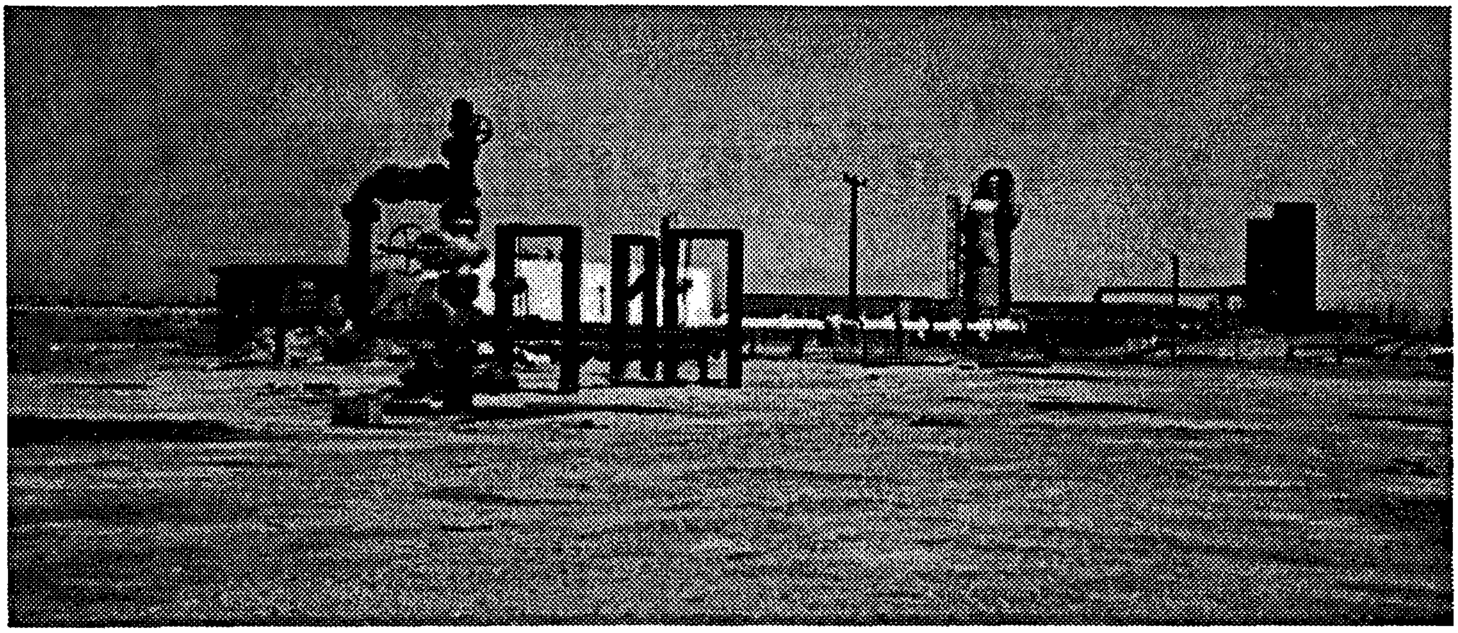
G-L00501

DOE/CE-0000

SALTON SEA SCIENTIFIC DRILLING PROJECT

A Summary of Drilling and Engineering Activities and Scientific Results



FINAL REPORT
April 1992

Prepared By

Howard P. Ross, Editor
C. Kelson Forsgren, Assistant Editor

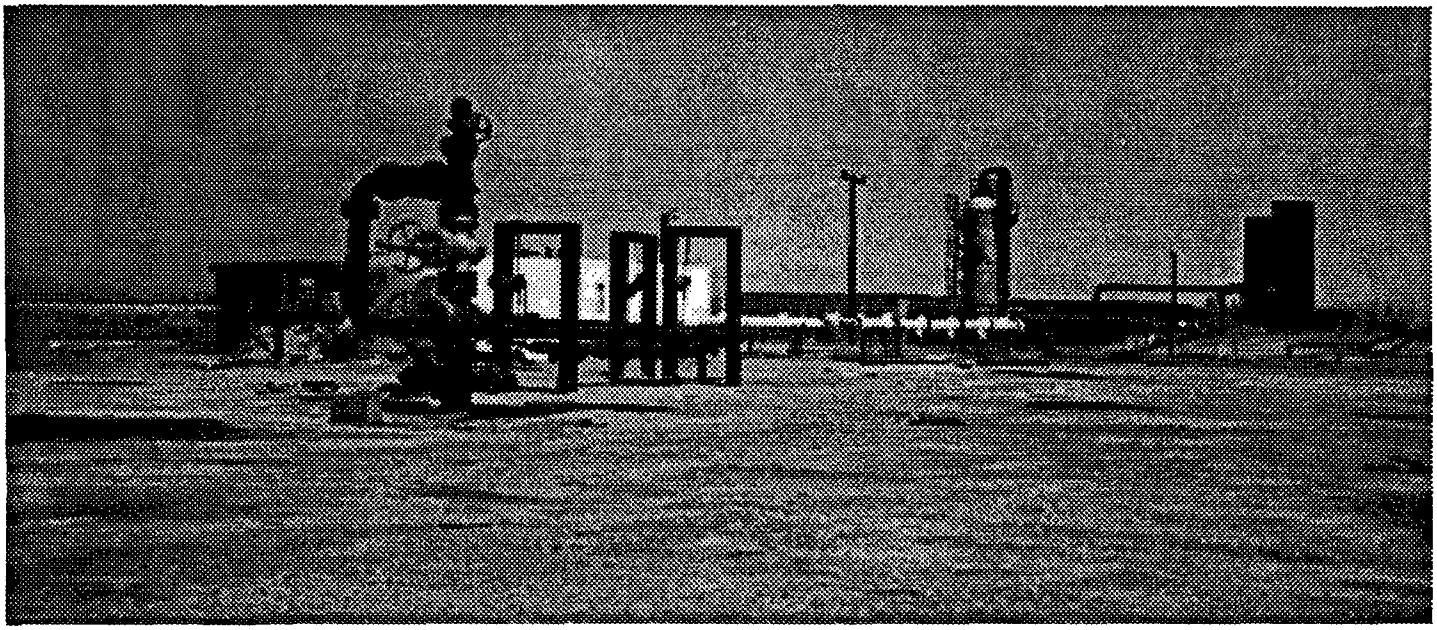
Prepared For

The U. S. Department of Energy
Assistant Secretary, Conservation and Renewable Energy
Geothermal Division

DOE/CE-0000

SALTON SEA SCIENTIFIC DRILLING PROJECT

A Summary of Drilling and Engineering Activities and Scientific Results



FINAL REPORT
April 1992

Prepared By

Howard P. Ross, Editor
C. Kelson Forsgren, Assistant Editor

The University of Utah Research Institute
391 Chipeta Way, Suite C
Salt Lake City, Utah 84108

with major contributions by

Bechtel National, Inc.; Geothermex, Inc.
Allan Jelacic (DOE/GD), Marshall Reed (DOE/GD)
Raymond Wallace (USGS)

Prepared For

The U. S. Department of Energy
Assistant Secretary, Conservation and Renewable Energy
Geothermal Division
Washington, DC 20585

DISCLAIMER

TABLE OF CONTENTS

		Page
	ABSTRACT	vi
	EXECUTIVE SUMMARY	vii
	CONVERSION FACTORS	xii
	TABLE OF ACRONYMS	xiv
	ACKNOWLEDGEMENTS	xvi
1.0	INTRODUCTION	1
2.0	PROJECT MANAGEMENT	8
3.0	OPERATION AND SAFETY PROCEDURES	13
4.0	DRILLING ENGINEERING AND FACILITIES DESIGN	14
5.0	DRILLING SUMMARY	35
6.0	WELL REWORK (PHASE 2)	58
7.0	COMMERCIAL GEOLOGY AND LOGGING	64
8.0	RESEARCH LOGS AND BOREHOLE STUDIES	83
9.0	FLOW TESTS AND WELL PRODUCTIVITY	91
10.0	FLUID CHEMISTRY	115
11.0	OTHER GEOSCIENCE STUDIES - STATE 2-14	138
12.0	SITE RESTORATION AND BRINE POND CLEANUP	152
13.0	COST SUMMARY	173
14.0	SUMMARY AND RECOMMENDATIONS	177

APPENDICES

A	REPORTS SUBMITTED TO BECHTEL NATIONAL, INC.	A-1
B	SUMMARY OF DAILY DRILLING ACTIVITY, PHASE 1	B-1
C	ESTIMATED DRILLING PROGRAM SUBCONTRACTOR COSTS	C-1

LIST OF ILLUSTRATIONS

		Page
Figure 1.1	Location and Geologic Setting of the Salton Sea Geothermal System	2
Figure 1.2	SSSDP Project Site Location	4
Figure 2.1	SSSDP Management Structure	9
Figure 2.2	SSSDP On-Site Organization	10
Figure 4.1	State 2-14 Well Site Location and Nearby Wells	15
Figure 4.2	Site Layout	17
Figure 4.3	Cleveland Rig No.6 Layout	18
Figure 4.4	Final Well Configuration, State 2-14	20
Figure 4.5	Wellhead Design	22
Figure 4.6	Flow-Test Facility Assembly	26
Figure 4.7	Process and Instrumentation Diagram	27
Figure 4.8	Typical Pipe Support	29
Figure 4.9	Thrust Block	30
Figure 4.10	Constant-Support Hangers	31
Figure 4.11	Typical Sample-Spool Sampling Points - 3 through 6	32
Figure 5.1	Depth Progress Chart, State 2-14	36
Figure 5.2	Plot of Temperature vs. Depth for State 2-14	48
Figure 5.3	Schematic of Wellbore Configuration after August 1986 Repairs	54
Figure 7.1	Location and Geologic Setting of the Salton Sea Geothermal System	65
Figure 7.2	Lithostratigraphic Summary for Sedimentary Rocks in State 2-14	70
Figure 7.3	Well Deviation Horizontal Plot, State 2-14	79
Figure 8.1	Summary of Temperature Logs Taken While Drilling State 2-14	86
Figure 8.2	Temperature Log Summary, March - October 1986, State 2-14	86
Figure 9.1	Simplified Diagram of Flow-Test Facility	96
Figure 9.2	Plot Plan of Flow-Test Facility	97

LIST OF ILLUSTRATIONS (continued)

		Page
Figure 9.3	Planned Schedule for 30-day Flow Test	103
Figure 9.4	Revised Schedule for Flow Test	103
Figure 9.5	Total Well-Flow Rate During June 1988 Test	105
Figure 9.6	Smoothed Wellhead Temperature and Pressure During June 1988 Test	105
Figure 9.7	Deliverability Curve, State 2-14, June 1988	107
Figure 9.8	Total Well-Flow Rate as a Function of Downhole Pressure	109
Figure 10.1	Smoothed Flow Curve Showing Times For Collection of Samples for Signature Tests	118
Figure 10.2	Total Dissolved Solids During Long-Term Flow Test, June 1988	118
Figure 10.3	Variation of Total Dissolved Solids with Flow Rate	123
Figure 10.4	Locations of Other Wells in the Salton Sea Field in Relation to State 2-14	129
Figure 10.5	Characteristics of Fluids from Geothermal Wells in the Vicinity of State 2-14	130
Figure 11.1	Schematic Diagram of Particle Meter Test Equipment	141
Figure 11.2	Test Facility State 2-14 Showing Locations from which Scale Samples Were Taken	143
Figure 12.1	Location of Brine Pond and Mud Sump with Schematic of Cleanup Units	153
Figure 12.2	Sampling Program - SSSDP Brine Pond, Kennecott - State 2-14 Well, September 15, 1988	157

LIST OF TABLES

		Page
Table 1.1	Salton Sea Scientific Drilling Program Major Objectives	6
Table 1.2	Salton Sea Scientific Drilling Program Preliminary Flow-Test Results	6
Table 4.1	Technical Data: Cleveland Drilling Co. Rig No. 6	19
Table 4.2	Wellhead Equipment List	23
Table 5.1	Summary of Coring Operations	41
Table 5.2	Summary of Core Bit Performance	42
Table 5.3	Bit Usage Summary	44
Table 5.4	Drilling Rate Versus Depth	45
Table 5.5	Fishing Operations/Stuck Pipe Summary	46
Table 5.6	Lost Circulation and Remedial Action	50
Table 5.7	Diagnostic Logging Summary	53
Table 7.1	Summary of Single-Shot Directional Surveys	78
Table 8.1	Summary of Geophysical Logs, Dates, and Depth Intervals over which logs were run in the State 2-14 Borehole	84
Table 8.2	Downhole Experiments	88
Table 9.1	Summary of Results from Short-Term Flow Tests	95
Table 10.1	Analytical Results for Brines Collected During the December 29, 1985, Flow Test of the State 2-14 Well	116
Table 10.2	Calculated Preflash Concentrations of Selected Elements in Brine from a Depth of 1829-1898m in the State 2-14 Well, December 1985 Flow Test	116
Table 10.3	Summary of Gas Contents, December 1985 Flow Test	117
Table 10.4	Brine Chemistry, State 2-14 Geothermal Well, June 1988 Flow Test	120
Table 10.5	Noncondensible-Gas Content, State 2-14 Geothermal Well, June 1988 Flow Test	121

LIST OF TABLES (continued)

		Page
Table 10.6	Noncondensible-Gas Composition, State 2-14 Geothermal Well, June 1988	121
Table 10.7	Geothermometer Cations, State 2-14 Geothermal Well Flow tests in June 1988, March 1986, December 1985	124
Table 10.8	Concentrations Compared to Hazardous Limits	126
Table 10.9	Brine Chemistry of State 2-14 and Nearby Geothermal Wells	128
Table 10.10	UURI Fluid Analyses from State 2-14 Well, June 8, 1988	132
Table 10.11	UURI Gas Analyses from State 2-14 Well, June 8, 1988	133
Table 10.12	Neutron-Activation Analysis of Precious Metals in Salton Sea Geothermal Water: Well State 2-14	135
Table 11.1	Description of Scale Samples, June, 1988. Idaho National Engineering Laboratory	144
Table 11.2	Major Elements in Weight Percent, INEL Scale Study	145
Table 11.3	Minor Elements in ppm, INEL Scale Study	145
Table 11.4	Phases Identified by X-ray Diffraction Analysis, INEL Scale Study.	146
Table 11.5	Fluid Compositions, State 2-14 Flow Test, June, 1988. INEL Scale Study.	146
Table 11.6	Summary of Analyses Showing Inferred Mineral Phases Present. INEL Scale Study, Well State 2-14.	147
Table 12.1	Sludge Physical Properties	158
Table 12.2	Brine-Pond Sludge, Analytical Results: June 1987-July 1988	159
Table 12.3	Comparison of Analytical Results with Threshold Limits, NET Pacific Laboratory Results, October 14, 1988	161
Table 12.4	Analytical Results for Sludge, Brookhaven National Laboratory	162
Table 12.5	Brine Pond Cleanup Chronology: Phase 2	165
Table 12.6	Summary of Materials Processed and Removed	167
Table 12.7	Analytical Results: Post Cleanup Brine Pond Sample	168
Table 12.8	Brine Pond Cleanup Costs	168
Table 13.1	SSSDP Project Cost Summary	174
Table 13.2	Summary of Salton Sea Scientific Drilling Program Costs	175
Table 13.3	Drilling and Coring Performance Trends	176

ABSTRACT

The Salton Sea Scientific Drilling Project (SSSDP) completed the first major well in the United States Continental Scientific Drilling Program. The well (State 2-14) was drilled to 10,564 ft (3,220 m) in the Salton Sea Geothermal Field in California's Imperial Valley, to permit scientific study of a deep, high-temperature portion of an active geothermal system. The program was designed to investigate, through drilling and testing, the subsurface thermal, chemical, and mineralogical environments of this geothermal area. Extensive samples and data, including cores, cuttings, geothermal fluids and gases, and geophysical logs, were collected for future scientific analysis, interpretation, and publication. Short duration flow tests were conducted on reservoirs at a depth of approximately 6,120 ft (1,865 m) and at 10,136 ft (3,089 m).

A 20-day, multi-step flow test completed in June 1988, showed that the well has high productivity and is capable of flow rates greater than 800,000 lbm/hr (363,000 kg/hr) at 250 psig (1,724 kPa) wellhead pressure. This flow rate could produce 12 MWe in a dual-flash power plant. Total dissolved solids of the preflash brine are about 250,000 mg/kg.

This report summarizes all major activities of the SSSDP, from project inception in the fall of 1984 through brine-pond cleanup and site restoration, ending in February 1989. The reader is referred to papers by Elders (1985), Elders and Sass (1988), and Sass et al. (1986) for more details on project origin, organization, and science management. This report presents a balanced summary of drilling, coring, logging, and flow-test operations, and a brief summary of technical and scientific results. Frequent reference is made to original records, data, and publication of results.

The report also reviews the proposed versus the final well design, and operational summaries, such as the bit record, the casing and cementing program, and the coring program. Summaries are presented of the geological features encountered, and the results of three flow tests. Several recommendations are made, based on the lessons learned during the project.

Total project costs for the SSSDP design, drilling, engineering, flow testing, site restoration, and some of the science costs are estimated to be approximately $9,583,000. The total science costs for several national laboratories, the U.S.Geological Survey, and several university and industry investigators exceeds another $1,000,000. The resulting data have been the subject of five technical sessions at three international scientific meetings and the topics of more than 40 technical papers.

EXECUTIVE SUMMARY

The Salton Sea Scientific Drilling Program (SSSDP) originated with the desire by scientists studying hydrothermal processes to directly observe temperatures and to sample fluids deep within an active geothermal system. The U. S. Congress added $5.9 million for the first phase of the SSSDP to the 1984 budget of the Department of Energy—Geothermal Technology Division. The original intent was to use this funding to deepen an existing Republic Geothermal well in the Niland area from 12,000 to 18,000 ft. Control of the wells in the Niland area, on the eastern margin of the Salton Sea geothermal anomaly, transferred to Parsons Corporation in 1983, and the agreement to deepen the well was voided. In order to closely follow the intent of Congress, in 1984, the DOE solicited proposals to drill a new deep test well and an associated injection well in the Salton Sea geothermal system.

In response to an open solicitation by the Department of Energy, San Francisco Operations Office (DOE/SAN), Bechtel National, Inc., a major engineering company, was selected to manage the drilling of the deep scientific borehole on a site proposed by Kennecott, Inc., a resource company with exploration permits in the Salton Sea Geothermal System. The SSSDP became the first major project performed in the United States under the Interagency Accord on Continental Scientific Drilling, a cooperative agreement among the Department of Energy, the U.S. Geological Survey, and the National Science Foundation.

The well, State 2-14, was drilled to 10,564 ft (3,220m) in 160 days and achieved most of the planned technical objectives. A management organization was established that included both off-site and on-site management. This management organization achieved most of the scientific objectives within engineering constraints, but at a final cost nearly twice the initial funding level. The project was completed without lost time due to injury.

DRILLING

Although most of the major engineering objectives of the SSSDP were achieved, severe drilling problems and adverse borehole conditions limited the final scientific results, increased project task times, and escalated project costs. The Department of Energy, Bechtel National, Inc., and subcontractor personnel involved in the program did not have experience in drilling geothermal wells, and many of the drilling problems would have been less severe if experienced engineers were available. Drilling progress was excellent to a depth of 6,227 ft (1,898 m; 62 days) after which hole deviation and lost circulation problems, together with coring and logging activities, greatly reduced downhole progress. Both the hole deviation and lost circulation problems can be attributed to geologic conditions (highly fractured formations, alteration zones, etc.) at the well site. These geologic conditions were expected, based on reports of nearby wells.

Separation of the uncemented 7 in. (17.8 cm) liner occurred sometime after the April 22, 1986 temperature logging (38 days after liner installation) and before a May 28 logging attempt (74 days after running the liner). Diagnostic logging showed the liner separated at a collar at 6,195 ft (1,888 m). Metallurgical studies by Brookhaven National Laboratory concluded that the collar probably failed by a stress-corrosion-hydrogen embrittlement mechanism, perhaps due in part to introducing oxygen during injection of the produced brine, and additional stresses from the 5-degree dogleg in this zone. Normal geothermal practice is to use buttress-threaded 7 in. liner in applications like this rather than the weaker 8-round threaded liner that was used. The liner separation prevented logging below 6,195 ft (1,888 m) and terminated access to the bottom of the hole.

Liner repair work of August 1986 reestablished tool access to approximately 8,005 ft (2,440 m) through the temporary installation of 793 ft (242 m) of 7-in. (17.8-cm) patch liner (5,728 to 6,521 ft; 1,746-1,988 m). Direct project costs of this first well remedial work exceeded $290,000.

In the first logging attempt following remedial work (October 22), a dewared Kuster tool encountered a soft bridge at 5,800 ft (1,768 m) and stopped at 5,810 ft (1,771 m). A sinker bar was worked to 6,717 ft (2,047 m), but the temperature tool was again stopped by a gel bridge, at 5,822 ft (1,775 m) on October 24. It was concluded that the liner was full of gel from 5,800 ft (1,768 m) to at least 8,000 ft (2,438 m) and logging attempts were discontinued. Bechtel suggested that during the final water displacement of mud in the August remedial work, the water may have flowed around the top of the replacement liner rather than down through it, and that mud located below 5,800 ft (1,768 m) was not circulated out. Alternatively, the mud may have migrated back up into the liner from the lower part of the well. The inability to run logging tools to the bottom of the well and the need for a flow test of deeper reservoir zones led to additional well rework which was performed in August 1987. The 7-in. temporary liner was retrieved with some difficulty, related to pulling the liner through the dogleg at about 6,200 ft (1,890 m). Four attempts to sidetrack the hole using mud motors failed because of the high temperature. One attempt to effect a sidetrack, using a locked bottom-hole assembly, drilled out the cement plug. After setting a new cement plug, a second run with a whipstock apparently wandered back into the original hole and encountered a major obstruction at a depth of 7,180 ft (2,188 m). At this point, Bechtel was directed by DOE to stop drilling and prepare for a flow test of accessible zones (6,100-7,100 ft; 1,859-2,164 m). This marked the greatest depth tested by all subsequent logging, except for temperature logging, although flow tests may have produced fluids from greater depths. The two well rework attempts were largely failures. The drilling techniques used were unable to regain access to the bottom of the hole. Direct project costs for the drilling contractor for the Phase 2 rework exceeded $330,000.

GEOSCIENCE

Geologic, mineralogic, permeability, and temperature data were obtained for most of the 10,564-ft (3,220-m) total depth of the hole, subject to lack of cuttings from lost-circulation zones, and were not seriously limited by loss of access to the hole due to the liner separation and subsequent hole obstruction. The obstruction did prevent controlled flow-testing of individual permeable zones and the acquisition of samples for fluid chemistry from known depths. Nonetheless, an impressive amount of geoscientific information was obtained from well State 2-14 and entered into the public domain.

Only two major sedimentary-rock intervals can be readily distinguished in the borehole. The upper, consisting of poorly indurated clay, silt, and sand, extends from the surface to about 1,100 ft (335 m) depth. The lower unit, extending from a depth of about 1,100 ft to total depth of the well, consists of an assemblage of alternating claystones, siltstones, and sandstones. These sediments were deposited in the continental basin of the Salton Trough, and are interpreted as the basinward facies of the Borrego and Brawley formations, which range from Pliocene to Pleistocene in age (Herzig et al.,1988). Lacustrine shale and siltstone are the dominant lithologies, but sandstones were deposited in lake margin, meander-channel fill, and lacustrine-delta environments.

Alteration generally increases with depth and is superimposed on, and partly controlled by, pre-existing sedimentary features. The rocks below about 2,760 ft (841 m) show evidence of greenschist facies metamorphism, with the first appearance of vein epidote noted at this depth. Alteration is enhanced along permeable zones, primarily the sandstone units. Two mafic intrusive bodies were intersected between 9,440 and 9,589 ft (1,963-2,923 m). Both were cut by high angle veinlets of epidote + sulfide + quartz + actinolite (?). The self-sealed cap rock extends from depths of 1,100 to 1,900 ft (335-579 m), and the main reservoir extends to about 3,000 ft (914 m) depth. In the altered reservoir, below 3,000 ft, intergranular permeability is destroyed by metamorphic minerals and permeability is entirely due to fracturing.

Temperature data and petrologic results clearly demonstrate that well State 2-14 is located off-axis, and on the southeast flank, of the Salton Sea high-temperature hydrothermal anomaly. Fluid inclusion studies indicate that the system has cooled in the vicinity of State 2-14, or that an older, hotter, system had been present in the same area. A key finding with implications for commercial resource evaluation and development throughout the Salton Sea geothermal system is that, although porosity decreases and rock induration increases with depth, permeability-controlling fractures increase with depth.

PRODUCTION POTENTIAL

A number of possible production zones were identified from mineralogy, lost circulation, drilling rate, mud-return temperatures, mud resistivity, and dissolved gases (mainly CO_2). These zones occur at: 2,619-3,160 ft; 5,450-5,460 ft; 6,110-6,130 ft; 6,635-6,650 ft; 8,090-8,100 ft; at 8,580 ft, 8,950 ft, and 9,000 ft; 9,095-9,125 ft; and below 10,475 ft.

