.9
14.0 Liner Hanger	
14.1 Liner Hanger, PBR & Packer	25.2
14.2 Freight	1.2
Subtotal	26.4
15.0 Commercial Logging	
15.1 Schlumberger (geophysical)	86.7
15.2 Dia-Log (casing caliper)	3.5
15.3 Otis (wireline service)	16.2
15.4 Agnew & Sweet (fluid sampler)	2.6
15.5 Welex (casing inspection)	6.7
Subtotal	115.7
16.0 Drill Pipe Inspection and Repair	
16.1 Inspection	17.6
16.2 Repair	27.8
16.3 Other (trucking)	2.6
Subtotal	48.0
17.0 Directional Work	
17.1 Directional Drilling	47.2
17.2 Multi-Shot (3,500; 6,000; 10,000)	12.8
17.3 Single-Shot Surveys	16.4
17.4 Inspection and Repair (turbo drills and Monel D.C.)	10.4
17.5 Trucking	4.0
Subtotal	90.8
18.0 Flow-Test Facility Construction	306.6
19.0 Well Stimulation	5.3

Drilling and Flow-Test Activities (Cont'd)	Cost $1,000's
20.0 Flow-Test Contractor	59.8
21.0 Drill Fluid/Cuttings Disposal	
21.1 Vacuum Trucks	21.9
21.2 Dump Trucks	4.5
21.3 Dragline	4.1
21.4 Other (cement and backhoe)	5.1
Subtotal	35.6
22.0 Miscellaneous Site Support	
22.1 Telephone	19.3
22.2 Potable Water	5.7
22.3 Sanitation/Garbage	3.1
22.4 Trailer Rental/Hauling	7.2
22.5 Electricity	2.9
22.6 Welding	12.8
22.7 Fencing/Security	6.1
22.8 Other	2.5
Subtotal	59.6
TOTAL	**4,133.0**

Remedial Operation		Cost $1,000's
1.0	Drilling Contractors	120.1
2.0	Drilling Supervisor	5.0
3.0	Drilling Fluids	17.2
4.0	Rental Equipment	8.0
5.0	Fishing Tools	22.5
6.0	Casing (7" liner)	6.6
7.0	Casing Crew	19.4
8.0	Liner Hanger	11.7
9.0	Drill Pipe Inspection and Repair	5.3
10.0	Drilling Fluid/Cuttings Disposal	3.5
11.0	Miscellaneous Site Support	1.0
	TOTAL	**220.3**