Well State 2-14 provided a unique opportunity to investigate the physical properties of sediments in a high-temperature environment deep within the Salton Trough. A broad suite of conventional geophysical well logs was obtained in the upper parts of the borehole, but *in situ* temperatures greater than 572°F (300°C) and an inability to cool parts of the borehole by circulation limited the suite of logs run below 6,000 ft (1,829 m). Log interpretation assisted in the identification of lithologic units and potential production zones, but the qualitative and quantitative interpretation of most logs was hampered by borehole conditions, the relative absence of "clean" sandstones and good lithology contrasts, and the effects of hydrothermal alteration at depth. Also, the burnout of the caliper motor precluded calibration of logs below 6000 ft (1,829 m). The trend of increasing alteration is evident as a general increase in deep-induction resistivity with depth.

Temperature logs indicate permeable zones at depth and a low-permeability overlying strata that extends to a depth of more than 2,950 ft (900 m). Indicated formation temperatures are 581°F ± 9°F (305°C ± 5°C) at about 6,200 ft (1,890 m) and 671°F ± 18°F (355°C ± 10°C) at 10,400 ft (3,170 m).

A suite of injectivity and flow tests were performed to assess the potential productivity of different intervals of the State 2-14 borehole. A 29-hour flow test conducted on December 28-30, 1985, evaluated a permeable zone between 6,100 and 6,227 ft (1,859 and 1,898 m) in depth. The average well flow rate was 192,000 lbm/hr with wellhead temperatures of 400° to 460°F (204°C to 238°C). A second, short-term (38 hr), flow test was conducted March 20-21, 1986, after the well was completed to 10,564 ft (3,220 m). Several flow zones contributed to this test, with most production probably coming from zones near 8,800 ft (2,682 m) and between 10,475 ft (3,193 m) and total depth. The well was found to be capable of producing 710,000 lbm/hr at a wellhead pressure of 375 psig. Wellhead temperatures ranged from 445° to 490°F (229° to 254°C).

A long-term (19 day), step-rate flow test was conducted from June 1-20, 1988, after completion of the flow-test facility. The mechanical condition of the well below 5,500 ft (1,676 m) was uncertain, but the primary entry zone was believed to be at 6,200 ft (1,890 m). The well deliverability was determined to be about 800,000 lbm/hr (370,000 kg/hr) for a typical operating wellhead pressure of 250 psig (1,724 kPa). At this flow rate, the well could produce approximately 12 MWe in a two-stage, flash power plant. An average productivity index of 1,527 lbm/hr per psi (100 kg/hr per kPa) was calculated, but the well productivity was observed to increase during the course of the test. Reservoir engineering analysis of the pressure-buildup test indicates that the near-well reservoir has a transmissivity of about 233,600 md-ft and a skin factor of +23.1. These results indicate a highly productive reservoir with some near-well impairment, probably caused by drilling and workover operations.

BRINE CHEMISTRY

One major objective of the SSSDP was to characterize the chemistry of the geothermal brines. This information contributes to understanding the geothermal system, the development of alteration processes, and the formation of base-metal deposits. The surface flow system lacked a full-phase separator , and the geochemists were forced to sample mixtures of unknown ratios of steam and brine available from multiple ports of the two-phase pipe. More than 20 geochemists participated in sampling and analyzing brines and related materials from the three flow tests. Additional studies included collection and analysis of downhole-fluid samples.

The brine chemistry varied somewhat for the different flow tests, and as a function of flow rate during the long-term flow test. Based primarily on data obtained from the long-term flow test, the brines may be characterized as follows. The brines are Na-Ca-K-Cl-type waters with very high metal and low SO_4 and HCO_3 contents. The total dissolved solids of the reservoir fluid varied from 232,000 to 249,000 mg/kg, increasing with flow rate. This is somewhat lower than the 25.05 weight percent reported for the December 1985 flow test, and suggests that multiple producing zones may have contributed to the fluids sampled during the long-term flow test. The noncondensible gas content (NCG) varied from 0.57 to 0.39 mass percent, depending on flow rate, with CO_2 comprising more than 98 percent of the NCG. The Na-K-Ca geothermometer calculated for fluids from the December 1985 flow test (6,000-6,227 ft; 1,829-1,898 m) gives a temperature of 590°F (310°C), close to the measured 581°F (305°C). The concentrations of four metals (arsenic, barium, lead, and zinc) exceed the California Department of Health Services soluble threshold limit concentrations (STLC) and must be considered potentially hazardous for surface disposal.

OTHER STUDIES

A variety of other studies were completed during the SSSDP that did not focus on temperature and heat flow, production testing or fluid chemistry. Seismic monitoring of the June 1988 flow test did not detect microearthquakes of magnitude 0.0 or larger. A vertical seismic profile (VSP) completed in State 2-14 appears to have detected the "cap rock" zone, the top of the fractured reservoir, and the presence of fracturing near 3,000 ft (915 m). A borehole-gravity survey produced a gravimetric-density log for the interval 3,369-5,699 ft (1,027-1,737 m) that is in general agreement with densities determined from the gamma-gamma log. Coupled with surface gravity data, lateral density changes away from the borehole were also inferred.

The SSSDP provided an opportunity for testing downhole fluid samplers under adverse borehole conditions, and for testing the Battelle Pacific Northwest Laboratories on-stream particle meter. These tests showed that several modifications were needed to improve the reliability of the equipment. A downhole-recording digital temperature tool with sensitive components housed in a dewar container (built by Madden Systems, Inc.) proved capable of repeated logs with high data density, rapid response, and good reproducibility. Rock property and fluid-transport studies were also completed. The chemistry of scale deposits was studied by Idaho National Engineering

Laboratory. Brookhaven National Laboratory used State 2-14 brine residue samples to investigate the use of acidophilic microorganisms as active agents in the detoxification of geothermal brine residues. 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.

SITE RESTORATION

Waste materials resulting from the drilling and reservoir testing of well State 2-14 included drilling muds and geothermal fluids (brines). Drilling muds were placed in a mud sump located near the wellhead and geothermal brines were discharged into a holding pond located 300 ft (91 m) east of the wellhead, across Davis Road. The geothermal fluids were high in total dissolved solids, including several heavy metals, and these precipitated and settled out, leaving a salt crust, liquid brine and a sludge in the brine pond. Phase-2 work conducted by Bechtel included site cleanup and restoration that would leave the mud sump and brine pond ready for reuse, as a condition of returning the site to the leaseholder. Cleanup activities were conducted to comply with regulations adopted by the California Regional Water Quality Control Board (CRWQCB), because some samples from the brine pond exceeded the STLC in arsenic, barium, lead and zinc.

Sampling of the brine pond, evaluation of the analytical results, and processing and disposal of the brine-pond waste at the IT Corporation waste-disposal site near Westmoreland, all proved difficult, and accounted for a significant part of the total cost of the SSSDP. The wastes were ultimately classified as nonhazardous, subject to further analysis at the disposal site. The salt crust was removed mechanically, and the brine and sludge centrifuged. The processed fluid was injected into the Imperial 1-13 well, and fly ash was added to the processed sludge prior to shipment to the IT waste-disposal site. The estimated total direct cost to DOE for site cleanup was $660,900, about 7 percent of the total $9,488,000 prime contract to Bechtel. Additional project cleanup costs were offset by cost shares from Kennecott ($40,000) and Bechtel National, Inc. ($55,000).

RESULTS

More than 50 scientists and several major science organizations participated in the SSSDP. A conservative estimate of the associated science costs would exceed $1,000,000, suggesting a total cost for the SSSDP in excess of $10,500,000. The resulting data have been the subject of five technical sessions at three international scientific meetings and the topics of more than 40 technical papers. Additional technical papers can be expected in future years, as other researchers are able to use the cores and well cuttings from the archives. Modified versions of the successful management system developed for this effort are now being used to manage other scientific drilling projects of the national Continental Scientific Drilling Program. Well State 2-14 was released to the leaseholder and subsequently sold to another geothermal power producing firm. The well was demonstrated to have a high productivity, being capable of flow rates greater than 800,000 lbm/hr (363,000 kg/hr) at 250 psig (1,724 kPa) wellhead pressure. At this flow rate, State 2-14 could produce 12 MWe in a dual-flash power plant.

UNITS OF MEASURE

A dilemma encountered during preparation of this final report concerns the system of units for reporting technical data. The U.S. Department of Energy is committed to use of the International System of Units (SI) for technical reporting. Most of the engineering, drilling, geophysical logging and production testing completed in the SSSDP was completed using English or mixed English and metric units. Many of the resulting technical reports however, express the technical data in SI units.

Most of the Executive Summary of this report has been completed using dual English-(SI) units, but this is impractical for the full text and would undoubtedly introduce some error in conversion, roundoff, etc. A number of illustrations, tables, and appendices have been incorporated into this report without change, in an attempt to expedite reporting. For this reason, and to encourage a through reading by drilling and engineering segments of the geothermal industry, this report will incorporate the usage of original reports and data, with selective use of dual units. A table of conversion factors is included here to facilitate the understanding of all the units used.

CONVERSION FACTORS

Length:	1 centimeter (cm) = 0.3937 inch (in.) 1 meter (m) = 3.281 feet (ft) 1 kilometer (km) = 0.6214 mile (mi)
Area:	1 m^2=10.76 ft^2 1 km^2=0.3861 mi^2
Volume:	1 liter (L)= 0.2642 gallon (gal) 1 km^3=0.2399 mi^3
Mass:	1 kilogram (kg)=2.205 pound (lb)
Pressure:	1 kPa= 6.8960 lb/in.^{2} (psi)
Flow rate:	1 L/s = 15.85 gal/min 1 kg/hr = 0.4536 lbm/hr
Temperature:	degrees Celsius (°C)=5/9 (degrees Fahrenheit [°F]-32) Kelvin (K)=°C+273.15
Temperature gradient:	1°C/km=0.05486°F/100 ft
Energy:	1 joule (J)=0.2390 calorie (cal) 1 J=9.485x10^{-4} British thermal unit (Btu) 1 J=2.777x10^{-4} watt-hour (W•hr) 10^{18} J=0.9485 quad (10^{15} Btu) 1 MW$_t$ for 30 yr=9.461x10^{14} J
Power or work:	1 watt (W)=1 J/s 1 megawatt (MW)=3.154x10^{13} J/yr

Heat flow: 1 mW/m^2=2.390x10^{-8} cal/cm^2•s
1 mW/m^2=2.390x10^{-2} heat-flow unit (HFU)

Thermal conductivity: 1 W/m•K=2.390 mcal/cm•s•°C

ABBREVIATIONS: UNITS OF MEASURE

Abbreviation	Meaning (area used)
bbls	barrels
BPM	Barrels per minute
Btu	British thermal unit (energy)
hp	horsepower (work)
Hz	Hertz (frequency)
kPa	kiloPascals (pressure)
kW	kilowatts (power)
lbm/hr	pounds-mass per hour (flow rate)
md-ft	millidarcy-feet (permeability)
MPa	MegaPascals (pressure)
MWe	Megawatts - electricity (energy)
MWt	Megawatts - thermal (energy)
mW/m^2	milliwatts per meter^2 (heat flow)
μD	microDarcies (permeability)
ppb	parts per billion
ppg	parts per gallon
ppm	parts per million
psia	pounds per inch^2 - absolute (pressure)
psig	pounds per inch^2 - gauge (pressure)
spm	strokes per minute
Th	Temperature of homogenization

ACRONYMS

Acronyms commonly used in the drilling industry or associated with the Salton Sea Scientific Drilling Project appear frequently throughout this report. A complete listing of acronyms used follows. A table of drilling acronyms is also included in Appendix B.

TABLE OF ACRONYMS

AC;DC	alternating current; direct current
AIC	Adjusted Indirect Costs
ANSI	American National Standards Institute
API	American Petroleum Institute
ASTM	American Society of Testing Materials
BHA	bottom-hole assembly
BHT	bottom-hole temperature
BNI	Bechtel National, Inc.
BNL	Brookhaven National Laboratory
BOPE	Blowout Prevention Equipment
BTC	Bow-type centralizers
CAM	California Assessment Manual
CDOG	California Division of Oil and Gas
CRWQCB	California Regional Water Quality Control Board
CSH	cotton-seed hulls
CSP	cotton-seed pellets
DOE	Department of Energy
/GD	/Geothermal Division
/GTD	/Geothermal Technology Division
/OBES	/Office of Basic Energy Sciences
/SAN	/San Francisco Operations Office
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute
HDR	hot dry rock
HP	High Pressure
I.D.	inside diameter
IID	Imperial Irrigation District
INEL	Idaho National Engineering Laboratory
IT Corp.	International Technology Corporation
JGR	Journal of Geophysical Research
LANL	Los Alamos National Laboratory
LBL	Lawrence Berkeley Laboratory
LCM	lost-circulation material
LLNL	Lawrence Livermore National Laboratory
NCG	noncondensible gas
ND	natural diamond
NET	National Environmental Testing, Inc.
NSF	National Science Foundation
PBR	polished-bore receptacle
PD	polycrystalline diamond
PDM	positive displacement motor
POH	pull out of hole
PNL	Battelle Pacific Northwest Laboratory
QAL	Quality Assurance Laboratory

RCRA	Resource Conservation Recovery Act
RIH	run in hole
RTD	platinum resistance thermometer
SBB&M	San Bernadino Base and Meridian
SCC	Site Coordination Committee
SEM	Scanning Electron Microscope
SI	Le Système International d'Unites
SP	sponteneous potential
SRS	Separation and Recovery Systems
SSGS	Salton Sea Geothermal System
SSSDP	Salton Sea Scientific Drilling Project
STLC	soluble threshold limits concentrations
TD	total depth
TDS	total dissolved solids
TPCA	Toxic Pit Cleanup Act
TTLC	total threshold limits concentrations
UCR	University of California-Riverside
USGS	United States Geological Society
UURI	University of Utah Research Institute
VSP	vertical seismic profile
WHP	wellhead pressure
WHT	wellhead temperature
WOC	wait on cement

ACKNOWLEDGEMENTS

A large number of scientists and engineers contributed to the technical data and other information presented in this final report. Much of this report is abstracted from preliminary reports completed by Bechtel National, Inc., the prime contractor for the SSSDP. Reports by several subcontractors, identified in the text, were abstracted to provide important sections of the report. Memoranda, correspondence, and interim reports of the Department of Energy/San Francisco Operations Office (DOE/SAN) and the DOE Geothermal Division (DOE/GD) were made available to the editor and have been used extensively.

The editor gratefully acknowledges the personal insight, information, editing, and encouragement provided by Allan Jelacic and Marshall Reed of DOE/GD, and Raymond Wallace of USGS. This report has benefited from the careful review and comments of several reviewers. The editor especially wishes to acknowledge the thoughtful comments of Paul Kasameyer and Steve Pye. Several tables and figures have been reproduced from the Journal of Geophysical Research, volume 93, B11, 1988, published by the American Geophysical Union. Allan Jelacic provided photographs for the cover and Chapter 12. Merrianne Tolbert (UURI) provided word processing support and Robert Turner (UURI) provided drafting services.

This report was prepared with the support of the U.S. Department of Energy (DOE), Contract No. DE-AC07-90ID12929. However, any opinions, findings, conclusions, or recommendations expressed herein are those of the editor and do not necessarily reflect the views of DOE.

1.0 INTRODUCTION

1.1 ORIGIN

The Salton Sea Scientific Drilling Project (SSSDP) originated with the desire by scientists studying hydrothermal processes to directly observe temperatures and to sample fluids deep within an active geothermal system. In the fall of 1982, Dr. W. A. Elders, University of California (Riverside), proposed to the National Academy of Sciences to drill a series of research boreholes in the Salton Sea geothermal system of California (SSGS), one of the largest and hottest geothermal fields in the world (Figure 1.1). Although the proposal received widespread support from fellow scientists, funding was not immediately available from the United States Geological Survey (USGS), the National Science Foundation (NSF), or the Department of Energy (DOE), for such an undertaking. The U. S. Congress added $5.9 million for Phase 1 of the SSSDP to the 1984 budget of the Department of Energy - Geothermal Technology Division. Additional funding was later provided by the USGS, NSF, and DOE.

The SSSDP was the first major project performed under the Interagency Accord on Continental Scientific Drilling, a cooperative agreement among the Department of Energy, the U. S. Geological Survey, and the National Science Foundation.

1.2 PURPOSE AND OBJECTIVES

The primary objectives of the project were to:

- Explore the roots of the Salton Sea Geothermal System by drilling into a hotter part of the system than had previously been drilled;
- Collect and place in the public domain samples and data, including core, cuttings, geothermal fluids and gases, and geophysical logs, including temperature and pressure surveys.

1.3 PROJECT FORMATION AND SITE SELECTION

Although the major scientific objectives of the project were well defined, the drilling of a deep well into a very hot geothermal system, with provision for research experiments, constituted a major engineering effort and required an appropriate site within a major geothermal resource. Funding was obtained from Congress with the intent, and the agreement of Republic Geothermal, to deepen an existing geothermal well in the Niland area from 12,000 to 18,000 ft. Control of the wells in the Niland area, on the eastern margin of the Salton Sea geothermal anomaly, transferred from Republic Geothermal to Parsons Corporation in 1983, and the agreement to deepen the well was voided. To most closely follow the intent of Congress, DOE decided to solicit proposals to drill a new deep test well and an associated injection well in the Salton Sea geothermal system. The DOE, San Francisco Operations Office (DOE/SAN) issued a solicitation for the SSSDP (Number DE-RP03-84SF12194) inviting proposals from contractors to perform the work and from resource-permit holders who could provide a site for the project in the Salton Sea Geothermal Field. In May 1984, DOE selected Bechtel National, Inc. (Bechtel), a major engineering company, to drill the deep scientific borehole on a site proposed by Kennecott, Inc., a resource company with exploration permits in the SSGS.

In response to the original solicitation, Kennecott proposed to provide two well sites for which it

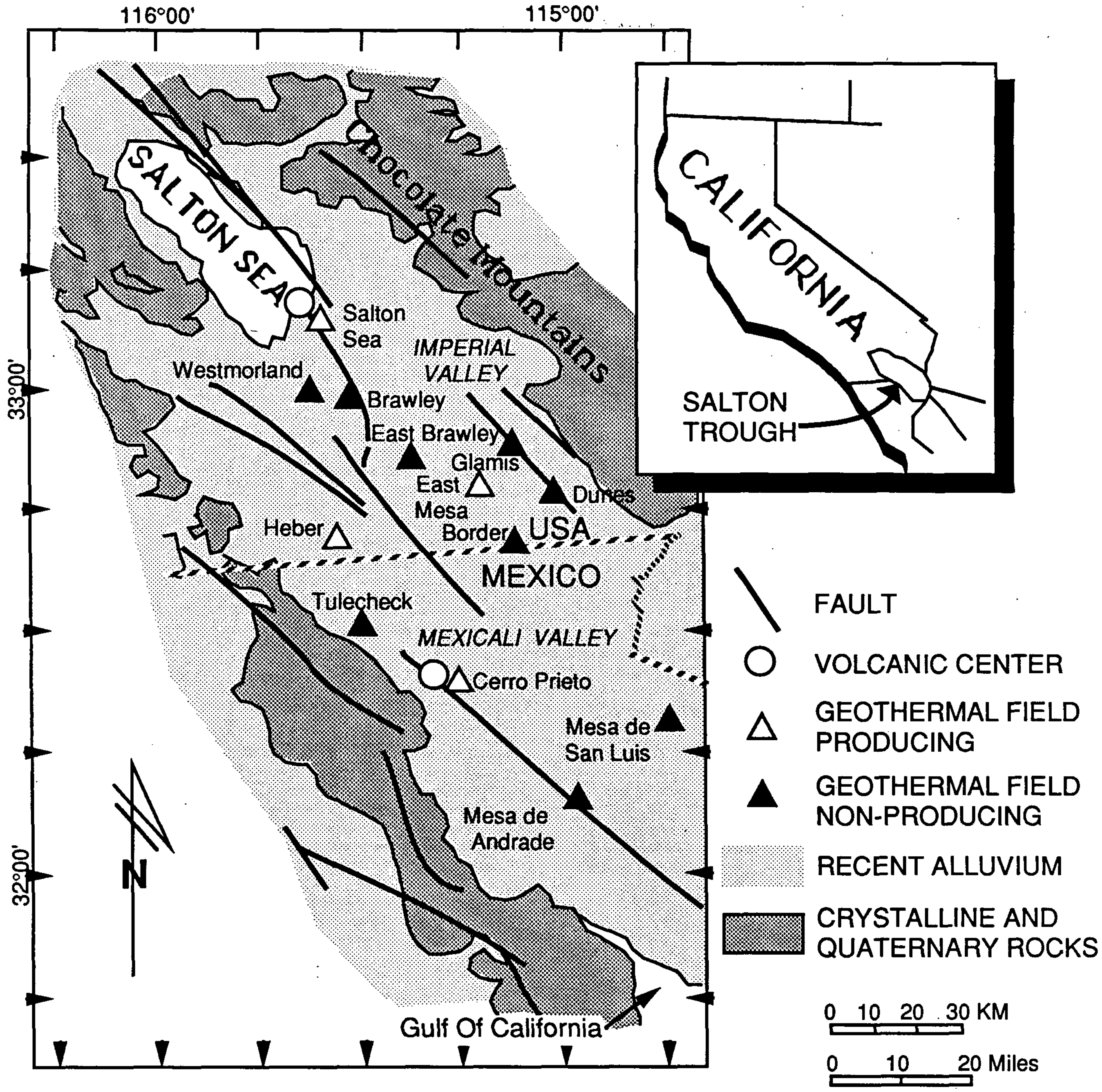


Figure 1.1. **Location and geological setting of the Salton Sea Geothermal System** (Elders and Sass, JGR v.93, B11, 1988, copyright by the American Geophysical Union).

had previously secured drilling permits, one for deep drilling and the other for reinjection of spent brine. The project site (Figure 1.2) is located in the southeast corner of Section 14, Township 11 S, Range 13 E, near the intersection of McDonald and Davis Roads, approximately 225 ft (68.6 m) below sea level. This site is in the northeastern part of the Salton Sea Geothermal Field, within one mile of five previously drilled wells, several of which have subsequently been inundated by the rising level of the Salton Sea. The well site originally proposed as an injection well, State 2-14, became the primary well when the proposed injection well was deleted from the project due to budgetary limitations. Kennecott provided use of the property on the east side of Davis Road for a brine storage pond. Additional site details are presented in Section 4.

The well site is located in the easternmost part of two former brine storage ponds that had been allowed to flood by previous lease holders prior to the start of this project. One of the first steps in site preparation was to repair the dike and pump the pond dry. The southern half of the pond, where well 2-14 was sited, is owned by the State of California. Kennecott had exploration rights to the property via their Prospecting Permit No. 6378 with the State Lands Commission. In exchange for making this site available for the SSSDP and for providing all of the necessary permits except the drilling permit, Kennecott required that a flow test or tests be performed. Data from the test(s) would be made available to Kennecott, as appropriate, for use in converting their exploration permit to gain a preferential right to lease the property. Kennecott actively monitored the progress of the project, providing on-going assistance with regulatory and other matters.

As the prime contractor, Bechtel National, Inc., in association with Kennecott Corporation, was responsible for overall project management. Bechtel's responsibilities included planning, design, and drilling of the well, provision of surface facilities and site support, environmental monitoring, preliminary resource evaluation, and reporting to the DOE. The project provided opportunities to scientists from many organizations for collection of samples and data within the limitations of technical feasibility, safety, well integrity, and project budget.

The SSSDP was completed as a two-phase project from October 1985 to February 1989. The main objectives for Bechtel's Phase-1 scope of work were:

- Drill to an initial depth of 4,000 ft (1,220 m), where the 572°F (300°C) isotherm was expected, and then drill an additional 6,000 ft (1,830 m);
- Take cores at depths selected by science management, up to a total cost to the project of $1 million;
- Provide at least 250 hours in the drilling schedule for downhole investigations, including logging and fluid sampling;
- Conduct three, limited, flow tests in the course of drilling:
  - from the first lost-circulation zone below 3,000 ft (914 m);
  - from the first lost-circulation zone below 6,000 ft (1,830 m);
  - at total depth of the well;
- Provide collection stations for liquid and gas sampling during the flow tests;
- Acquire selected commercial geophysical logs to support research logging to be performed by the USGS;
- Place the site on a 6-month, post-drilling standby with the well shut in, providing access for scientific study, such as temperature and pressure-buildup monitoring.

Phase-2 additions to the Bechtel scope of work included:

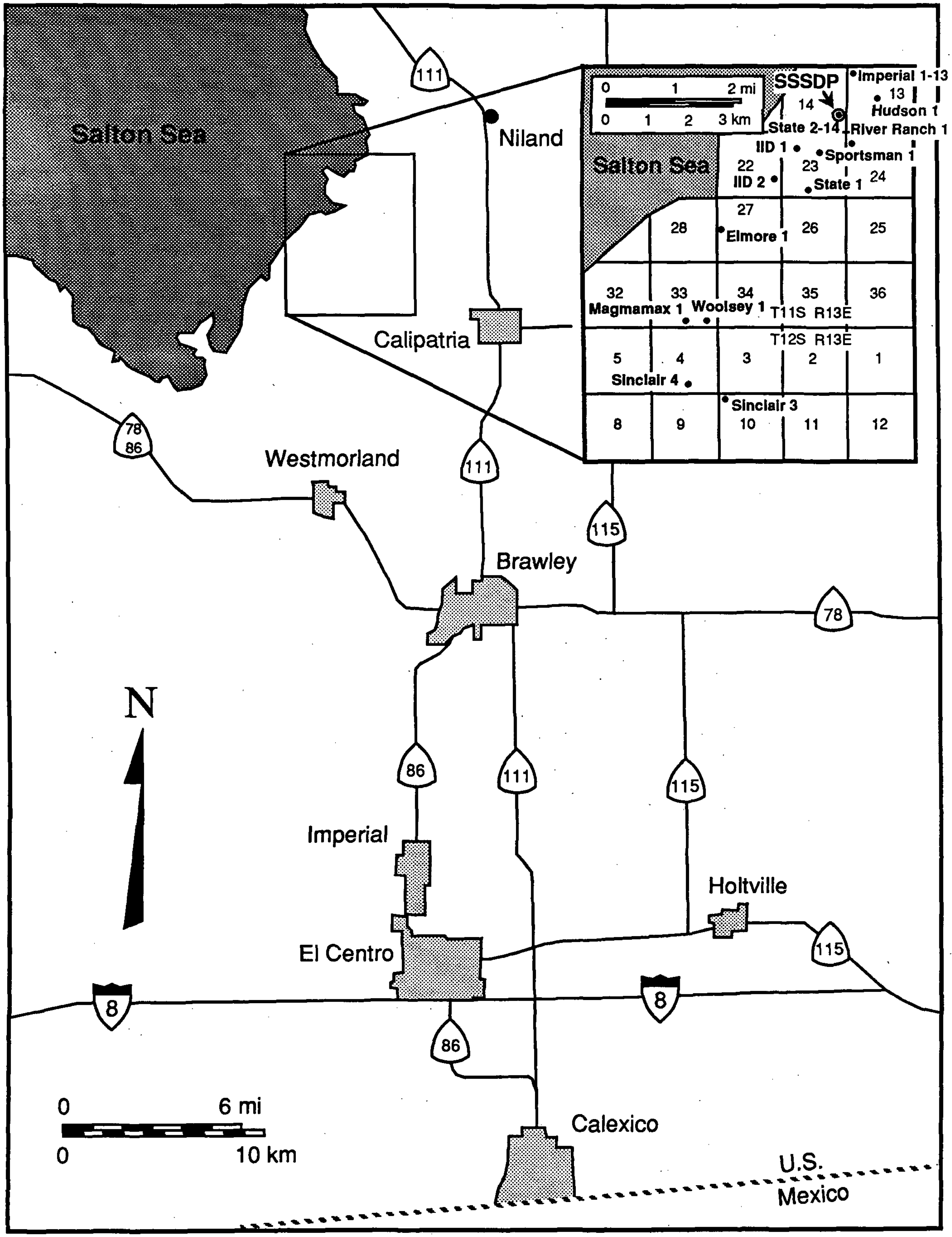


Figure 1.2. SSSDP project site location

- Rework of the well in August 1987 to reestablish a passageway to the bottom of the hole and to isolate production zones above 8,000 ft (2,440 m) with a new 7-in. liner cemented in place from approximately 5,700 to 8,600 ft (1,739 to 2,623 m);

- Construct facilities for a well-flow test of 30-days duration;

- Conduct a 30-day well-flow test of the deep flow zones;

- Clean up and return the site to Kennecott.

While several of the major operational and scientific objectives of the SSSDP were achieved (Table 1.1), budget limitations forced the project, in general, to settle for lesser accomplishments. Preliminary and extended flow tests indicated an economic production potential for well State 2-14, as shown in Table 1.2. The well was spudded in on October 23, 1985, and in the following 160 days was drilled to a depth of 10,564 ft. Approximately 730 ft of core sample was recovered, flow tests were completed, and the site restored to a condition ready for reuse. Several hundred scientists and engineers from more than 40 different laboratories and other organizations participated in the overall project.

1.4 FINAL TECHNICAL REPORT

This report is submitted as the final technical report for the SSSDP project. Most of the scientific results of the SSSDP have already been published, including 18 papers in a special issue of the Journal of Geophysical Research (JGR,1988). The project management, drilling, engineering, and other aspects of the project have not been previously reported in final form and are not readily available, and the site restoration activities are not reported elsewhere. This report presents an integrated summary of all major aspects of the SSSDP, describes the technical and scientific results in brief, and indicates the availability of technical publications, engineering studies, and other publications, reports, and open-file data.

Much of the information presented here is taken from two (draft) final reports written by Bechtel National, Inc. for Phase 1 and Phase 2 of the SSSDP (Bechtel, 1987; 1988). This report describes Phase 1 and Phase 2 activities in a single volume and identifies subcontractor reports, open-file data, and scientific publications for more detailed study. The emphasis of this report is on engineering, management, and project integration rather than scientific results, since these are described in much greater detail elsewhere.

Appendix A of this report provides a listing and brief description of all reports submitted to Bechtel (1987, 1988) in connection with the conduct of Phase 1 and Phase 2. These reports are referred to frequently but are not included as part of this report. Copies of these reports are available on a limited basis, and at cost for reproduction, from the SSSDP Archivist, the University of Utah Research Institute (Appendix A).

Table 1.1

SALTON SEA SCIENTIFIC DRILLING PROGRAM MAJOR OBJECTIVES

	Objective	Achieved
Depth, ft	10,000	10,564
Coring, ft	1,000	730
Logging, hrs	250	487
Flow tests	3	2
Schedule, days	160	160

Table 1.2

SALTON SEA SCIENTIFIC DRILLING PROGRAM PRELIMINARY FLOW-TEST RESULTS

	Flow Zone(s) depth (ft)	Flow Rate (lbs/hr)	Wellhead Temperature (°F)	Wellhead Pressure (psig)	Estimated Enthalpy (Btu/lb)
First Test	6,120	600,000	400	200	400
		80,000	460	440	400
		430,000	410	220	400
		150,000	460	450	400
Second Test	6,100	475,000	445	310	520
	6,600	280,000	475	450	480
	8,800	700,000	460	380	480
	10,475	300,000	490	485	450

1.5 REFERENCES (ABSTRACT, EXECUTIVE SUMMARY, SECTION 1)

Bechtel National, Inc., March 1987, Salton Sea Scientific Drilling Program - Drilling and Engineering Program: (Draft) Final Report, Prepared for U.S. Department of Energy, 98 p.

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.

Elders, W.A., 1985, Continental Scientific Drilling in California: The Saga of the Salton Sea Scientific Drilling Project (SSSDP): Geothermal Resources Council Transactions, Vol. 9, Part I, pp.107-112.

Elders, W.A. and Sass, J.H., 1988, The Salton Sea Scientific Drilling Project: Its Scientific Significance: J. Geophys. Res., Vol. 93, No. B11 pp. 12,953 - 12,968.

Herzig, C.T., Mehegan, J.M., and Stelting, C.E., 1988, Lithostratigraphy of the State 2-14 Borehole: Salton Sea Scientific Drilling Project: J. Geophys. Res., Vol. 93, No. B11 pp. 12,969 - 12,980.

Sass, J.H., Priest, S.S., Robinson, L.C., and Hendricks, J.D., 1986, Salton Sea Scientific Drilling Project On-Site Science Management: U. S. Geol. Surv. Open-File Report 86-397, 24 p.

2.0 PROJECT MANAGEMENT

2.1 MANAGEMENT ORGANIZATION

The management of such a complex undertaking as the SSSDP required extensive coordination within and between each of the major project groups, including scientific activities, drilling and engineering operations, and other project participants. The original management structure established for the project is summarized in Figure 2.1 (see Adduci et al., 1986, and Sass et al., 1986). The overall planning, integration, resolution of policy issues, and assessment of progress were achieved through the interagency Executive Steering Committee. Evaluation of proposals for scientific investigations and the recommendation of those to be funded and incorporated into the science program were made by the Scientific Experiments Committee. The interagency Science Coordinating Committee worked to resolve issues concerning priorities for scientific experiments and funding. The recommended science program content was transmitted through the Executive Steering Committee to the Drilling and Engineering Program Management Office, directed by DOE's Geothermal Technology Division and the San Francisco Operations Office. The engineering team received direction on the desired program content largely through proposed scope of work changes. Feedback was provided by the contractor on the technical feasibility and costs of various parts of the proposed science program for consideration by each group back through the management chain. In some cases, reprioritization, modification, or deletion of proposed activities occurred. This iterative process led to the consensus program which was in place when drilling began. The consensus program compromise balanced scientific objectives that were deemed to be of greatest importance and established limits on expenditures.

2.2 SITE COORDINATION COMMITTEE

Once drilling began, however, the day-to-day management and resolution of problems shifted increasingly to the site. As shown in Figure 2.2, representatives of the scientific activities, drilling and engineering operations, and industry were brought together on-site. A standing committee known as the Site Coordination Committee was formed, chaired by the site manager, and included the on-site science manager, drilling supervisor, drilling foreman, drilling engineer, and the DOE on-site drilling and engineering consultant. This committee met each morning, or more frequently if required, to review operating status, identify problems, develop solutions, and plan for the day's work activities.

Off-site management personnel, the chief scientist, and the Kennecott representative were automatically invited to attend, whenever they visited the site. Subcontractor representatives and other guests were invited to attend, when appropriate. This group became the focal point for implementing the science plan and integrating it into the constraints of engineering and drilling activities. Reporting lines to the various off-site management committees extended from the on-site science manager through the chief scientist for the science activities, and from the DOE on-site consultant through the DOE/San Francisco project manager for drilling and engineering operations.

Morning meetings of the Site Coordination Committee were held to:

- Review the prior day's results, including drilling reports, science activities, and costs incurred;
- Plan the day's events, including requests from the on-site science manager for coring, logging, or other science activities;

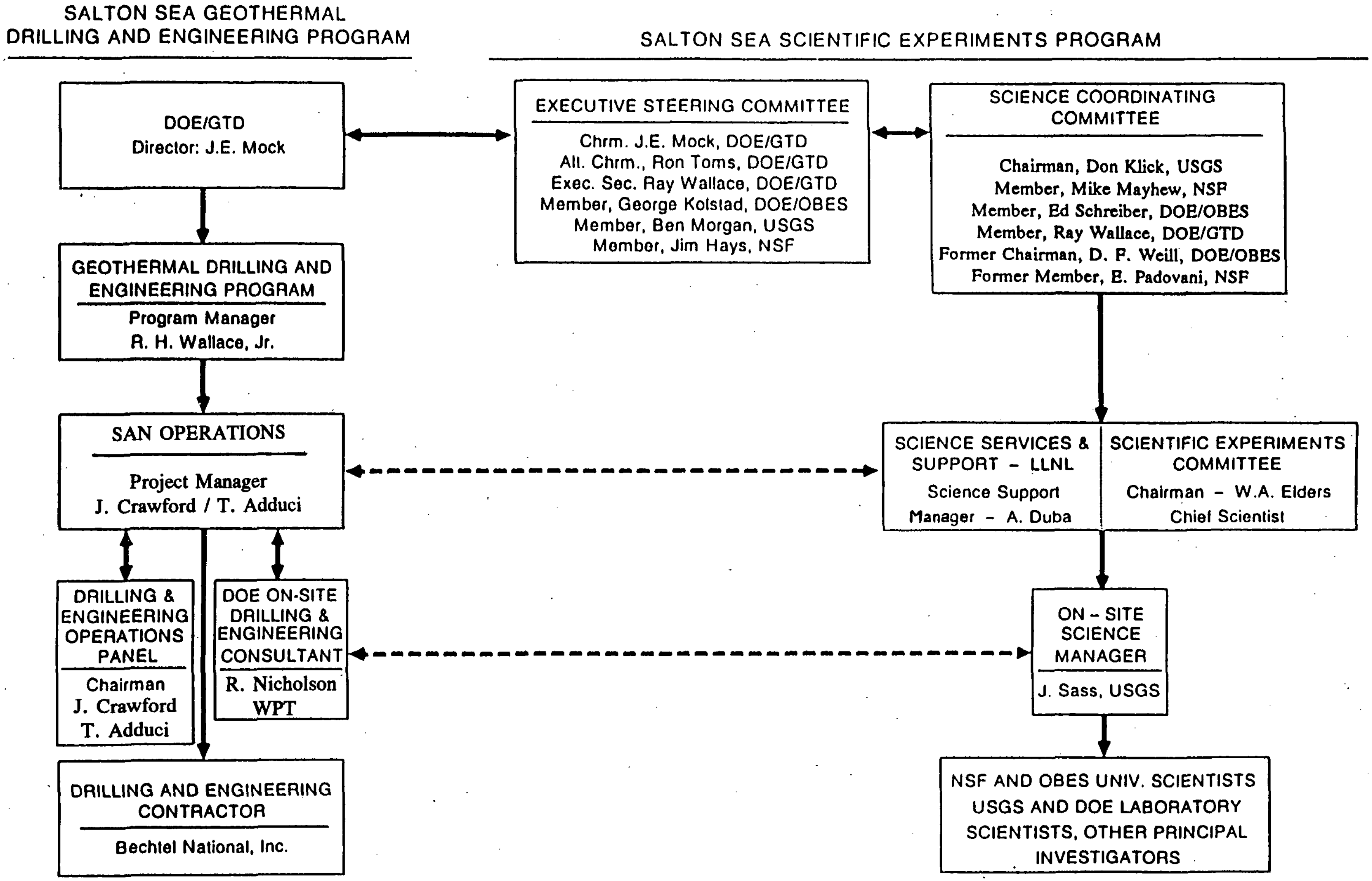


Figure 2.1 SSSDP Management Structure

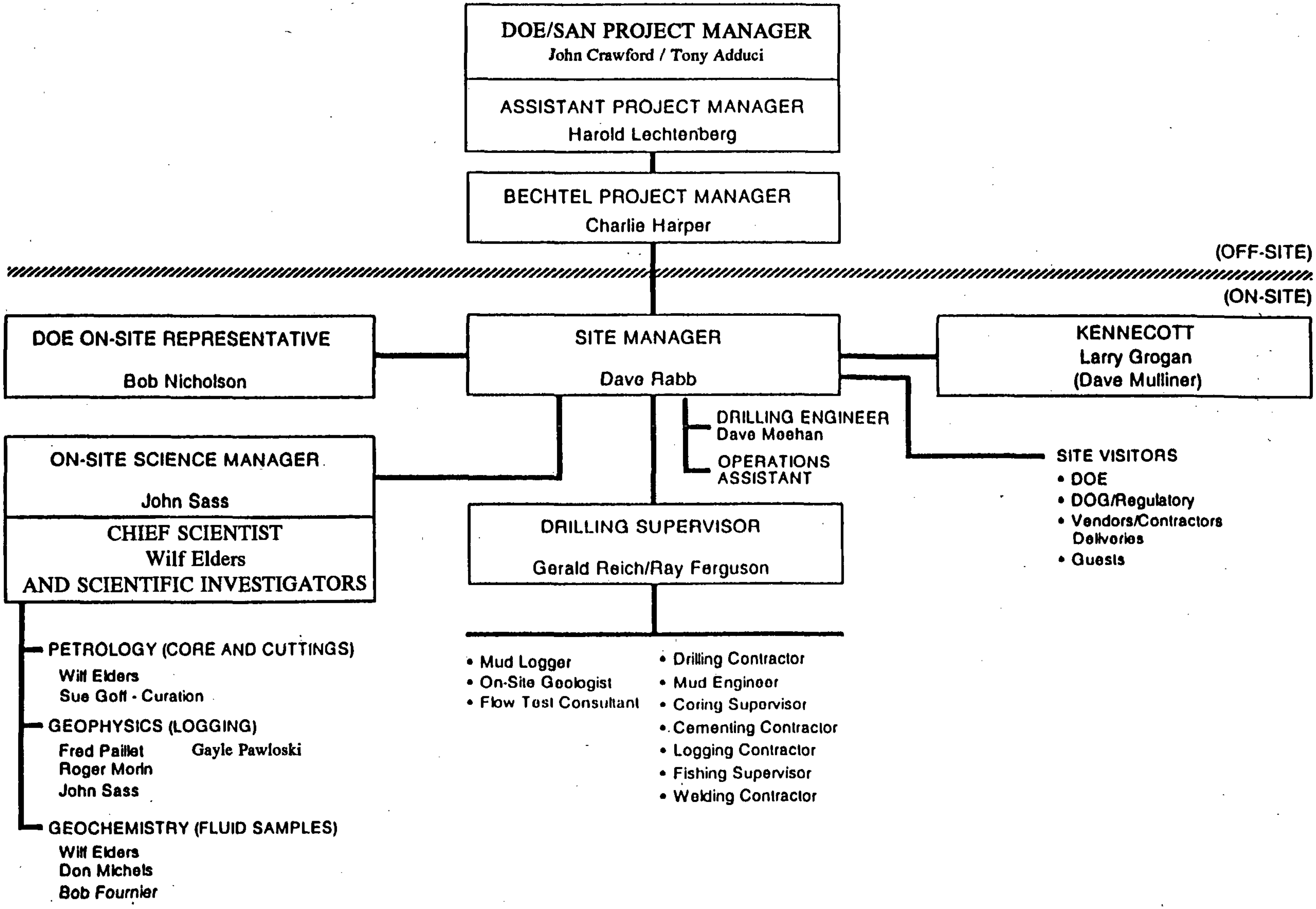


Figure 2.2 SSSDP On-Site Organization

- Investigate special problems that had developed or were anticipated;
- Schedule major upcoming events;
- Review any safety or coordination problems.

At each meeting, the drilling supervisor turned in his morning report, the drilling contractor's tour report, drilling recorder charts, mud log, mud engineer's report, coring engineer's report (if any), geology summary, geophysical logs (if any), and all field invoices and usage estimates from other subcontractors. The on-site science manager made available any data or logs taken. Copies of all material, except the invoices, were made available to the other members of the committee and to Kennecott.

The effectiveness of operation of the Site Coordination Committee (SCC) eventually caused the Executive Steering Committee to delegate increased site-operational authority to the SCC. This further encouraged cohesive and timely decision making.

2.3 SUBCONTRACTORS

Over 60 subcontracts and purchase orders were established for drilling and for engineering support during the project. Drilling and service contractors and equipment suppliers were selected by competitive bidding.

2.4 QUALITY ASSURANCE

The Bechtel quality assurance program, including procedures, was prepared in response to DOE Order 5700.6A. Originally prepared for a project of larger scope, the program was reissued after the project's scope was reduced. Eventually, eleven procedures were issued and implemented for the project.

As the project evolved, the programmatic-procedural approach was found to be weak in several areas and additional efforts were required to implement appropriate controls. The relatively small size, remote location, and rapid pace of the project were primary contributors to the problems encountered. The following quality assurance lessons were learned and are offered for consideration to similar projects:

- Procurement Specifications — Separate control, review, and approval of procurement specifications and requisitions were found to be redundant and time consuming. It was determined that all necessary technical and quality requirements could be satisfied and controlled by a single control, review, and approval of requisitions, with an adequate text or specification attached.
- Supplier Submittals — Because of the small number of project personnel, it was found that a much simpler vendor document-control approach was beneficial. A correspondence-control system was used to accomplish the necessary tracking, along with a modified subject filing system.
- Procurement Actions — Because of the rapid pace, formal procurement actions lagged the project actions. Simplifying the project procurement documentation reduced the lag period.

- Engineering Procurements — Problems were encountered with one engineering procurement. Although procedural and programmatic controls were adequate, inspection or assembly of parts at the fabrication shop could have avoided field problems.

- Communication — Project field conditions were difficult on the SSSDP job. Field personnel were assigned on a rotating basis, thus creating a need for communication between personnel assigned to different periods. Incoming personnel accomplished this by reviewing the previous day's logs for drilling, coring, and logging, and by briefings from the outgoing personnel.

2.5 REFERENCES

Aducci, A.J., Klick, D.W., and Wallace, R.H., Jr., 1986, Management of the Salton Sea Scientific Drilling Program: Geothermal Resources Council Transactions, Vol. 10, pp.445-448.

Sass, J.H., Priest, S.S., Robinson, L.C., and Hendricks, J.D., 1986, Salton Sea Scientific Drilling Project On-Site Science Management: U.S. Geol. Surv. Open-File Report 86-397, 24p.

3.0 OPERATION AND SAFETY PROCEDURES

3.1 SAFETY PROGRAM

All major engineering projects, including drilling activities, are undertaken with some element of risk to personnel health and safety. The preparation and implementation of operation and safety procedures laid the framework for orderly, safe activities.

The Site Procedures Manual, (Report V of Appendix A; Bechtel, 1987), explained the roles and responsibilities of the primary on-site personnel and established operating guidelines. The manual was endorsed by the DOE/SAN Program Manager, the Bechtel Site Manager, the On-Site Science Manager, and the Chief Scientist. Individual copies were given to all "full-time" personnel who were stationed at, or who repeatedly visited, the site.

The same group of people also received a Health and Safety Manual, (Report W, Appendix A; Bechtel, 1987). This manual contains safety rules and personnel guidelines to minimize the chances of accidents and injuries. An emergency contingency plan was included, providing action plans in case of loss of well control or other major accident. Day visitors to the site received a Visitor Safety Procedures handout, (Report X, Appendix A; Bechtel, 1987), which presented a condensed list of basic safety rules. Each guest was assigned a sponsor from among the full-time personnel, who was responsible for providing an orientation briefing and providing basic safety equipment.

The program was completed accident-free. There were no lost-time accidents or injuries requiring physician's care.

3.2 REFERENCES

Bechtel National, Inc., March 1987, Salton Sea Scientific Drilling Program — Drilling and Engineering Program: (Draft) Final Report, Prepared for U.S. Department of Energy, 98 p.

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.

4.0 DRILLING ENGINEERING AND FACILITIES DESIGN

4.1 DRILL PAD AND SITE LAYOUT

The permitted site of State 2-14 was 1,020 ft north and 230 ft west of the southeast corner of Section 14, Township 11 South, Range 13 East, San Bernadino Base and Meridian (Figure 4.1). This location is approximately five miles southwest of Niland, California, near the intersection of Davis Road and McDonald Road (Figure 1.2).

The well site was in an abandoned evaporation pond. The pond contained 1 in. to 2 ft of salt water from the Salton Sea that had entered via three breaches in a dike located 770 ft west of the well site. In March 1985, the breaches in the dike were repaired and the site was pumped dry.

Prior to drying the site, surface corings to 80 ft-depth were taken to establish soil stability at the site. The soils were soft, saturated clay with some layers of fine- to medium-grained silty sands at greater depths. The soil was very moist and saturated below 3 ft in all borings. Horizontal bedding indicated that the soil was formed by ancient fresh- and salt-water lake deposits. A sample taken at the well site, while still covered with water, showed 2 in. to 4 in. of blackish "slime" followed by approximately 2 ft of saturated, suspended clay-soil, termed "muck." The clay soils below the "muck" layer were consolidated, with moisture contents similar to the 80 ft corings.

Triaxial compression tests indicated that the upper soil had an allowable bearing capacity of 1,000 lb/ft^2 with a factor-of-safety of 3.0 applied to Terzaghi equations. The soils study indicated that the natural soils would allow an unacceptable subsidence under the rig or heavy truck traffic. Consequently, a drill pad was designed based on the load information for the rig, drill pipe, and casing. The drilling pad was constructed to a depth of 5 ft from compacted road-bed material placed over a 50 ft by 60 ft area. Site areas subject to heavy wheel loads were covered with compacted road-bed material, to a minimum depth of 12 in.

Other design requirements, prevailing conditions, and considerations for the site included the following:

- Assembly of the drill rig mast was required to be at least 200 ft from power lines at Davis Road, 250 ft to the east
- Distance required from the well to the mud sump was 40 ft, allowing space for mud coolers and mud tanks
- Adequate distance from the well to the back edge of the mud tanks and mixing platform
- Space for heavy truck turn-around
- Space for five live-in and four service trailers
- Lay-down area for casing, tools, drillpipe, blowout prevention equipment (BOPE), mud and chemicals, and Baker tanks
- Vacuum truck and dragline access to mud pit
- Water table in March 1985 was 4.5 ft below ground level

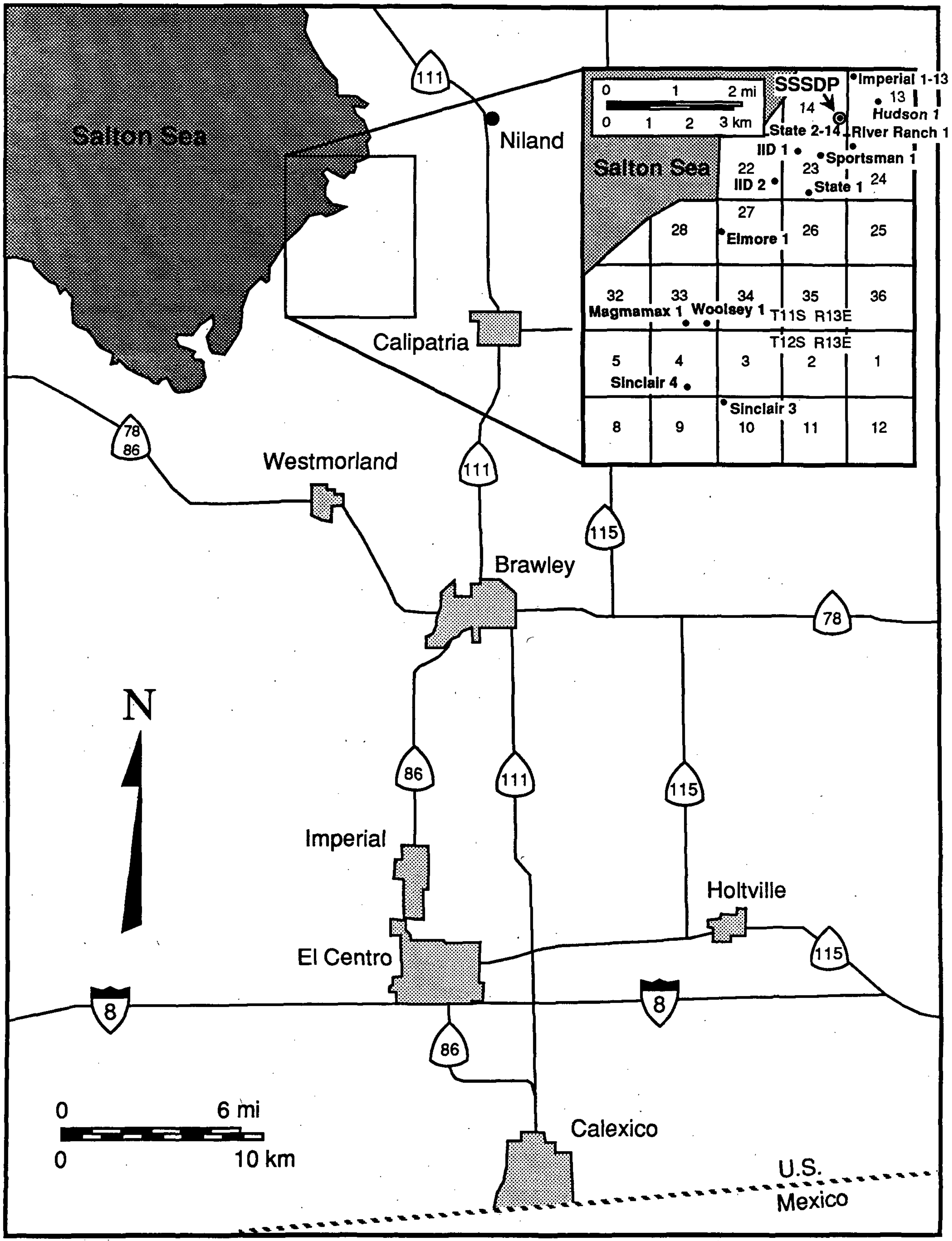


Figure 4.1. State 2-14 well site and nearby wells.

- Mud pit and brine pond permits from the California Regional Water Quality Control Board allowed for 200,000 gallons and 1.1 million gallons, respectively. Other conditions included a 2 ft freeboard and an allowable permeability for temporary fluid storage of 1 x 10^{-6}cm/sec, a condition met by compacted native soils. The permitted locations of the pit and pond were SE1/4, NE1/4, SE1/4 of Sec. 14, T11S, R13E, SBB&M and W1/2, SW1/4 of Sec. 13, T11S, R13E, SBB&M, respectively

- Prevailing wind was from the west

- Core ramada and mud-log trailer were to be close to the rig and near the mud pit to allow water disposal.

The site layout developed to accommodate these design conditions, the flow-test facility, and other personnel requirements, are shown in Figure 4.2. The overall drill site was 350 ft by 350 ft. The mud pit and brine pond were 62 ft by 192 ft (5.5 ft deep) and 112 ft by 287 ft (8 ft deep), respectively. All dikes and pond floors were compacted to 90 percent. Pond excavations were limited to 4 ft or less, because of the shallow water table.

The Cleveland Rig No. 6 layout is shown in Figure 4.3. Specifications for the components of the rig are summarized in Table 4.1.

Power and water supply services were laid out as follows:

- 400 Amp service. Service pole located at the southeast corner of the drill site. Excluding the rig (which provided its own power), all on-site power, either 110 V or 220 V, was provided by the Imperial Irrigation District (IID). All power lines were underground.

- Service water was via the IID P-Lateral feeder canal located at Davis Road and Hazard Road (approximately 1,500 ft north of the site).

4.2 WELL DESIGN

The final configuration of the well is shown schematically in Figure 4.4. Those sections of the original Well Design & Drilling Plan that address formation characteristics and well design are discussed in report D, Appendix A.

Deviations from the original plan were minor and are discussed in the drilling summary section of this report. Two of the changes made were requested by the California Division of Oil and Gas (CDOG) to further improve the design. The first request was that the surface casing be set at 1,000 ft instead of 700 ft; the second request was that a slab gate valve be installed below the blowout preventers, before drilling out of the 13-3/8 in. casing.

4.3 WELLHEAD DESIGN

Two worst-case conditions were employed in calculating the wellhead design and rating:

- A steam column in the wellbore at the bottom-hole temperature (i.e., 715°F)

- A gas (50:50, $H_2S:CO_2$) column in the wellbore to the bottom of the cemented casing (6,000 ft) at an assumed average temperature of 500°F.

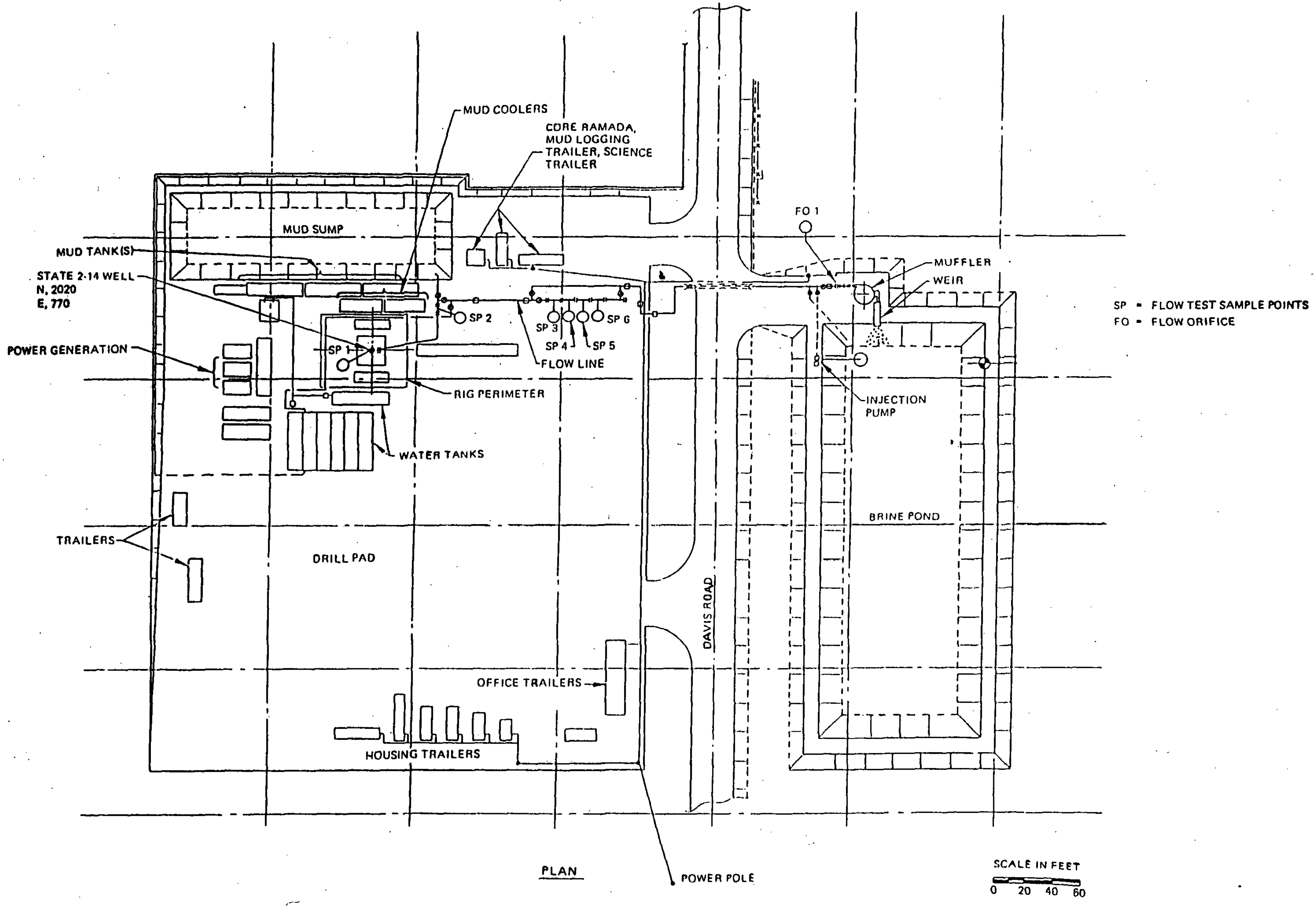
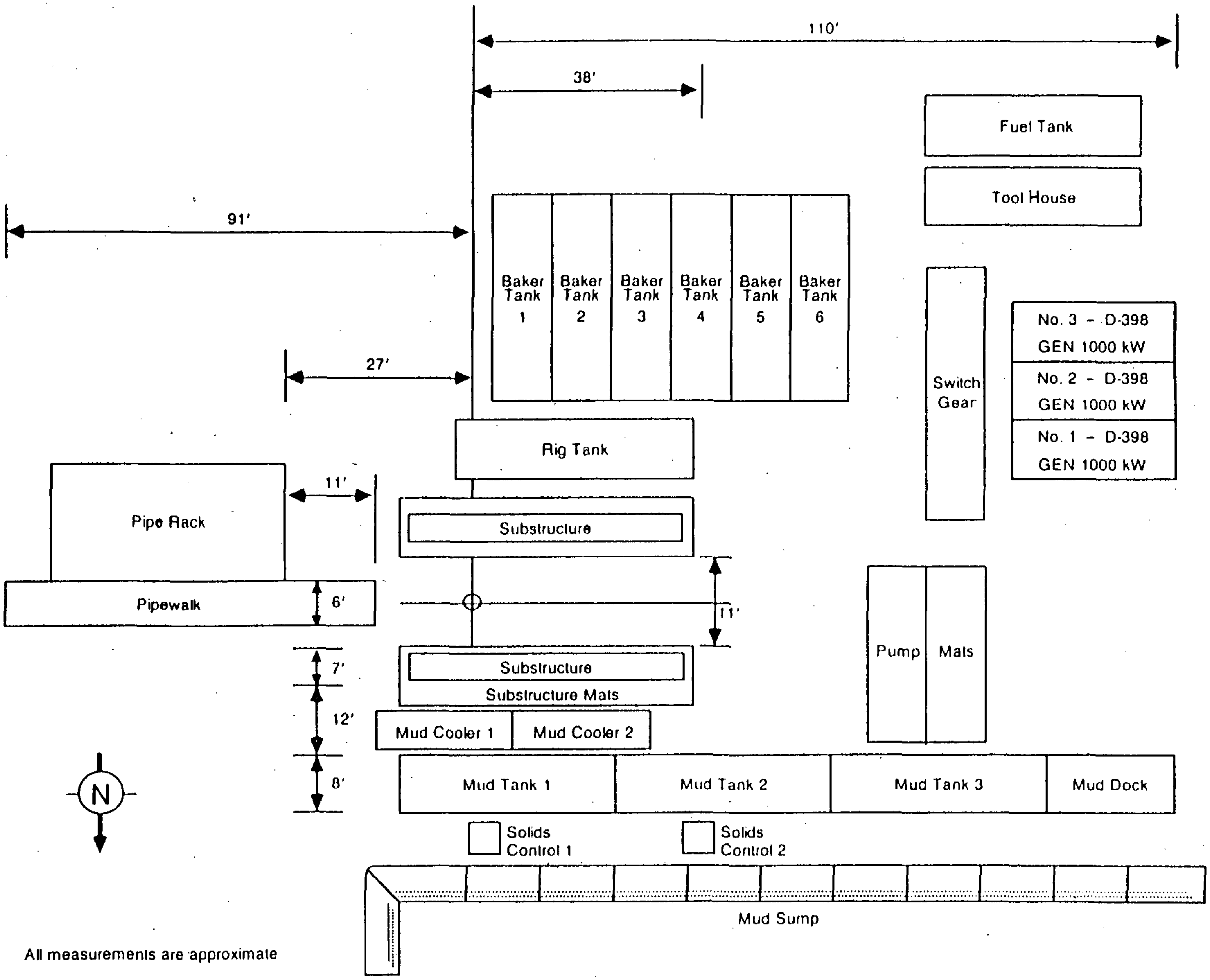


Figure 4.2 Site Layout



All measurements are approximate

Figure 4.3 Cleveland Rig No. 6 Layout

Table 4.1

TECHNICAL DATA:
CLEVELAND DRILLING CO. RIG NO.6
(18,000 ft Range)

Item	Description
Drawworks:	National 110-UE
Drawworks Drive:	Two GE-752 DC motors, 1,600 continuous hp, 2,000 peak hp Lima AC generators
Engines:	Three Caterpillar D-398 engines driving three 1,000 KW Lima AC generators
Switchgear House:	Ross Hill Model 1,400 SCR cubicles rated 1,800 amps DC
Mast:	Superior Derrick Services, 768,000 lbs static hook load with 12 lines
Substructure:	Superior Derrick Services, 28 ft 4 in. high with mats, 700,000 lbs casing load, 500,000 lbs set back
Rotary Table:	National C275 independently driven with one GE-752 electric motor
Mud Pumps:	Two National N-1300 pumps — 1,300 hp
Mud System:	1,000 barrel active system with two Rumba double shale shakers, low-pressure mixing system

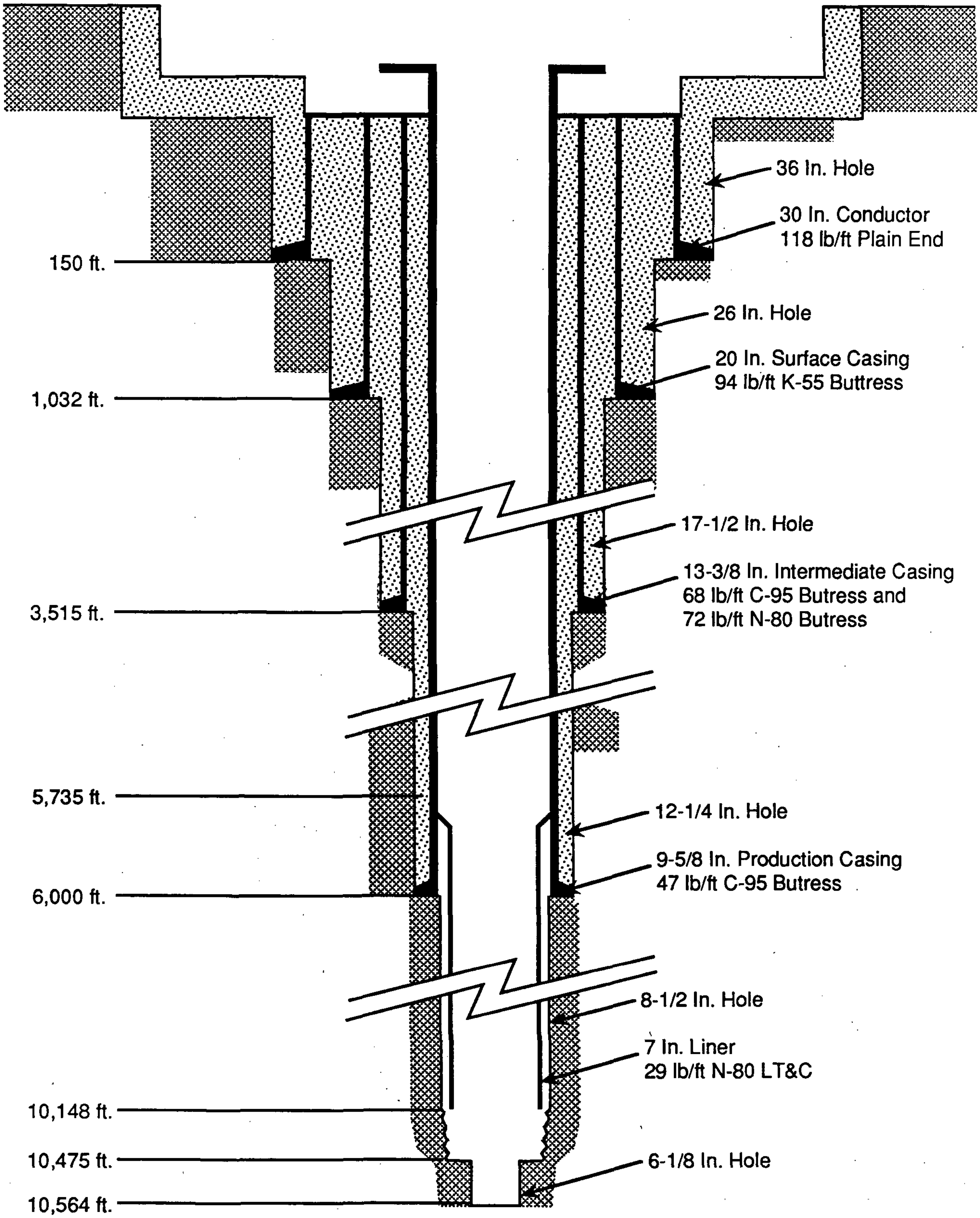


Figure 4.4 Final Well Configuration, State 2-14

The first condition resulted in a maximum wellhead pressure of 2,200 psia and the second condition resulted in a maximum wellhead pressure of 2,250 psia. Based on these design criteria, critical wellhead components meeting ANSI 1,500 class service rating (2,620 psi at 715°F) were recommended. The critical components included the expansion spool and the double 10 in. master valves, as shown on Figure 4.5. The components of the wellhead are listed in Table 4.2, and are number coded to Figure 4.5. Components downstream of the double master valves were specified to meet ANSI 900 class service.

4.4 FLOW-TEST FACILITY

4.4.1 System Description

The flow-test facility assembly is shown in Figure 4.6 and the process and instrumentation diagram is presented in Figure 4.7.

The geothermal fluid flowed from the well bore through the two master valves and one wing valve on the wellhead, then into the flow line. The flow line piping directed the fluid to either: (a) the mud-pit via a blooie line; or, (b) the brine pond via a blooie line; or, (c) the brine pond via the muffler and weir box. During normal operation, the fluid was sent through the muffler and weir box. Fluid was sent through the mud-pit blooie line only during initial start up, and through the brine-pond blooie line when modifications or servicing of the muffler and weir box system was required.

Physical measurements taken during the flow tests provided the data needed to estimate flow rate and enthalpy. As a cost-saving measure, the surface flow system did not have a full-phase separator to provide independent measurements of steam flow and brine flow for the calculation of enthalpy. For these short-term flow tests, the flow rates and enthalpies were estimated using the design and correlations devised by R. James (1975a, 1975b). In addition, sampling points were provided to draw samples of the vapor and liquid components of the geothermal fluid. These sampling points provided mixtures of steam and brine flow at unknown ratios, and the estimated enthalpy was used to calculate ratios for chemical analyses.

4.4.2 Design Basis

The design basis for the flow-test facility included the following:

- Flow conditions
  - Pressure 700 psig (maximum)
  - Temperature 650°F (maximum)
  - Flow 620,000 lbs/hr (two phase) (maximum)
- Estimated operating life — 21 days: 3 flow tests, 7 days each
- Wellhead rise from thermal expansion — maximum, 4 ft
- Insulated — where operating personnel are present
- All high-pressure valves — Class 600
- Temperature indicators — bimetallic
- Pressure indicators — Bourdon-tube type

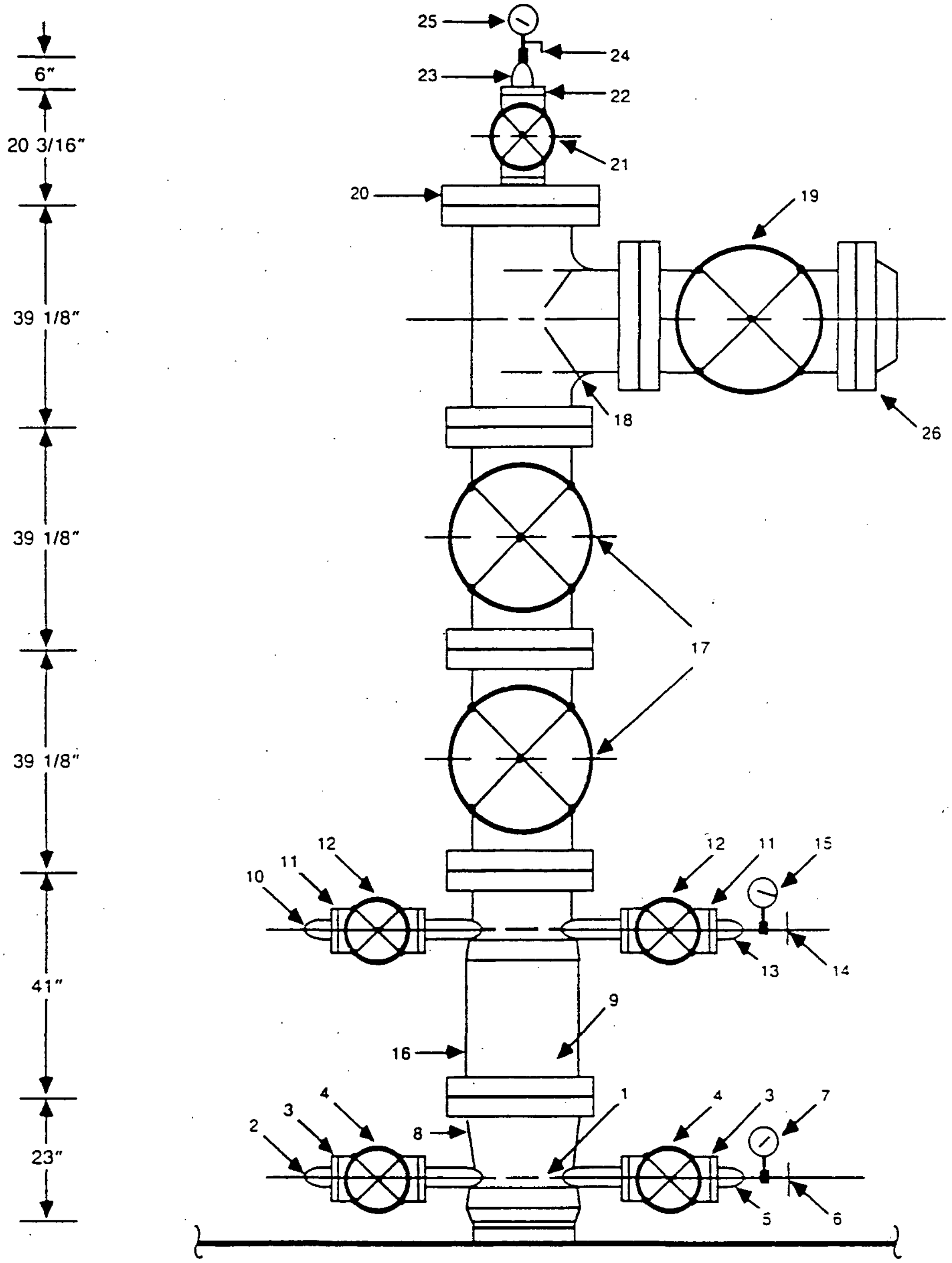


Figure 4.5 **Wellhead Design**
(see **Table 4.2** for Wellhead Equipment List)

Table 4.2

WELLHEAD EQUIPMENT LIST

Item Number (Fig. 4.5)	Quantity	Description
1	1	Casing head, 13-5/8 in., API 3000 x 13-3/8 in., SOW with two 3-1/8 in., API 3000 flange outlets
2	1	Bull-plug, 3 in., LP threads, plain
3	2	Companion flange, 3-1/8 in., API 3000 with 3 in. LP threads
4	2	Gate valve, 3-1/8 in., API 3000
5	1	Bull-plug, 3 in., LP threads with 1/2 in. NPT
6	1	Needle valve, 1/2 in., NPT, angle
7	0	Not installed, see item 15
*	4	Ring gasket, R-31 (3-1/8 in. API 3000)
*	32	Studs, 7/8 in. x 6 in., ASTM A193, Grade B7, HRC22 maximum hardness, with two nuts per stud
*	1	Ring gasket, R-57 (13-5/8 in. API 3000)
*	20	Studs, 1-3/8 in. x 10-1/4 in., ASTM A193, Grade B7, HRC22 maximum hardness, with two nuts per stud
8	1	Annular seal and centralizer, nominal 13-5/8 in. x 9-5/8 in. casing
9	1	Expansion spool, 13-5/8 in. API 3000 x 11 in. API 5000, with two 3-1/8 in. API 5000 flange outlets, 41 in. overall length with 18 in. of expansion on 9-5/8 in. production casing. Top of spool bored to accommodate a 7-in. hang-down liner, donut assembly
10	1	Bull-plug, 3 in., LP threads, extra heavy, plain
11	2	Companion flange, 3-1/8 in., API 5000 with 3 in. LP threads

* Not shown in Figure 4.5

Table 4.2 (Cont'd)

WELLHEAD EQUIPMENT LIST

Item Number (Fig. 4.5)	Quantity	Description
12	2	Gate valve, 3-1/8 in., API 5000
13	1	Bull-plug, 3 in., LP threads, extra heavy with 1/2 in. NPT
14	1	Needle valve, 1/2 in. NPT, angle, high temp.
15	1	Gauge, 0-3000 psi reading, 4-1/2 in. face, 1/ 2 in. NPT connection
*	4	Ring gasket, R-35 (3-1/8 in. API 5000)
*	8	Studs, 1-1/8 in. x 7-1/4 in., ASTM A193, Grade B7, HRC22 maximum hardness, with two nuts per stud
*	1	Ring gasket, R-54 (11 in. API 5000 and 10 in. ANSI 1500)
*	12	Studs, 1-7/8 in. x 13-3/4 in., ASTM A193, Grade B7, HRC22 maximum hardness, with two nuts per stud
16	1	Production expansion seal, nominal 13-5/8 in. x 9-5/8 in. casing
17	2	Gate valve, expanding gate, 10 in., ANSI 1500 RTJ x RTJ
18	1	Flanged tee, 11 in., API 5000 bottom flange x 11 in., API 3000 top and side outlet
19	1	Gate valve, expanding gate, 10 in., ANSI 900 RTJ x RTJ (wing)
20	1	Adaptor flange, 11 in., API 3000 drill x 4 in., API 3000 studded
21	1	Gate valve, 4 in., API 3000
22	1	Companion flange, 4 in., API3000 with 4 in. LP threads

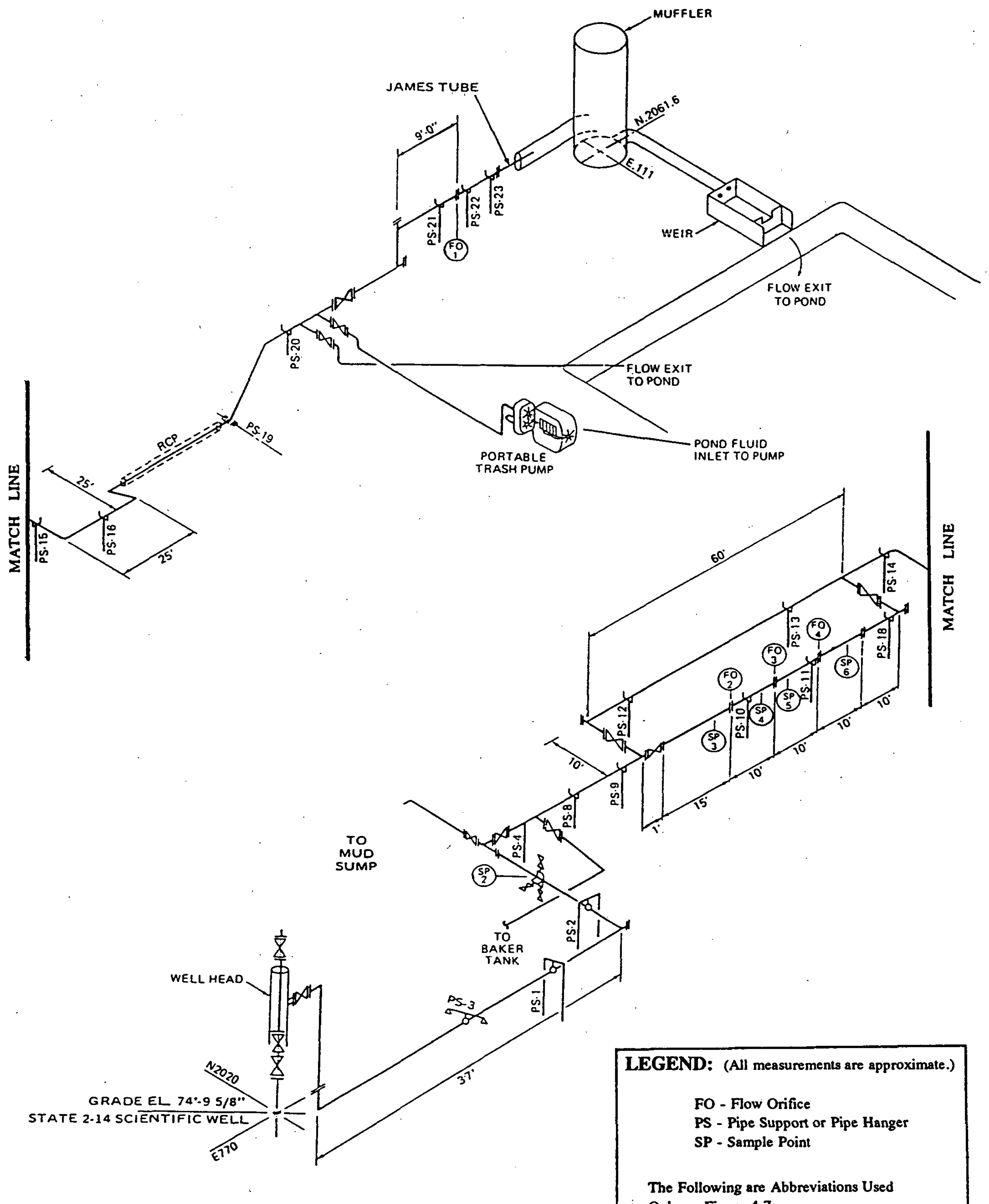
* Not shown in Figure 4.5

Table 4.2 (Cont'd)

WELLHEAD EQUIPMENT LIST

Item Number (Fig. 4.5)	Quantity	Description
23	1	Bull-plug, 4 in., LP threads, extra heavy with 1/ 2 in. NPT
24	1	Needle valve, 1/2 in. NPT, straight, high temp.
25	1	Gauge, 0-3000 psi reading, 4-1/2 in. face, 1/2 in. NPT connection
*	2	Ring gasket, R-37 (4 in. API 3000)
*	8	Studs, 1-1/8 in. x 7-1/4 in., ASTM A193, Grade B7, HRC22 maximum hardness, with two nuts per stud
26	1	Weld-neck flange, 10 in., ANSI 900
*	2	Ring gasket, R-54 (10 in. ANSI 1500)
*	24	Studs, 1-7/8 in. x 13-3/4 in., ASTM A193, Grade B7, HRC22 maximum hardness, with two nuts per stud
*	3	Ring gasket, R-53 (11 in. API 3000 and 10 in. ANSI 900)
*	48	Studs, 1-3/8 in. x 9-1/2 in., ASTM A193, Grade B7, HRC22 maximum hardness, with two nuts per stud

* Not shown in Figure 4.5



LEGEND: (All measurements are approximate.)

- FO - Flow Orifice
- PS - Pipe Support or Pipe Hanger
- SP - Sample Point

The Following are Abbreviations Used Only on Figure 4.7:

- DPI - Differential Pressure Indicator
- DPR - Differential Pressure Recorder
- LI - Level Indicator
- PI - Pressure Indicator
- PR - Pressure Recorder
- TI - Temperature Indicator

Figure 4.6 Flow-Test Facility Assembly

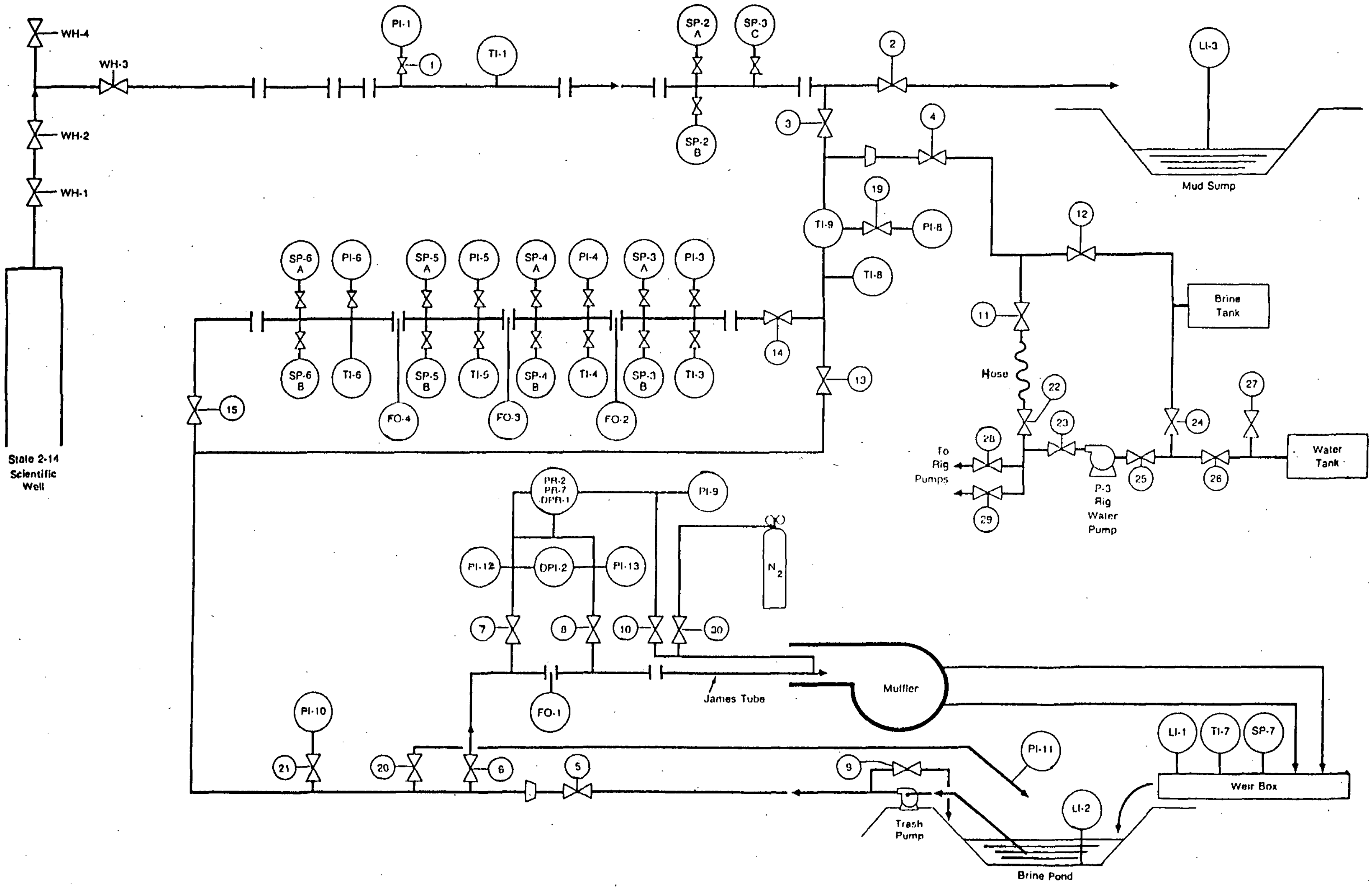


Figure 4.7 Process and Instrumentation Diagram

- No low points in the flow line prior to the science-sample loop
- Negligible corrosion allowance

4.4.3. Design

The main brine flow line was new, 10 in. nominal diameter, Schedule-60 pipe. Except for the use of elbows at stress points in the expansion loop, tees with one blind end were used for all turns. The 25 ft by 25 ft expansion loop was cold-sprung, 4 in. on each leg, during installation to accommodate the expected total linear expansion of approximately 15 in. from the wellhead to the James tube.

To prevent a low point from occuring in the flow line prior to sampling, the piping was elevated approximately 3-1/2 ft above ground level from the wellhead to the road crossing. The typical pipe support, shown in Figure 4.8, allowed unrestricted axial movement and approximately 3 in. lateral movement.

Fixed points in the horizontal plane on the flow line were: (a) a thrust block of the design shown in Figure 4.9 at pipe support No.4 (Figure 4.8); (b) the wellhead; and (c) the discharge area of the flow line, pipe support Nos. 21, 22 and 23 (Figure 4.6). The location of the thrust block, a W12 x 27 I-beam set in 2.4 cu. yds of concrete, was selected to mitigate occasional axial pipe movement due to slug flow.

In anticipation of a possible 4 ft wellhead growth during the flow test, three Bergen Paterson, Type 4000, constant-support pipe hangers (Figure 4.10) were installed at pipe supports Nos. 1, 2, and 3 (Figure 4.6). The pipe hangers had capacities of 1,400, 2,100, and 2,100 lbs, respectively; a stroke of 10 in.; and provision to be reset by adjusting the length of supporting, all-thread rod. The arrangement proved very effective in accommodating flow line position changes at all stages of the flow test.

Except for one WKM Class 600 valve from the DOE East Mesa site, all 10 in. valves were reconditioned, steam-service, Kitz gate valves, ANSI Class 600. All valves performed satisfactorily for the flow period. Only minor eddy erosion in the valve body downstream of the valve gate and minor uniform rusting were observed on the valves. Flange gaskets were composition Garlock Type.

The sampling ports for brine sampling included one requested by Kennecott (SP-2) and five for the scientists (SP-3, -4, -5, -6, and -7), as shown in Figure 4.6. Sampling points 2 and 7 were simply 1 in. diameter pipe taps and a weir box for grab sampling. Sampling points 3 through 6 were intended to take the place of a full-phase separator, as shown in Figure 4.11, were considerably more elaborate, and could be characterized as in-line separators. The top part was designed to sample vapor only; the bottom part was to sample liquid. Ports were provided for temperature and pressure measurement in conjunction with step-down orifice plates upstream of sampling points 4, 5, and 6, to collect four sets of data that defined four thermodynamic conditions of the geothermal fluid. The multiple pressure drops caused problems with precipitation of solids and clogged the sampling points. The in-line separators failed to adequately separate steam and brine, so most chemical samples were contaminated to some extent.

4.5 DRILLING AND COMPLETION PLAN

The drilling and completion program is described in Bechtel (1987) report E, "Well Design & Drilling Plan" (see Appendix A). Deviations from the original program are discussed in the drilling summary in Section 5 and subsequent sections of this report. Some changes were made in

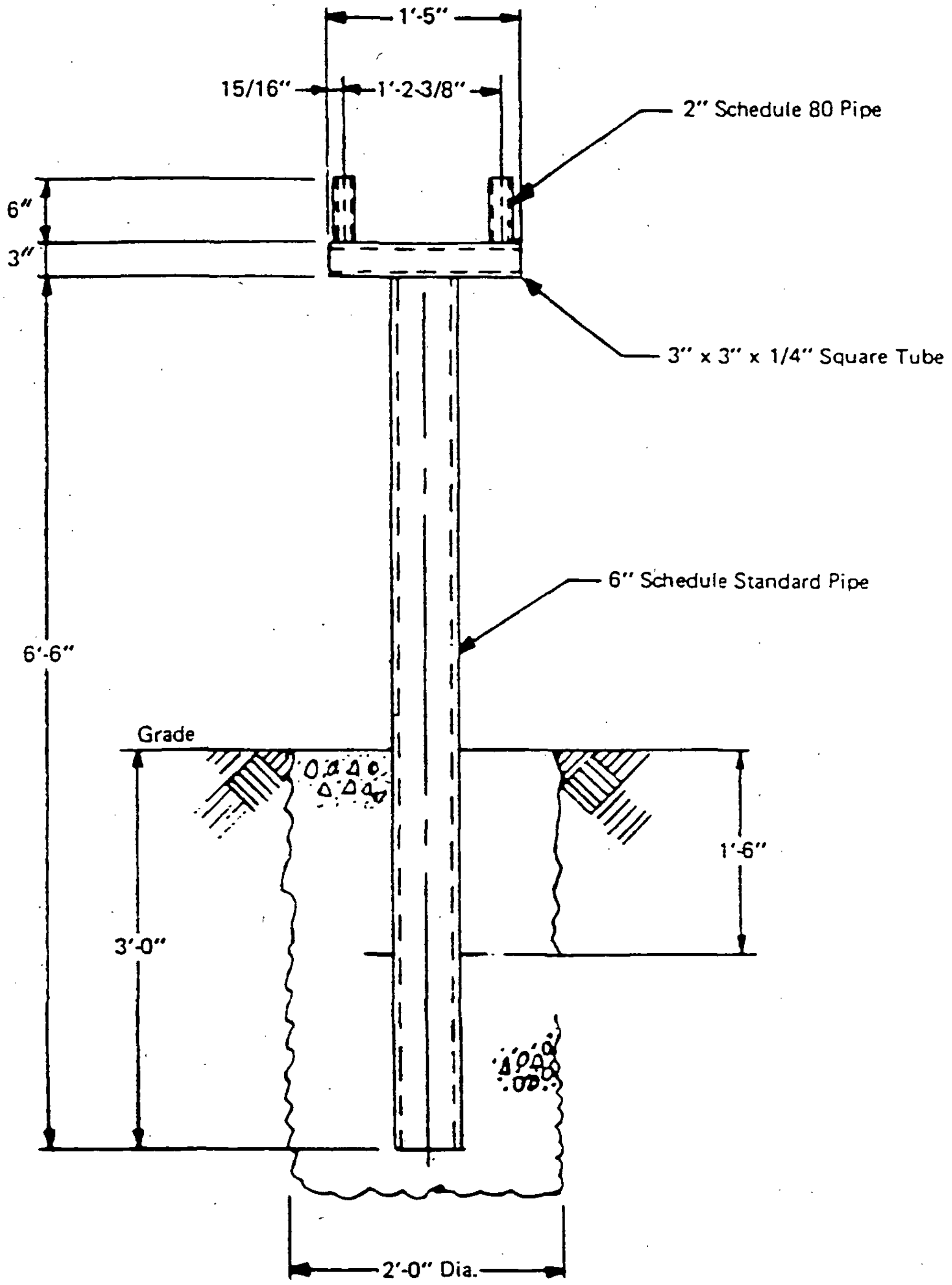


Figure 4.8 Typical Pipe Support

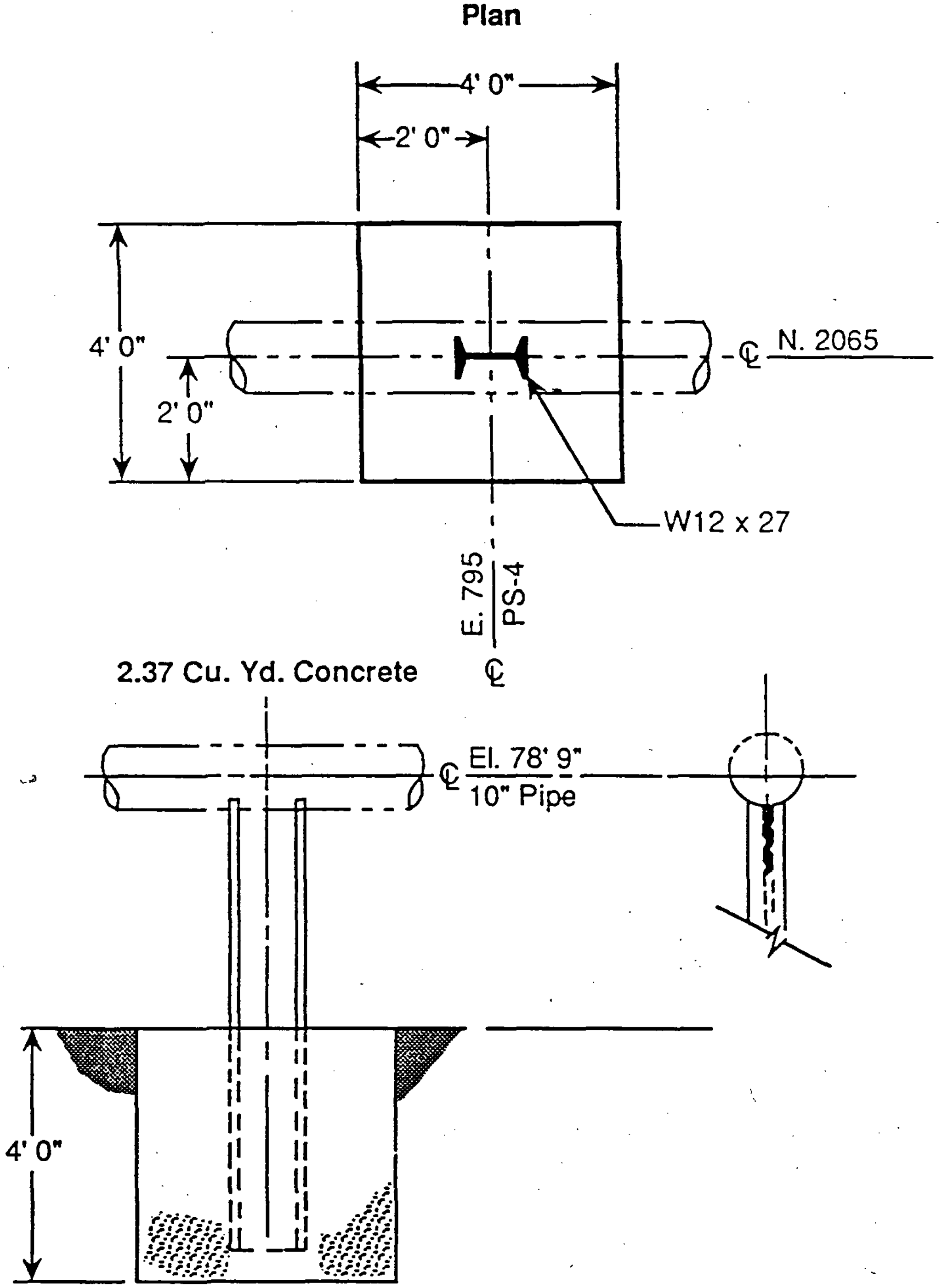


Figure 4.9 Thrust Block

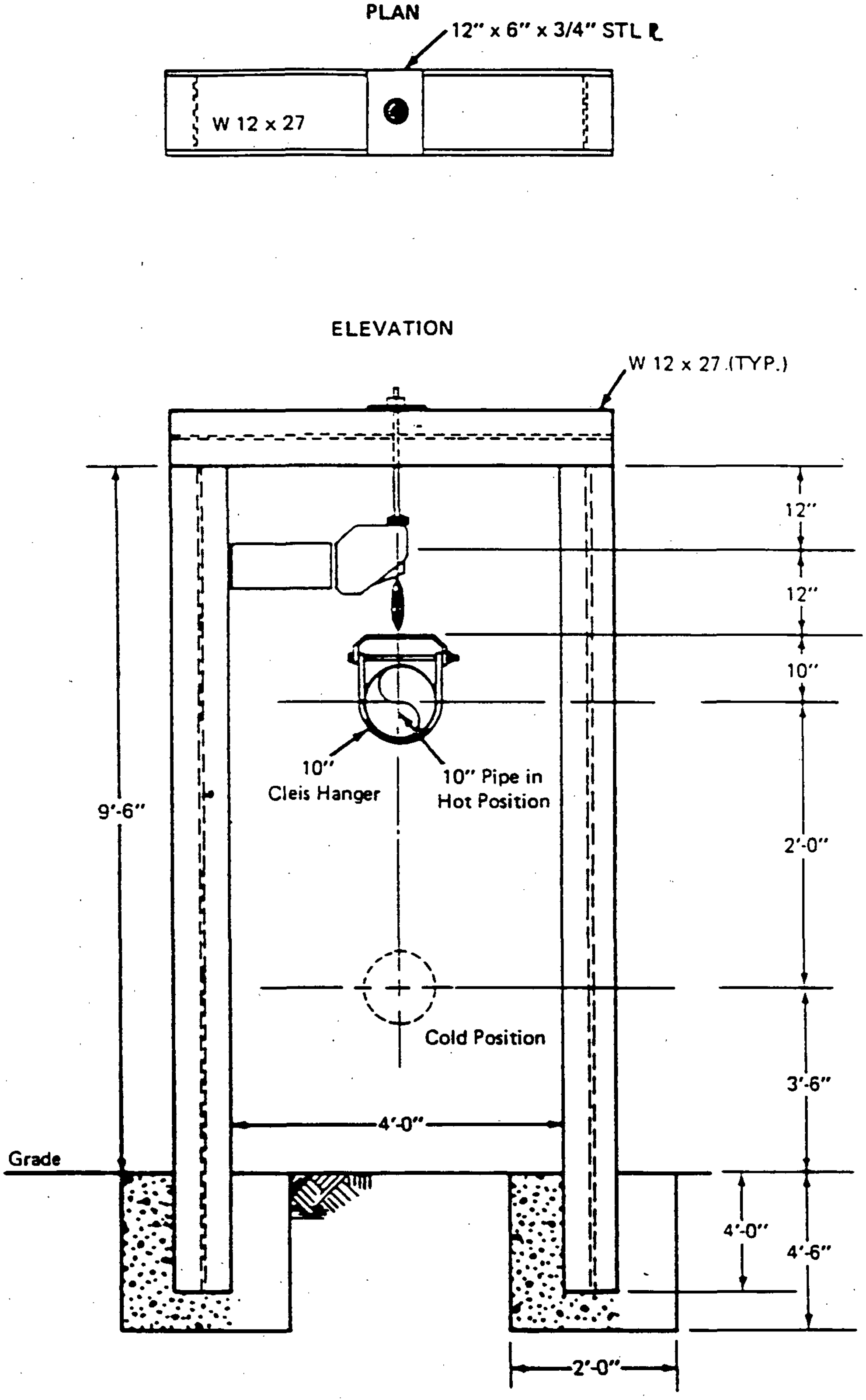


Figure 4.10 Constant-Support Hangers

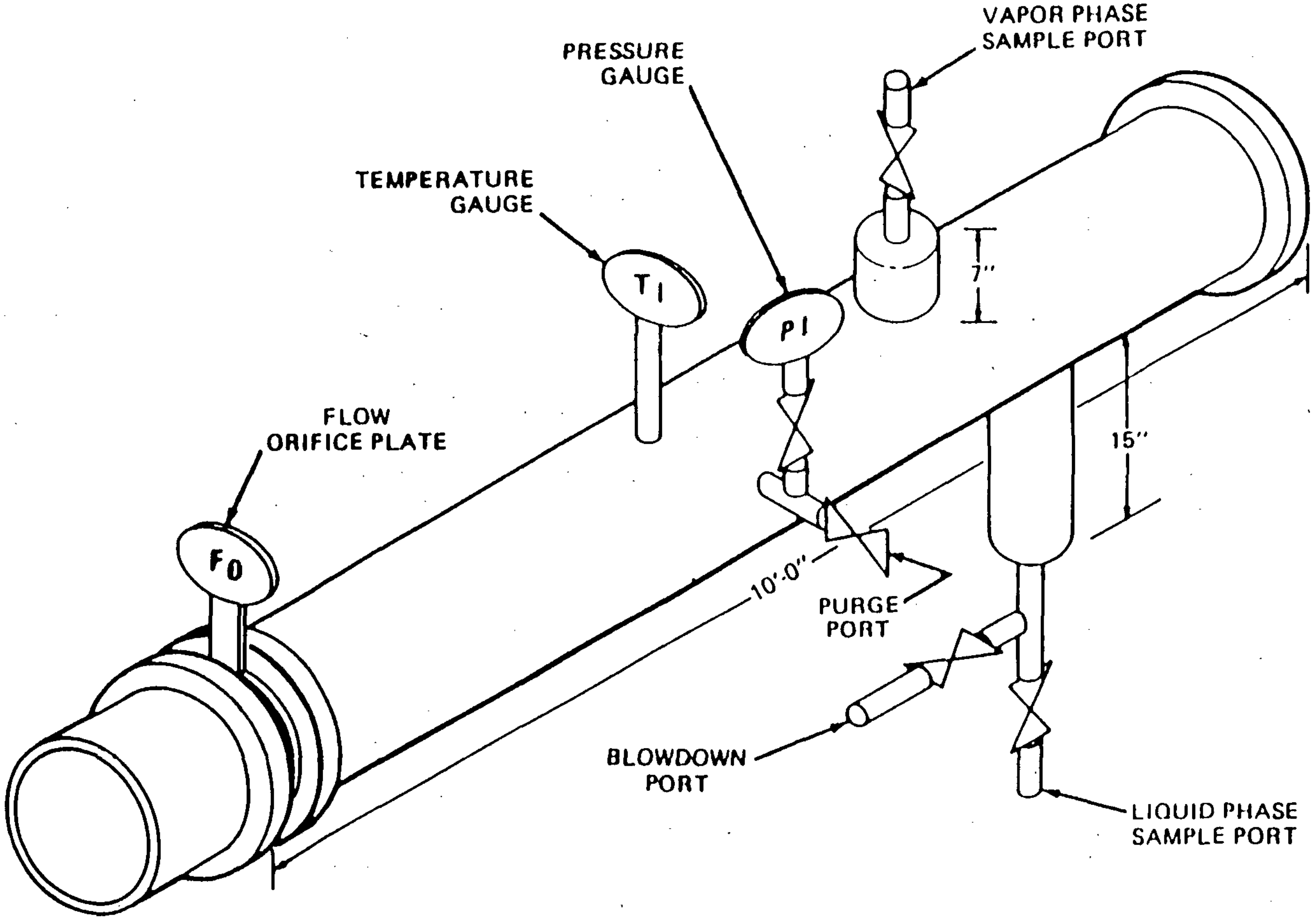


Figure 4.11 Typical Sample-Spool Sampling Points — 3 through 6

the drill-rig equipment supply responsibility, in that the burden of furnishing such items as the 30 in. and 20 in. BOPE, fishing tools, survey instruments, and other high-cost expendable items, were deleted from the drilling subcontract and assumed by Bechtel.

4.6 CORING

There was significant discussion before drilling began about the method to be used for coring. The two methods considered were conventional rotary drilling, with spot coring of isolated 30 ft intervals, and continuous wireline coring.

Dr. Peter Lysne, Sandia National Laboratories, was asked by DOE to conduct a brief, independent survey to further investigate the feasibility of continuous wireline coring. No compelling reasons for eliminating the method from consideration were identified. To resolve the conflicting information and recommendations that had emerged, a consultant, Mr. Jack D. Powers, was employed to prepare a definitive analysis of the methodology, including an evaluation of the estimated cost and the timely availability of commercial equipment to perform the work. His report, Continuous Slim-Hole Wireline Coring Study, is listed as Report A in Appendix A.

In summary, Mr. Powers identified a large number of unknown performance characteristics for the wireline coring method in the conditions anticipated for the SSSDP. In his opinion, the risks associated with the numerous unknowns resulted in an unacceptably low probability that a 10,000 ft well could even be completed. He recommended that a $1 million research program be completed before attempting continuous wireline coring of a well like the SSSDP. Such a coring system (i.e., 8-1/2 in. core) was not commercially available. As a result of Mr. Powers' recommendations, the option of continuous wireline coring was abandoned.

In retrospect, the problems encountered when drilling State 2-14, using conventional drilling and coring techniques, were properly anticipated in Powers' analysis. Among the most difficult problems were:

- Control of lost-circulation zones
- Control of well flowing periods
- Drilling fluid temperature control, especially at the bit
- Disking of core in highly fractured rock
- Directional control and drilling in a deviated borehole
- Accelerated corrosion from brine-contaminated drilling fluids, leading to drill-rod failure or high rejection rates during the frequent inspections of drill rod that would have been required.

4.7 REFERENCES

Bechtel National, Inc., 1987, Salton Sea Scientific Drilling Program - Drilling and Engineering Program: (Draft) Final Report, Prepared for U.S. Department of Energy, 98p.

James, R., 1975a, Rapid estimation of electric power potential of discharging geothermal wells: Proceedings, Second United Nations Symposium on the Development and Use of Geothermal Resources, May 20-29, pp. 1685-1687.

James, R., 1975b, Drawdown test results differentiate between crack flow and porous bed permeability: Proceedings, Second United Nations Symposium on the Development and Use of Geothermal Resources, May 20-29, pp. 1693-1696.

5.0 DRILLING SUMMARY

5.1 DRILLING OPERATIONS

The drilling and flow-test operations of Phase 1 took 160 working days, starting on October 23, 1985, and concluding on April 1, 1986. A rotary drilling rig and standard oil field technology, modified for high temperatures, was used to drill the hole. It was recognized at the beginning that none of the personnel involved in the program from the Department of Energy, Bechtel National Corporation, or the subcontractor drilling engineer had experience in drilling geothermal wells. The initial drilling plan of operations, submitted to the California Division of Oil and Gas for approval, required extensive modifications to meet well safety requirements. The depth progress chart for this period is shown in Figure 5.1. A brief summary of each day's activities is presented in Appendix B. An abstract of drilling activities follows.

Drilling proceeded uneventfully at first and good progress was made. On day 3, (10/25) the 30-in. conductor pipe was cemented in and blowout prevention equipment was installed. Two days later, a 17-1/2 in. hole had been drilled to 1,000 ft. The first drill core was taken at 1,553 to 1,576 ft on day 9. A depth of 3,030 feet was reached on day 13; geophysical logs were run and core (#4) was taken. A hole depth of 5,167 ft was reached on day 39 (11/30), after reaming 37 feet of hole. Drilling stopped on day 62 (12/23) at a depth of 6,227 ft for temperature logs, standby for holidays, and the first flow test (12/28 - 12/30/85).

Drilling resumed on January 2, 1986 (day 72) after nine days with no new footage. Directional drilling was required from 7,700 to 8,070 ft (day 90 - 95) to reduce hole deviation from vertical. On day 100 (1/30/86), the hole, now reduced to 8-1/2 in. diameter, reached 8,395 ft after penetrating several lost-circulation zones. A deviation survey (DS) indicated a hole inclination of 4-1/4°, S23°W and true depth of 8,342 ft. Much of the interval 8,585 to 8,800 ft was drilled without return of cuttings to the surface. The well began to flow several times between depths of 9,248 and 9,473 ft, and had to be killed repeatedly during an eight-day period, (2/09 - 2/17). Lost-circulation problems continued to impede progress, and the hole depth on day 129 (02/28) was only 9,698 ft.

Drilling improved until major lost-circulation zones were penetrated from 10,306 to 10,475 ft. Total depth of 10,564 ft was reached on day 146 (03/17). Logging, fluid sampling attempts, vertical seismic profiling (VSP) and borehole-gravimeter surveys, and injection of produced brine into the well continued until April 1, 1986. The rig was released, but remained on-site.

As Elders and Sass (1988) note, the primary goals of the SSSDP were scientific rather than commercial, and research was given priority over engineering, consistent with safety considerations and maintaining borehole integrity. Attempts to mitigate drilling problems consumed $1.3 million of the drilling and testing budget. These activities included fishing and stuck pipe (8 days), directional drilling (18 days), and lost circulation and well control (20 days) (Harper and Rabb, 1986). The highly-fractured formations drilled caused directional problems below 3,514 ft, and at 6,000 ft-depth the borehole had deviated to the east at an angle of over 8° from vertical, requiring directional drilling. Nine major fluid-loss zones below 6,000 ft caused slow progress and caused the well to flow and boil when the drill string was removed to change bits (Elders and Sass, 1988). Aggressive treatment, using lost-circulation materials and cement, was necessary to quench the well and restore borehole integrity.

The drilling supervisor's and drilling contractor's daily reports (Bechtel, 1987; reports B and C, Appendix A), can be ordered for more complete information.

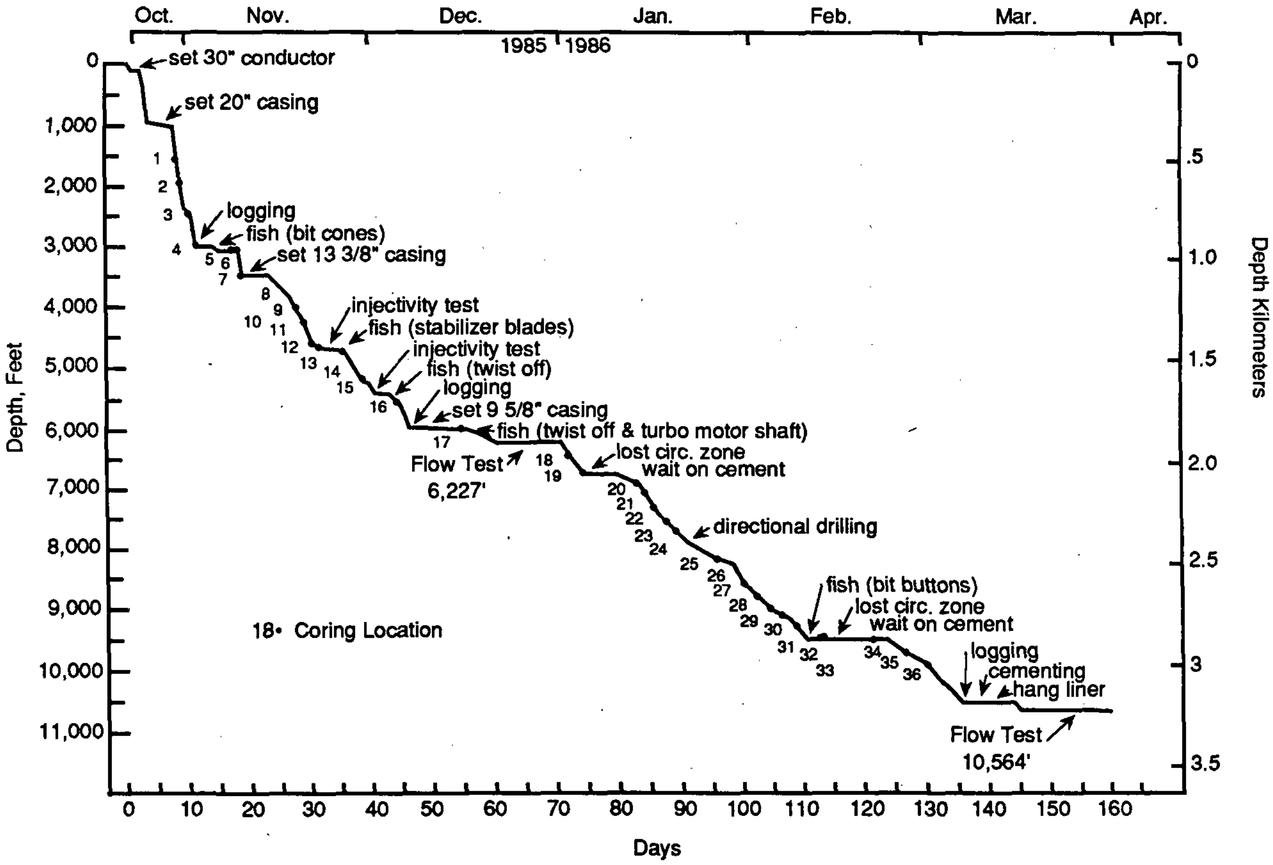


Figure 5.1 **Depth Progress Chart, State 2-14**
(Elders and Sass,JGR v.93, Bll, 1988, copyright by the American Geophysical Union).

5.2 CASING AND CEMENTING

The original well design plan and the drilling and completion program are listed in Appendix A, reports D and E, respectively. The casing and cementing program that was implemented is outlined below.

5.2.1 Conductor Pipe

Number of Joints	Size (in.)	Section (ft)	Length (ft)	Weight (lb/ft)	Wall (in.)	Coupling	Range
4	30	0-150	150	157.5	0.50	Plain end	3

The conductor pipe was welded into double joints on the ground while drilling was in progress in order to minimize welding time while running the casing. The double-joint sections were picked up by the rig on slings, while the bottom of the pipe was directed into the well with a forklift. The first section was lowered by means of a pump rod inserted through holes cut near the top of the joint. The second section was then lifted up and welded to the first. The pump rod was removed and the holes in the casing patched before lowering the casing. The 30-in. conductor pipe was cemented through two strings of 2-7/8 in. tubing run in the annulus. Twenty-six cubic yards of Redi-Mix (8 sacks of cement and sand mix) were placed in the annulus using a concrete pump truck to transfer the cement from the mix truck to the tubing.

5.2.2 Surface Casing

Number of Joints	Size (in.)	Section (ft)	Length (ft)	Weight (lbs/ft)	Grade	Coupling	Range
1	20	0-42	42	133	K-55	BTC	3
13	20	42-572	530	94	K-55	BTC	3
11	20	572-1,032	460	133	K-55	BTC	3

The casing was run in the foregoing sequence by a casing crew employing power tongs and a pickup machine. All threads were cleaned and coated with a geothermal thread lubricant prior to coupling. A float shoe was run on the bottom of the casing, and bow-type centralizers were placed at depths of 1,020 ft, 999 ft, 776 ft, 569 ft, 361 ft, 162 ft, and 123 ft.

The casing was cemented as follows:

Preflush:	750 gallons, water 500 gallons, Flowcheck 750 gallons, water
Lead slurry:	1,869 ft^3 1:1 Class-G cement and perlite, 40 percent silica flour, 3 percent gel, 0.65 percent CFR-2
Tail slurry:	500 ft^3 Class-G cement, 40 percent silica flour, 1 percent CFR-2

The top wooden plug was released and the cement displaced with 1,936 ft^3 of mud at 14 bbl/min. The casing was reciprocated throughout the cementing operation except for the last 100 ft^3 of displacement that was staged in. Approximately 536 ft^3 of cement was circulated out in the returns.

5.2.3 Intermediate Casing The 13-3/8-in. intermediate casing was run in the following configuration:

Number of Joints	Size (in.)	Section (ft)	Length (ft)	Weight (lbs/ft)	Grade	Coupling	Range
69	13-3/8	0-3,039	3,039	68	C-95	BTC	3
11	13-3/8	3,039-3,475	436	72	N-80	BTC	3
Float Collar	-	3,475-3,477	2	-	-	-	-
1	13-3/8	3,477-3,513	36	72	N-80	BTC	3
Float Shoe	-	3,513-3,515	2	-	-	-	-

It had been intended to set the 13-3/8 in. casing at 3,000 ft; however, a lost-circulation zone was encountered between 2,900 ft and 3,200 ft, and the well had to be deepened to 3,515 ft to obtain a better casing seat. This required procuring an additional 472 ft of special 72 lb/ft, N-80, BTC casing to complete the casing string. A total of 25 bow-string centralizers were installed starting at 3,505 ft and 3,484 ft, then every third joint back to 736 ft. The last centralizer was installed at 46 ft.

The casing was cemented as follows:

Preflush:	750 gallons water 500 gallons Flowcheck 750 gallons water, followed by the bottom plug
Lead slurry:	3,570 ft^3 1:1 Class-G cement and perlite, 40 percent silica flour, 3 percent gel, 0.65 percent CFR-2 and 0.5 percent Halad 22A
Tail slurry:	500 ft^3 Class-G cement, 40 percent silica flour, 1 percent CFR-2, and 0.75 percent Halad 22A

The top plug was dropped and displaced with 2,950 ft^3 of mud. All returns were lost after 2,200 ft^3 of displacement. A top cement job was done, after removing the BOPE, by running a string of 1-in. tubing down the annulus to 180 ft and cementing back to surface with 200 ft^3 of 1:1 class-G cement and perlite, 40 percent silica flour, 3 percent gel and 0.65 percent CFR-2. A cement bond log indicated poor to no bonding from the surface down to about 100 ft. Bonding in the bottom few hundred feet appeared excellent.

5.2.4 Production Casing

The 9-5/8 in. production casing was run in the following sequence:

Number of Joints	Size (in.)	Section (ft)	Length (ft)	Weight (lbs/ft)	Grade	Coupling	Range
76	9-5/8	0-3,314	3,314	47	C-95	BTC	3
Stage Collar	-	3,314-3,318	4	-	-	-	-
59	9-5/8	3,318-5,905	2,587	47	C-95	BTC	3
Float Collar	-	5,905-5,907	2	-	-	-	-
2	9-5/8	5,907-5,998	91	47	C-95	BTC	3
Float Shoe	-	5,998-6,000	2	-	-	-	-

The 9-5/8 in. casing was run to 3,500 ft at which point the hole was circulated and cooled while changing out the 150-ton drilling rig elevators for 250-ton slip-type elevators. Centralizers were 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, 133 ft, 87 ft and 42 ft. A cement basket was installed below the stage collar at a depth of 3,446 ft.

The cementing plan was changed from a single stage to a two-stage operation to ensure a good cement job in the annulus between the 9-5/8 in. and 13-3/8 in. casings and to minimize the lost-circulation problems that occurred on the 13-3/8 in. casing cement job.

Prior to cementing, mud was circulated in the well for three hours to condition and cool the hole. The 9-5/8 in. casing was then cemented in two stages as follows:

Stage #1

Preflush:	1,125 gallons water with inert dye 500 gallons Flowcheck 1,125 gallons water
Lead slurry:	200 ft^3 Class-G cement, 40 percent silica flour, 0.75 percent CFR-2, 1 percent HR-7
Intermediate slurry:	1,053 ft^3 Class-G/Spherelite blend, 1 percent HR-7
Tail slurry:	500 ft^3 Class-G cement, 40 percent silica flour, 0.75 percent CFR-2, 1 percent HR-7

The dart was dropped and displaced without bumping the plug. The opening plug was then dropped and the two-stage tool opened. The hole was circulated for 4 hours, getting some dye marker back in the returns.

Stage #2

Preflush:	450 gallons water 750 gallons silica flour/sepiolite blend
Slurry:	1,280 ft^3 Class-G cement, 40 percent silica flour, 3 percent gel, 1 percent CFR-2, 0.1 percent HR-7

The closing plug was then displaced and bumped with 2,000 psi, closing the stage tool. Although cement was circulated to the surface, a subsequent cement bond log indicated poor bonding in the top 3,000 ft of 9-5/8 in. casing.

5.2.5 Liner

One hundred-two (102) joints of solid, 7-in. liner, totaling 4,401 ft with the hanger, seal, safety joint, and polished-bore receptacle (PBR), were run and set from 5,735 ft to 10,136 ft, as follows:

Number of Joints	Size (in.)	Section (ft)	Length (ft)	Weight (lbs/ft)	Grade	Coupling	Range
PBR	-	5,735 - 5,755	20	-	-	-	-
Hanger	7x9-5/8	5,755 - 5,773	18	-	-	-	-
1	7	5,773 - 5,816	43	29	N-80	LTC	3
Safety joint	-	5,816 - 5,817	1	-	-	-	-
101	7	5,817-10,135	4,318	29	N-80	LTC	3
Guide shoe	-	10,135-10,136	1				

After setting the liner-hanger seal, the setting tool was retrieved and the 7 in. liner left as an uncemented completion. This liner operation differed from normal geothermal practice. Instead of using buttress-threaded 7 in. liner, the weaker, 8-round threaded liner was used. The 8-round liner has less strength at high temperatures and in deviated holes. Normal geothermal practice would be to use two liner hangers for the greater strength required in hot environments.

5. 3 CORING OPERATIONS

Thirty-four conventional cores were drilled and two additional cores (Nos. 5 and 14) were obtained from junk-basket runs made during fishing operations, accounting for a total of 36 cores recovered. The total footage recovered was 728.5 ft. Core recovery was good to a depth of about 5,000 ft. Recovery declined markedly from there to 9,907 ft, where the last coring operation was attempted. Coring rates approached 27 ft/hr in the upper sections of the hole in competent rock formations, but decreased to less than 1 ft/hr at the last coring point. The average coring rate was 8 ft/hr. Both 30 ft and 60 ft core barrels were used from 1,553 ft to 4,680 ft. Nine runs were made with the 60 ft barrel between 3,107 ft and 4,680 ft, at which point the longer barrels were discontinued due to jamming in hard, fractured rock. Frequent jamming of the core barrels was a major problem. Attempts to use chrome-plated and aluminum core barrels failed to alleviate the problem. On some coring runs, where the aluminum barrel was used, it was difficult to remove the core from the barrel once the barrel had cooled. This necessitated cutting the barrel into sections for core recovery. In addition, two types of core catchers (slip-and-dog and slip-and-knife) were used in attempts to improve core recovery. The slip-and-knife catcher worked best in fractured formations.

Loss of circulation at intended coring points also contributed to poor core recovery. Five cores were attempted while drilling blind (without circulation), which resulted in early core-barrel jamming and bit damage.

Three 9-7/8 in. x 5-1/4 in. core bits were used in the first 6,000 ft of hole, and seven 8-1/2 in. x 4-in. core bits were used from 6,000 ft to 9,912 ft. Coring was terminated at 9,912 ft because major loss of circulation problems occurred. Both polycrystalline-diamond (PD) soft formation and natural-diamond (ND) medium-hard formation bits were used down to 7,100 ft, while ND hard-abrasive formation bits were used for the remaining part of the hole. A summary of coring and bit records is presented in Tables 5.1 and 5.2. Additional information is presented in Report F (Appendix A; Bechtel, 1987), which includes the coring engineer's daily reports.

5.4 DIRECTIONAL DRILLING

After setting the 9-5/8 in. casing at 6,000 ft, it was necessary to directionally drill the hole to keep it from crossing the eastern lease boundary line. A summary of the directional surveys and the projected path of the borehole are presented in Section 7, based on data from Reports H and I, Appendix A. The first turn was made from 6,045 ft to 6,316 ft in four runs, using two Eastman-

Table 5.1 Summary of Coring Operations

Core Number	Depth Started (ft)	Bit Diameter (in.)	Bit Type - Formation	Average Penetration Rate (ft/hr)	Core Diameter (in.)	Barrel Type	Catcher Type	Barrel Length (ft)	Distance Drilled (ft)	Length Recovered (ft)	Percent Recovery	Reason for Stopping
1	1,553	9.875	PD - soft(a)	6.9	5.25	S(b)	S/D(c)	30	25	24.6	98.4	Completed
2	1,983	9.875	PD - soft	8.5	5.25	S	S/D	30	30	29.2	97.3	Completed
3	2,448	9.875	PD - soft	8.6	5.25	S	S/D	30	30	30.0	100.0	Completed
4	2,970	9.875	PD - soft	26.7	5.25	S	S/D	60	60	58.4	97.3	Completed
5	3,080	17.5(d)	-	-	12.00	-	-	-	-	4.0	-	-
6	3,107	9.875	PD - soft	23.5	5.25	S	S/D	60	60	54.7	91.2	Completed
7	3,470	9.875	PD - soft	6.4	5.25	S	S/D	60	35	34.0	97.1	Jammed
8	3,790	9.875	PD - soft	13.3	5.25	S	S/D	60	60	56.6	94.3	Completed
9	4,007	9.875	PD - soft	12.0	5.25	S	S/D	60	60	60.0	100.0	Completed
10	4,241	9.875	PD - soft	16.7	5.25	S	S/D	60	60	59.4	99.0	Completed
11	4,301	9.875	PD - soft	9.4	5.25	S	S/D	60	36	36.0	100.0	Bit damaged
12	4,643	9.875	ND - med to hd(e,f)	9.4	5.25	S	S/D	60	38	37.5	98.6	Jammed
13	4,680	9.875	ND - med to hd	3.0	5.25	S	S/D	60	5	2.0	40.0	Jammed
14	4,710	12.25(d)	-	-	6.00	-	-	-	-	0.5	-	-
15	5,188	9.875	ND - med to hd	3.5	5.25	A(g)	S/D	30	30	30.0	100.0	Completed
16	5,574	9.875	ND - med to hd	2.6	5.25	A	S/D	30	17.5	17.5	100.0	Jammed
17	6,027	8.5	SCP	1.6	4	A	S/D	30	18	14.8	82.2	Twist off
18	6,506	8.5	PD - soft	7.6	4	A	S/K(h)	30	11	11.0	100.0	Jammed
19	6,758	8.5	PD - soft	16.3	4	S	S/K	30	13(i)	8.0	61.5	Jammed
20	6,880	8.5	PD - soft	19.6	4	S	S/K	30	9(i)	9.0	100.0	Jammed
21	7,100	8.5	PD - soft	6.0	4	S	S/K	30	9	7.0	77.7	Jammed
22	7,300	8.5	PD - hd,ab(j)	9.8	4	C(k)	S/K	30	13	11.5	88.5	Jammed
23	7,547	8.5	PD - hd,ab	10.0	4	C	S/K	30	30	27.5	91.6	Completed
24	7,708	8.5	PD - hd,ab	11.4	4	C	S/K	30	30	30.0	100.0	Completed
25	8,133	8.5	PD - hd,ab	5.6	4	C	S/K	30	29(i)	28.0	96.5	Jammed
26	8,395	8.5	PD - hd,ab	2.5	4	C	S/K	30	6	5.0	83.3	Jammed
27	8,585	8.5	PD - hd,ab	5.7	4	C	S/K	30	19	12.0	63.2	Jammed
28	8,800	8.5	PD - hd,ab	3.2	4	C	S/K	30	7(i)	4.5	64.3	Jammed
29	9,004	8.5	PD - hd,ab	4.9	4	C	S/K	30	23(i)	5.5	23.9	Jammed
30	9,095	8.5	PD - hd,ab	1.5	4	C	S/K	30	3	3.0	100.0	Jammed
31	9,248	8.5	PD - hd,ab	1.5	4	C	S/K	30	6	3.5	58.3	Jammed
32	9,453	8.5	PD - hd,ab	1.0	4	C	S/K	30	5	2.3	46.0	Bit damaged
33	9,458	8.5	PD - hd,ab	4.7	4	C	S/K	30	15	5.0	33.3	Bit dull
34	9,473	8.5	ND - med hard	4.2	4	C	S/K	30	4(i)	2.0	50.0	Jammed
35	9,694	8.5	ND - med hard	1.8	4	C	S/K	30	4	3.5	87.5	Bit damaged
36	9,907	7.625	ND - med hard	0.5	3.5	S		30	5	1.0	20.0	Bit damaged
							TOTALS:		805.5	728.5	90.4	

(a) PD = polycrystalline diamond
(b) S = unplated steel
(c) S/D = slip and dog catcher
(d) Recovered in junk basket
(e) ND = natural diamond
(f) hd = hard
(g) A = aluminium
(h) S/K= slip and knife catcher
(i) Coring done with lost circulation (blind)
(j) ab = abrasive
(k) Chrome-plated

Table 5.2 Summary of Core Bit Performance

Core No.	Bit Diameter, in.	Bit Type	Bit No.	Length Recovered, ft	Rotating Hrs	Trip Hours	Total Hours	Hourly Operating Costs(b)	Total Operating Cost, $	Coring Subcontractor Cost, $	Total Cost, $	Core Cost per Foot, $	Cumulative Cost, $	Cumulative Footage	Cumulative Cost per Foot, $
1	9.875	RC-476	1	24.6	3.5	8.0	11.5	600	6,900	3,250	10,150	413	10,150	24.6	413
2	9.875	RC-476		29.2	3.6	10.9	14.5	600	8,700	3,725	12,425	426	22,575	53.8	420
3	9.875	RC-476		30	3.5	9.5	13.0	600	7,800	3,725	11,525	384	34,100	83.8	407
4(e)	9.875	RC-476		58.4	2.25	10.75	13.0	600	7,800	6,000	13,800	236	47,900	142.2	337
6	9.875	RC-476	2	54.7	2.6	5.9	8.5	650	5,525	6,000	11,525	210	59,425	200.9	296
7	9.875	RC-476		34	5.5	7.0	12.5	650	8,125	4,100	12,225	360	71,650	234.9	305
8	9.875	RC-476		56.6	4.5	9.0	13.5	650	8,775	6,000	14,775	261	86,425	291.5	296
9	9.875	RC-476		60	5.0	12.0	17.0	650	11,050	6,000	17,050	284	103,475	351.5	294
10	9.875	RC-476		39.6	3.5	9.5	13.0	650	8,450	6,000	14,450	243	117,925	410.9	287
11	9.865	RC-476		36	3.5	5.0	8.0	650	5,200	3,950	9,150	254	127,075	446.9	284
12	9.857	C-201	3	37.5	3.5	7.75	11.25	700	7,875	3,950	11,825	315	138,900	484.4	287
13(e)	9.875	C-201		2	2.0	9.0	11.0	700	7,700	2,200	9,900	4,950	148,800	486.4	306
15	9.875	C-201		30	6.5	13.25	19.75	700	13,825	4,925	18,750	625	167,550	516.9	324
16	9.865	C-201		17.5	8.5	10.5	19.0	700	13,300	2,750	16,050	917	183,600	534.4	344
17	8.5	SCP	4	14.8	11.0	17.0	28.0	700	19,600	3,125	22,725	1,535	206,325	549.2	376
18	8.5	RC-476	5	11	1.5	14.5	16.0	700	11,200	2,750	13,950	1,268	220,275	560.2	393
19	8.5	RC-476		8	0.8	16.2	17.0	750	12,750	2,850	15,600	1,950	235,875	568.2	415
20	8.5	RC-476		9	0.5	13.5	14.0	750	10,500	2,650	13,150	1,461	249,025	577.2	431
21	8.5	RC-476		7	1.0	13.5	14.5	750	10,875	1,900	12,750	1,821	261,775	584.2	448
22	8.5	SC-226	6	11.5	1.3	14.2	15.5	750	11,625	2,100	13,725	1,193	275,500	595.7	462
23	8.5	SC-226		27.5	3.0	14.0	17.0	750	12,750	3,000	15,750	572	291,250	623.2	467
24	8.5	SC-226		30	2.6	14.9	17.5	750	13,125	3,000	16,125	538	307,375	653.2	471
25	8.5	SC-226		28	4.5	15.0	19.5	750	14,625	2,900	17,525	626	324,900	681.2	477
26	8.5	SC-226		5	2.8	14.2	17.0	750	12,750	1,800	14,450	2,890	339,350	686.2	495
27	8.5	SC-226		12	3.3	16.7	20.0	800	16,000	2,425	18,425	1,535	357,775	698.2	512
28	8.5	SC-226		4.5	2.2	15.3	17.5	800	14,000	1,800	15,800	3,511	373,575	702.7	531

Table 5.2 (cont.) Summary of Core Bit Performance

Core No.	Bit Diameter, in.	Bit Type	Bit No.	Length Recovered, ft	Rotating Hrs	Trip Hours	Total Hours	Hourly Operating Costs(b)	Total Operating Cost, $	Coring Subcontractor Cost, $	Total Cost, $	Core Cost per Foot, $	Cumulative Cost, $	Cumulative Footage	Cumulative Cost per Foot, $
29	8.5	SC-226		5.5	4.5	15.0	19.5	800	15,600	2,625	18,225	3,314	391,800	708.2	553
30	8.5	SC-226		3	2.0	14.5	16.5	800	13,200	1,600	14,800	4,933	406,600	711.2	572
31	8.5	SC-226		3.5	3.5	17.5	21.0	800	16,800	1,700	18,500	5,286	425,100	714.7	595
32	8.5	SC-226		2.3	4.5	15.0	19.5	800	15,600	1,700	17,300	7,522	442,400	717	617
33	8.5	SC-226	7	5	3.5	9.5	13.0	800	10,400	2,225	12,625	2,525	455,025	722	630
34	8.5	C-201	8	2	0.75	20.75	21.5	800	17,200	1,600	18,800	9,400(c)	473,825	724	654
35	8.5	C-201	9	3.5	2.25	23.75	26.0	800	20,800	1,650	22,450	6,414	496,275	727.5	682
36	7.625	C-201	10	1	8.5	21.5	30.0	800	24,000	1,700	25,700	25,700(d)	521,975	728.5	717

(a) Coring engineering cost: $93\ \text{days x}\ \$525/\text{day} = \frac{\$48{,}825}{34\ \text{cores}} = \$1{,}436/\text{core}$

(b) Approximate for a typical drilling day, not including directional drilling, fishing, or other special operations

(c) 6,267 $/ft based on 3 ft cored

(d) 6,400 $/ft based on 5 ft cored

(e) Cores 5 and 14 were recovered in the junk basket

Whipstock 6-3/4 in. Turbo drills and a 1.5° bent sub. Turbo drills were used instead of positive-displacement type mud motors, because of the high temperatures. Thermal damage to gaskets of the turbos was still considerable. A second directional turn was required from 7,734 ft to 8,133 ft, after the hole again deviated towards the east boundary line. This last turn required nine runs, using four turbo drills. The directional drilling runs are summarized as follows:

Date	Run No.	Turbo-Drill No	Interval (ft)	Remarks
1985				
12-18, 19, 20	1	1	6,045-6,112	Turbo-drill mandrell twisted off
12-21, 22	2	2	6,112-6,166	
12-22, 23	3	2	6,166-6,227	
1986				
01-02	4	2	6,227-6,316	Finished first turn
01-21	5, 6	3	7,734-7,794	Started second turn
01-23	7, 8, 9	4	7,794-7,935	
01-24	10, 11	5	7,972-8,027	
01-25	12	6	8,027-8,070	
01-27	13	6	8,126-8,133	Finished second turn

No additional directional drilling was required.

5.5 BIT RECORDS AND PENETRATION RATES

A summary of bit usage is presented in Table 5.3. The 19 mill-tooth bits were used in the softer, upper formations and for reaming service. The 41 insert bits, which were effective in the harder formations, were predominantly API 537 and 637. The one Norton Christensen Stratapak bit was used on one of the six turbo runs.

Average hourly penetration rates during drilling are summarized in Table 5.4. The average penetration rate was relatively constant at approximately 25 ft/hr from 3,000 ft to 8,000 ft, including approximately 550 ft directionally drilled at an average penetration rate of 15 ft/hr. From approximately 9,500 ft, where intrusive igneous dikes were encountered, to total depth (TD), drilling became progressively slower. The siltstones, mudstones, and sandstones encountered at shallower depths had been converted to harder, hornfelsic and quartzitic forms. From 6,000 ft to 10,475 ft, the footage drilled per bit ranged from 150 ft to 234 ft. For the same interval, the

Table 5.3
BIT USAGE SUMMARY

Diameter (in.)	Type	Quantity	Well Depth (ft)
17-1/2	Mill Tooth	6	Surface to 3,500
12-1/4	Mill Tooth	7	3,500 to 6,000
	Carbide Insert	6	
8-1/2	Mill Tooth	6	6,000 to 10,475
	Carbide Insert	34	
	Stratapak	1	
6-1/8	Carbide Insert	1	10,475 to 10,564

Table 5.4
DRILLING RATE VERSUS DEPTH

Depth (ft)	Drill Rate (ft/hr) Range	Drill Rate (ft/hr) Approximate Average
1 to 1,000	60 to 1,000	100
1,000 to 2,000	15 to 300	75
2,000 to 3,000	15 to 125	50
3,000 to 8,000	5 to 100	25
8,000 to 9,000	5 to 75	20
9,000 to 10,000	5 to 75	15
10,000 to 10,564	5 to 18	10

average footage per bit for both spent bits and bits pulled to take core was 68 ft to 234 ft, lower than the expected rate of 400 ft originally suggested in the bit program. This was due, in part, to a decision not to rerun used bits with low remaining bit-life after coring trips; this would not be cost-effective, considering the cost of the trip. Therefore, some bits were not completely expended.

Seventeen bits were used during directional drilling operations (turbo drilling). Bit-life averaged about six hours. Total footage averaged about 30 ft per bit, rather than the 150 ft to 230 ft expected in normal service. The bit record is presented in Report J, Appendix A.

5.6 FISHING AND DIFFERENTIAL STICKING

A summary of the fishing operations and occurrences of stuck drill pipe is presented in Table 5.5. Six of the operations performed were to recover tools or junk lost in the hole and four operations were to free differentially stuck drill pipe. Approximately eight days were consumed in fishing operations with almost two days of that time attributed to waiting for tool delivery. The standby time while waiting for tools was used to run temperature and cement bond logs, and to perform a mini-injection test on a potential flow zone.

Brief descriptions of the fishing operations are as follows:

- The first fishing job occurred when two cones from a 17-1/2 in. bit were left in the hole during a reaming run. One magnet run was made without recovery. This was followed by one mill run and two junk-basket runs that recovered 1/2 of one cone and 1/4 of the second cone, plus some bearings. Drilling proceeded without further problems.

- The second fishing job resulted when poor welds broke on the 12-1/4 in. welded-blade stabilizers, leaving 4 blades in the hole. Two junk-basket runs were made without recovery; then three milling runs were made, which cleaned up the junk or pushed it aside into the borehole wall. The welded-blade stabilizers were replaced with integral-blade stabilizers. No similar problems were encountered during subsequent operations. The blades left in the borehole wall may have contributed to the failure of Phase-2 sidetrack operations, however.

- The third and fourth fishing jobs were caused by twist-off in the BHA (bottom-hole assembly). The first twist-off was caused by a washout in the box of a joint of heavy-weight drill pipe located one joint above the drill collars. The second twist-off was caused by a cracked pin in one of the 6-1/4 in. drill collars. Both fishing operations required only one run to recover the lost tools. A more frequent end inspection of the BHA was established to minimize the chance of reoccurrence.

Table 5.5
FISHING OPERATIONS/STUCK PIPE SUMMARY

Job No.	Date	Depth (ft.)	Operation	Waiting On Tools (hours)	Fishing Tools (hours)	Total Time (Hours)
	(1985)					
1	11- 8	3,078	Fish for two 17-1/2 in. bit cones	21	2	
	11- 9		Fish for two 17-1/2 in. bit cones	2	22	
	11-10		Fish for two 17-1/2 in. bit cones	-	12	59
2	11-26	4,710	Fish for four 12-1/4 in. stabilizer blades	19	2.5	
	11-27		Fish for four 12-1/4 in. stabilizer blades	-	24	
	11-28		Fish for four 12-1/4 in. stabilizer blades	-	19.5	65
3	12- 5	5,422	Twisted-off. Fish for BHA	-	7	7
4	12-18	6,043	Twisted-off. Fish for BHA and core bbl.	-	8	8
5	12-20	6,112	Fish for Turbo-Drill mandrel & 8-1/2 in. bit	4	5	
	12-21			-	2	11
	(1986)					
6	02-09	9,249	Work stuck pipe	-	6	6
7	02-11	9,450	Run junk sub to recover buttons from bit	-	8	8
8	02-22	9,473	Work stuck pipe	-	2	
	02-23		Work stuck pipe	-	3	5
9	02-24	9,517	Work stuck pipe	-	10	10
10	03-06	10,212	Work stuck pipe	-	9	9
			Total	46	142	188

- The fifth fishing job occurred when the mandrel in the Turbo-Drill twisted off while directionally drilling, leaving the mandrel and bit in the hole. The fish was recovered in one run and drilling proceeded without further incident.
- One junk-basket run was made to recover some tungsten carbide bit-buttons prior to making a coring run.
- Differential sticking of the drill string occurred at 9,249 ft, 9,473 ft, 9,517 and 10,212 ft. About 100 bbls of diesel, mixed with 5-10 gallons of oil-soluble surfactant, was used to free the pipe each time. Usually, freeing of the drill string was accompanied by well flow.

5.7 DRILLING FLUIDS PROGRAM

A fresh-water, gel-base mud was used to 1,983 ft. Below this depth, the mud system was converted to a high-temperature drilling fluid. The high-temperature mud was maintained throughout the remainder of the hole, except where loss of circulation occurred. It was necessary to drill or core with water when lost circulation occurred.

Control of mud weight and solids content was aided by the use of both a mud cleaner and a centrifuge which were used in conjunction with the rig's dual-tandem shakers. In addition to the 1,500-barrel surface mud capacity, two mud coolers were used to maintain mud temperatures below the flash point while drilling. Details of mud properties and daily costs are summarized in Bechtel (1987) Report X and in the mud engineer's daily reports, Bechtel (1987) Report L (Appendix A).

Ultimately, all drilling fluids were properly disposed. Some liquids were injected after completion of the flow tests. In addition, part of the drilling mud was disposed at a state-approved hazardous-waste site in the Imperial Valley. After all testing was completed, the remaining drilling fluids were disposed at the same hazardous-waste site (Section 12).

5.8 LOST-CIRCULATION CONTROL

The zones of major lost circulation occurred between 6,119 ft and 10,564 ft (total depth). The zones of primary loss occurred from 6,119 ft to 6,133 ft (first flow-test zone), 6,637 ft to 6,889 ft, 8,095 ft to 8,800 ft, 8,948 ft to 9,473 ft and 10,475 ft to 10,564 ft. Repeated loss of circulation was experienced in the zone at 8,095 to 8,800 ft. The fluid-loss zones can be readily seen as temperature reversals on the temperature plot in Figure 5.2. Only one fluid-loss zone was encountered above 6,000 ft. This zone, which occurred between 2,987 ft and 3,200 ft, was controlled by the addition of small amounts of lost-circulation material (LCM) to the mud system.

The LCM typically used was mostly organic, consisting of sawdust, cotton-seed hulls (CSH), cotton-seed pellets (CSP), cedar fiber and blended fibers, all of which were thermally degradable. In addition, 88 sacks of ground up battery cases were tried, but had little or no effect in reducing loss of circulation.

Standard methods of using LCM in the mud system were ineffective in the high fluid-loss zones below 6,000 ft. Methods used to control loss of circulation in these zones included LCM pills, LCM/cement pills and cement plugs.

Typical formulations and volumes for the pills and cement plugs were:

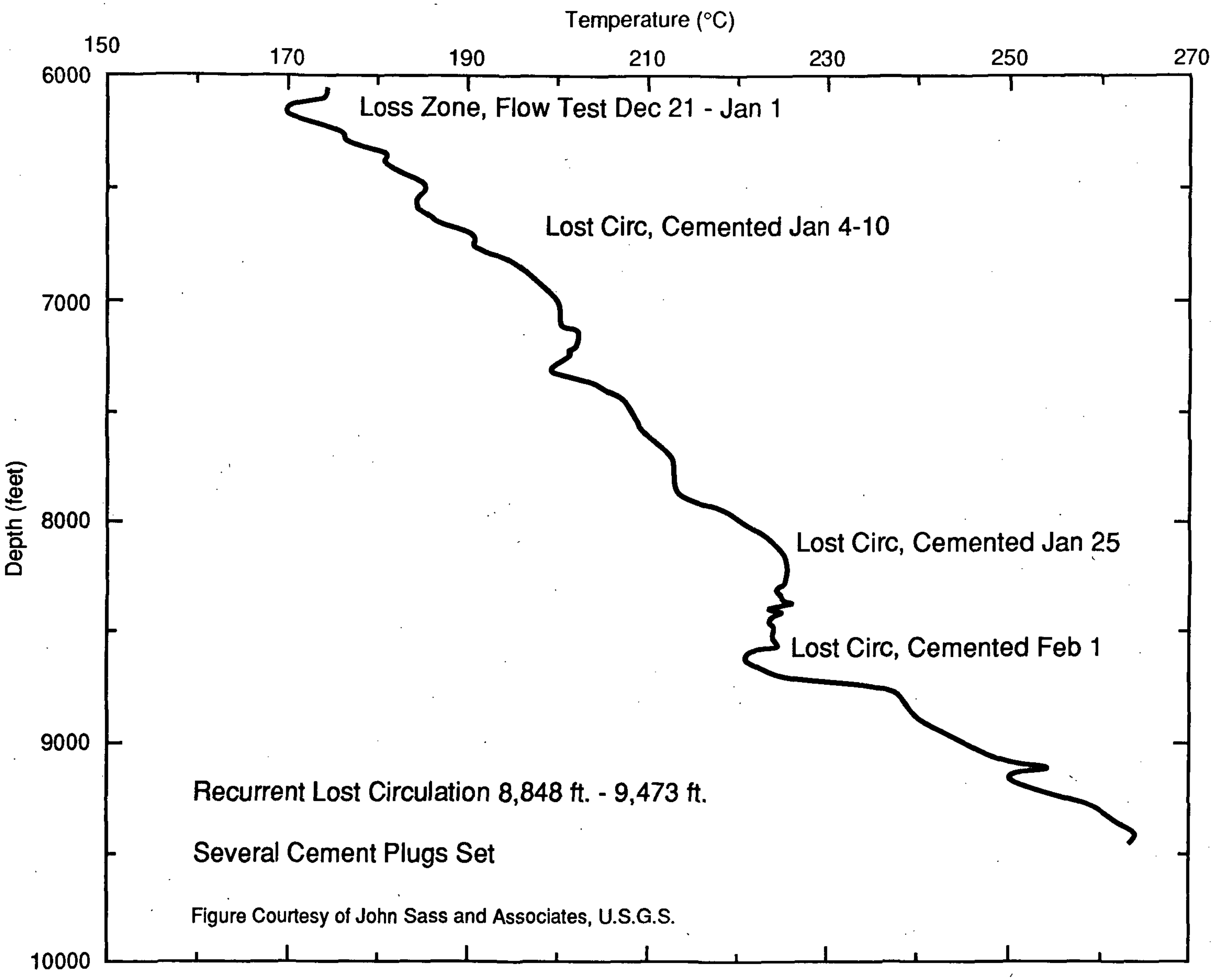


Figure Courtesy of John Sass and Associates, U.S.G.S.

USGS Temperature log, Feb 15, 1986, State 2-14 (SSSDP)

Figure 5.2 Plot of Temperature vs. Depth for State 2-14

- LCM Pill - Mixed 10 sacks each of CSH, cedar fiber, sawdust, and blended fiber with gel to make a 50 bbl to 100 bbl viscous pill
- LCM/Cement Pill - An LCM pill with 35 sacks of Portland cement added. Made up in 35- to 50-bbl batches
- Cement Plug - Class-G cement, 1:1 perlite, 40 percent silica flour, 3 percent gel, 0.65 percent CFR-2 and 2.5 percent HR-12. Usually implaced in 35 bbl batches

The LCM pills were partially effective in regaining circulation; however, once the pill was cleaned out and drilling resumed, loss of circulation would recur within hours to a few days, as the organic materials were degraded by the high downhole temperatures. The LCM/cement pills were more effective in regaining circulation, but also tended to degrade in a short period. The advantages of the LCM/cement pills were that they were relatively inexpensive, could be mixed and pumped by the rig, and minimized rig-standby time. The cement plug was the most effective means of combating lost circulation, but was more expensive and required the services of an oil-well cementing company. Although the cement plugs were effective, even these degraded with time, causing a recurrence of lost circulation.

The procedure used for spotting the pills was as follows:

- Pull up into casing while mixing pill
- Run in hole (RIH) and spot pill
- Pull back into casing and wait 2-4 hours
- Fill hole through annulus with water
- Close rams and pump 10 bbls slowly (10 strokes per minute) to obtain a squeeze of 200 psi
- Resume drilling, if successful, or repeat procedure

Precautions were taken to minimize damage to LCM "patches." They included tripping the drill string slowly, and staging in and breaking circulation in ten-stand increments from the shoe to TD to minimize pressure surges in the wellbore.

An additional problem, along with the loss of circulation, was that the well warmed sufficiently to flow when the mud weight was too low or the cooling rate was inadequate. An influx of brine usually occurred when the mud weight fell below 8.6 lb/gal or diesel was added to free stuck drill pipe. Discontinuing circulation for tripping was accompanied by well flow, especially below about 8,000 ft.

Conversely, if the mud weight was allowed to rise above 8.9 lbs/gal, circulation would usually be lost as LCM patches collapsed or the formation fractured. Usually 200 to 300 bbls of brine were circulated to the surface and dumped into the reserve pit before the flow was controlled. Normally, a 70 bbl pill of 9 to 11 lb/gal mud was sufficient to control the flow. The pill was either spotted at the shoe or "bullheaded" down the casing through the kill line, depending on whether or not tools were in the hole at the time. Maintaining a balance between mud weight and bottom-hole temperature, while conducting drilling and coring operations, was a continuing problem, from the perspective of both cost and safety.

A summary of lost circulation and remedial action is shown in Table 5-6.

Table 5.6

LOST CIRCULATION AND REMEDIAL ACTION

Date (1986)	Depth (ft)	No. LCM Pills	No. LCM/ Cem. Pills	No. Cem. Plugs	Well Flowing (x)	Remarks
01-04	6,637	2	-	-	-	Lost all returns
01-05	6,758	2	-	-	-	No returns
01-06	6,758	2	-	2	-	Waiting on Cement (WOC)
01-10	-	-	-	-	x	Tagged cement plug @ 6,410 ft
01-11	6,818	3	-	-	-	Lost returns @ 6,803 ft
01-12	6,850	2	-	2	-	Cemented-up 9 joints drill pipe
01-15	6,773	-		1	-	-Tagged plug @ 6,640 ft
01-26	8,126	2	-	-	-	Lost all returns @ 8,094 ft
01-27	8,133	3	-	-	x	Spotted last pill @ shoe
01-28	8,161	2	1	-	-	Lost returns @ 8,134 ft
01-29	8,161	1	1	-	-	Regained circulation
02-01	8,635	2	-	-	x	No returns @ 8,604 ft
02-02	8,692	2	1	-	x	Lost returns while circulating @ shoe
02-03	8,807	1	-	-	-	Regained clrculation @ 8,800 ft
02-04	9,004	2	-	-	-	Lost returns @ 8,948 ft
02-05	9,027	-	1	-	-	
02-06	9,095	3	-	-	-	
02-07	9,098	1	1	-	-	Squeezed plug to 400 psi
02-09	9,254	-	-	-	x	Spotted 9 ppg of mud to kill well
02-10	9,450	-	-	-	x	
02-11	9,453	1	1	-	x	Squeezed plug to 200 psi
02-13	9,473	1	-	-	-	
02-14	9,473	-	-	-	x	
02-15	9,473	-	-	-	x	Injected 300 bbls mud to kill well
02-16	9,473	-	3	-	x	Spotted plugs @ 9,200 ft, 8,500 ft and 7,400 ft
02-17	9,473	-	-	-	-	staged-in hole from shoe
02-19	9,473	-	-	4	-	Spotted plugs at 9,230 ft, twice, and 8,750 to 8,293 ft. Stuck pipe on first plug and pulled free. Squeezed to 200 psi. 10 bbl increments - 10 spm
02-20	9,473	-	-	3	-	Spotted plugs @ 8,105 ft, 7,390 ft and 6,292 ft Tagged cement @ 6,165 ft. Drill out cement
02-21	9,473	-	-	1	-	Lost returns @ 6095 ft. Spotted plug @ 6,500 ft. Drilled out cement to 8,303 ft with full returns

Table 5.6 (Cont'd)

Date (1986)	Depth (ft)	No. LCM Pills	No. LCM/ Cem. Pills	No. Cem. Plugs	Well Flowing (x)	Remarks
02-22	9,473	-	-	-	-	Stuck pipe at 9,440 ft . Full returns
02-23	9,517	-	-	-	x	Increased mud wt. 8.2-8.5 ppg
02-24	9,517	-	-	-	x	Stuck pipe 9,458 ft
02-27	9,694	-	-	-	x	Spotted 10 ppg pill
02-28	9,698	-	-	-	x	Spotted 10 ppg pill
03-05						Stuck pipe @ 10,212 ft
03-07	10,374	-	-	-	x	Killed well with heavy-weight pill
03-08	10,475	1	-	-	-	Lost returns @ 10,475 ft
03-09	10,475	1	-	-	x	Spotted sand plug w/LCM pill on top
03-10	10,475	1	-	-	x	
03-11	10,475	-	-	1	-	Spotted plug @ 10,414 ft
03-12	10,475	-	-	1	-	Spotted plug @ 10,414 ft.Plugged 42 joints drill pipe
03-13	10,475	3	-	-	x	Tagged plug @ 10,266 ft.Spotted pills @ 10,266 ft 8,000 ft and 10,266 ft
03-14	10,475	1	-	-	x	Killed well with 11 ppg pill
03-15	10,475	3	-	-	x	Spotted 70 bbl, 11.5 ppg pill @ shoe
03-17	10,564	1	-	-	x	Drilled blind from 10,475 ft to 10,564 ft

5.9 REMEDIAL WORK OF AUGUST 1986

5.9.1 Summary

On March 20, 1986, the second flow test was initiated. The well flowed for approximately 38 hr., producing 1.1 million gallons of brine. Estimates of downhole temperatures and pressures at 10,440 ft were 667°F and 4,287 psi, respectively, which were based on the Kuster tool runs. Surface analysis for H_2S indicated from 7-7.4 ppm. Reservoir H_2S was estimated at 50-70 ppm.

From March 26 to 27, 1986, the produced brine was injected into the well and displaced with 500 bbl of fresh water, containing an oxygen scavenging agent. During the 4 days between the flow test and injection, logging and fluid sampling operations were performed. Logging was conducted for 4 days after the injection. On April 22, 1986, a temperature log was run without incident. This was 38 days after installing the liner.

On May 28 through 29, 1986, USGS temperature logs that were scheduled to reach 10,000 ft were performed at State 2-14, only to a depth of 6,380 ft. Two problems were encountered during the run: the tool (a) repeatedly stopped at 6,380 ft going down, and (b) repeatedly hung-up at 6,195 ft coming up. After hours of attempting to withdraw the tool, it was finally recovered. The suspected cause of the logging problems was a liner separation of approximately 200 ft.

From June 24 to June 26, diagnostic testing of the 7 in. liner was performed, including a minimum I.D. caliper, continuous temperature/collar locator, and casing inspection runs. All tests were performed after the well was cooled by water injection. A summary of these logs is presented in Table 5.7. The key results were: (a) the liner had separated at a collar at 6,181 ft; (b) open hole existed from 6,181 ft to 6,422 ft; and (c) the liner was not badly corroded or internally worn.

The original design criteria for the well stated that the well would only have to stay open for 6 months after completion. Based on this and on casing costs, N-80, 8-round thread, 29 lb/ft LTC casing was used since N-80 quenched and tempered casing is recommended for H_2S environments above 150°F. This well, however, is low in H_2S compared to the environments that require N-80 casing.

Another decision made just prior to installation of the liner was that the liner guide-shoe would be drilled-out and a 6-1/8 in. hole would be drilled below the existing 8-1/2 in. hole at 10,475 ft to ensure a connection with a suspected lower flow zone. To ensure that the uncemented liner would not back-off during drilling operations, the casing makeup torque was increased above the optimum 5,970 ft-lb. However, it was kept below the maximum recommended torque of 7,460 ft lb.

Field work commenced August 7 with mobilization of the drill-rig contractor. The Drilling Supervisor's Report and other supporting documentation are reported in Bechtel (1987) report M, (Appendix A). The work was completed August 21 at an estimated project cost of $290,000. Accomplishments included the reestablishment of tool access to at least 8,005 ft and the temporary installation of 793 ft of a 7 in. patch liner from 5,728 ft to 6,521 ft. The final well configuration is shown in Figure 5.3.

Table 5.7
DIAGNOSTIC LOGGING SUMMARY

Date (1986)	Log	Interval, (ft)	Results
6-25	Minimum ID caliper	5,700 - 6,375	High noise level; collars were not located. Top of liner: 5,767 ft; bottom of liner: 6,180 ft, tagged bottom: 6,375 ft
6-25	Minimum ID caliper (rerun)	5,700 - 6,422	High noise level; collars were not located. Top of liner: 5,770 ft; bottom of liner: 6,181 ft; restriction in liner: 6,338 ft; tagged bottom: 6,422 ft
6-26	Temperature log and collar locator	4,994 - 6,180	Collars located. Top of liner: 5,770 ft; bottom of liner: 6,183 ft; log terminated due to rising temperature (220°F)
6-26	Casing inspection log	6,002 - 6,170	Good casing thickness (0.400 in.). Inside and outside radius determined

On August 7 to 12, 1986, the drill rig was mobilized for remedial work to repair the damaged liner. The objective was to remove the liner hanger and attached liner, replace it with a new hanger and liner sufficient to reach, and tie-into, the lower string of original liner. This was intended to reestablish continuity to the bottom of the liner, permitting measurement of the bottom-hole temperature.

At the conclusion of the remedial work, nine joints of liner were removed. A preliminary metallurgical analysis of the failed liner, prepared by Brookhaven National Laboratory (BNL), was included as Bechtel (1987) report GG (Appendix A). This analysis was based on four samples of the recovered liner that were submitted to them for analysis. Junction numbers 1 and 2, as listed by BNL, were collars with portions of the 7 in. liner still attached. Junction number 3 was the pin-end of the liner, where the initial parting of the liner had occurred. Junction number 4 was not part of the liner, but slip segments from the liner hanger that had been torn-off while retrieving the liner.

Observations of the liner and liner hanger are as follows:

- The liner hanger showed signs of erosion on the outside body indicating that the seals had leaked. Examination of the seals showed that they were all in place, but badly charred. The slip segments had come off the drag springs, because the Allen bolts holding the slips to the drag springs had completely corroded. Although the liner hanger was designed for geothermal use, the fasteners for the segments apparently were not. Inspection of the polished-bore receptacle (PBR) showed a high degree of pitting on the inside bore.

- Visual cracks were noted in the couplings with extreme cracking in the coupling on the bottom of the fourth joint (Junction 2 in the BNL report).

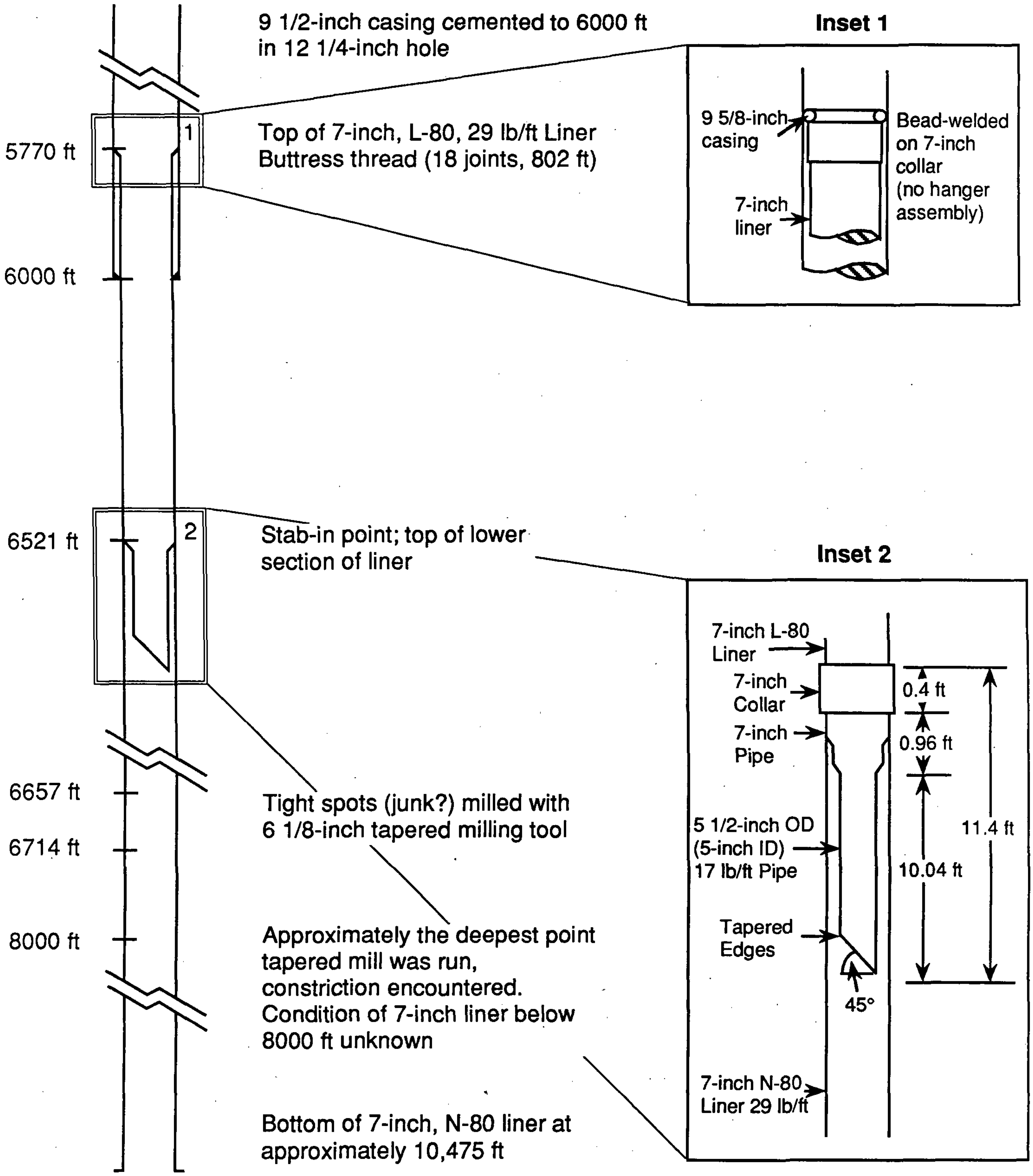


Figure Courtesy of R.H. Wallace, Jr.

Figure 5.3 **Schematic of Wellbore Configuration After August 1986 Repairs**

5.9.2 Remedial Operations

The specific chronology of events that occurred during the remedial work is as follows:

Date (1986)	Activity
August 7,8	Activated site, installed water lines and utilities, and assured that equipment was on site.
August 9,10	Killed well, nippled-up, installed and tested the Blowout Prevention Equipment (BOPE).
August 11,12	Picked-up drill collars and drill pipe, cooled well, and spotted lost-circulation material (LCM) pill. Ran-in hole (RIH) and tagged fish at 5,782. RIH with spear.
August 13	Speared fish and pulled-out of hole (POH). Fish became stuck in expansion spool; set cement plug at 450 ft.
August 14	Rigged-down rotary table and rig floor, nippled-down BOPE, including master valve and expansion spool. Nippled-up BOPE, and rigged-up floor and rotary table. Retrieved 4 joints of 7 in. liner, liner hanger, and polished-bore receptacle. Ran 8-1/2 in. bit to drill cement plug.
August 15	Tagged top of liner at 6,301 ft. POH, picked-up spear and RIH. POH with 5 joints of 7 in. liner. RIH, tagged lower section of liner at 6,519 ft.
August 16	RIH with 6-1/8 in. tapered milling tool and worked to 8,005 ft.
August 17	POH, layed down tapered mill. Picked-up and ran 8-1/8 in. pilot mill on top of collar, 6,519 to 6,521 ft. POH, all blades broken-off bit. Ran sawtooth mill.
August 18	Worked over at 6,519 ft and POH. Ran 18 joints (802 ft) of 7 in. liner with 10 ft of 5-1/2 in. tubing. Stabbed-into lower 7 in. liner section.
August 19	Set retrievable bridge plug at 260 ft. Nippled-down BOPE, master valve, and expansion spool. Replaced expansion-spool seal assembly. Reassembled wellhead.
August 20 21, 22	Retrieved bridge plug and deactivated both rig and site.

- No cracks were observed in any of the recovered liner. Note: BNL indicated that no cracks were observed in the sections of liner that they received.
- Both the collars and the liner showed signs of corrosion.
- There was a 5° dogleg in the zone where the liner parted.

Based upon the BNL report, the following conclusions were suggested:

- The collars probably failed by a stress-corrosion/hydrogen-embrittlement mechanism caused by the susceptibility of a martensitic structure at a marginal strength level, and the high hardness, especially on the outside surface, to stress corrosion and/or hydrogen embrittlement. The cracking resulted from a combination of this susceptibility with high tightening tensile stress, and the presence of H_2S in the environment, as well as the introduction of 0_2 and the lowering of temperature during injection of produced brine.
- The effects of the additional stresses from the dogleg in the well have not been determined. This could be determined when more of the liner is removed from the well.

Lessons: In retrospect, several actions should have been taken that may have prevented the liner failure. Normal geothermal practice would be to use buttress-threaded L-80 liner because the N-80, 8-round threaded liner was not adequate for the bending stresses or compressive stresses existing in the well. The L-80 liner is a lower-hardness type steel and less susceptible to embrittlement. Double liner hangers should have been used, as is normal practice in the Salton Sea Geothermal Field. On-site quality-control procedures should have rejected the substandard fasteners on the liner hanger. The torque ratings for the liner couplings should have been recalculated for service at over 600°F, and the torque used on the liner should have been reduced accordingly.

5.9.3 Followup Logging Attempts

The first downhole logging following the remedial work was performed the week of October 20. On October 22, a dewared Kuster tool lowered into State 2-14 encountered a soft bridge at 5,800 ft and stopped at 5,810 ft. After retrieving the tool and upon inspection of the bull nose, significant quantities of gel-like drilling mud were observed. On October 23, a 2 in. diameter sinker bar was worked through 917 ft of this gel from 5,800 ft to 6,717 ft in an attempt to loosen it. The next day, the digital temperature tool was run in the hole and was stopped by a gel bridge at 5,822 ft. Considering the risk of losing the tool, the log was terminated and the tool retrieved.

In light of the logging experience, the liner was assumed to be full of gel from 5,800 ft to at least 8,000 ft. During the final water displacement of the mud in August, the water may have flowed around the top of the replacement liner rather than down through it. If so, mud located below 5,800 ft was deadheaded and was not circulated out. It may be, however, that mud migrated back up into the liner from the lower part of the well, or that an early termination of the flushing operation left gel-mud in the well-bore to harden and plug.

5.10 REFERENCES

Elders, W.A., and Sass, J.H., 1988, The Salton Sea Scientific Drilling Project: Its Scientific Significance: J. Geophys. Res., Vol. 93, No. B11, pp. 12,953 - 12,968.

Bechtel National, Inc., March 1987, Salton Sea Scientific Drilling Program - Drilling and Engineering Program: (Draft) Final Report; Prepared for U.S. Department of Energy, 98 p.

Harper, C.A., and Rabb, D.T., 1986, The Salton Sea Scientific Drilling Project: Drilling Summary: Geothermal Resources Council Transactions, Vol. 10, pp. 455-459.

6.0 WELL REWORK OF PHASE 2 - AUGUST 1987

6.1 INTRODUCTION

Remedial work of August 1986 successfully removed the liner-hanger and nine joints of 7-in. liner, and installed 793 ft of 7-in. patch liner from 5,728 to 6,521 ft. On the first temperature logging attempt following the rework, October 20 to 24, 1986, the liner was found to be full of congealed drilling mud from 5,800 to at least 6,717 ft, the greatest depth to which a sinker bar could penetrate. On October 24 the digital temperature tool was stopped by a gel bridge at 5,822 ft, the log was terminated, and the tool retrieved.

The inability to access deeper parts of the well for the long-term flow test led to additional rework performed in August 1987. The well rework was to be the first of several Phase-2 activities at well State 2-14. Other Phase-2 activities included the construction of a flow test facility, performance of a 25-day flow test, brine chemistry studies, and site cleanup.

6.2 WELL REWORK IN AUGUST 1987

The primary objective of the rework in August 1987 was to reestablish a passageway to bottom-hole for conducting a long-term flow test of deeper reservoir zones. It would be necessary to isolate lost-circulation zones deeper than 8,000 ft from those shallower than 8,000 ft with a new 7-in. liner cemented in place. This would assure flow from only the deeper zones during a planned long-term flow test. In addition, access to deeper zones for logging would be reestablished.

The wellbore construction after the August 1986 repairs is shown in Figure 5.3. The scope of work called for removal of the 7-in. repair liner installed in August 1986 and as much of the original 7-in. liner as possible. If the removal of the 7-in. liner proved slower than redrilling, the hole would be sidetracked to the greatest depth possible below 8,000 ft. A new liner would be installed and cemented to isolate zones shallower than 8,000 ft from deeper production zones.

Field work began on August 1, 1987, with mobilization of the drilling rig for well repair and was terminated with demobilization of the drilling rig on September 2, 1987. The logging and surveying, liner retrieval, directional drilling, bit record, drilling-fluids program, and short flow test are summarized below.

6.2.1 Logging and Surveying

Before the well was disturbed by repair operations, the USGS ran two temperature surveys. The first survey was limited to 3,000 ft, where the temperature reached 610°F (321 °C), the maximum temperature allowed for the wirleine system. A second temperature log by the USGS was made to 6,000 ft with a digital temperature tool. This temperature logging run failed when fluid leaked into the tool, causing failure of the electronic circuits.

Directional surveys were made for orienting the mud motors and the whipstock tool, while attempting to sidetrack the hole. Only two surveys were run after drilling past the 7-in. liner stub at 6,741 ft (2,055 m). Results of the directional surveys are as follows:

Depth (ft)	Angle Degrees	Azimuth	Remarks
6,038	8	N75E	
6,537	5	N38W	
6,790	6-3/4	S13W	Possible magnetic interference
7,030	8-1/2		Film fogged by heat

6.2.2 Liner Retrieval

The 7 in. temporary-repair liner that was installed during the first rework operation in August 1986 was retrieved without incident. Eighteen joints of liner (802 ft), plus the 10 ft x 5-1/2 in. stab-in joint, were removed from the well. Inspection of the repair liner showed it to be in good condition with little or no corrosion.

A second retrieval (fishing)-spear run engaged the top of the original 7-in. liner at a depth of 6,529 ft. Pulling the liner through the dogleg at about 6,200 ft proved to be difficult. The liner stuck several times coming through the dogleg causing the jars to trip.

Five joints (210 ft., 67 m) of 7-in., 29 lb/ft., N-80, LTC liner were recovered. The pin-end of the fifth joint was split, indicating that it had dropped onto the collar of the liner section below it. Additionally, the last joint of liner was packed full of rocks, baked mud, and some centralizer springs. Inspection of the recovered liner showed it to be in relatively good condition, with some corrosion and no stress cracking in the collars.

Curtailment of fishing operations was considered prudent because of:

- Indications that the lower section of liner was probably full of debris
- Offset of the lower section of liner from the section removed, making success of further fishing operations improbable
- Difficulty experienced in pulling the liner through the dogleg
- High probability of the well flowing while the liner was in the blowout preventer, with no way to shut in the well

The decision was made to attempt to sidetrack the hole instead of continuing the fishing operations.

6.2.3 Directional Drilling

Methods for Directional Drilling. There are three fundamental methods for directional drilling to sidetrack a hole. The more common method in low-temperature wells is the mud motor, using a bent sub. The other methods are the conventional whipstock and locked bottom-hole assembly. The last two methods rely on setting a good cement plug at the point from which the hole is to be sidetracked.

Mud motors consist of two types:

- *Positive displacement motor (PDM).* PDMs use an elastomer stator to radially seal around a helical-spiraled steel rotor.

- *Turbine motor.* Turbine motors are comprised of a series of steel-bladded rotors and stators similar to a jet engine.

The turbine motor is more commonly used in geothermal drilling, because of its ability to operate at slightly higher temperatures [approximately 300 °F (149 °C) versus 260 °F (127 °C) for a PDM]. Turbine motors were used successfully in Phase-1 drilling operations to correct hole deviation problems. However, the radial and thrust bearings of a turbine motor can also be destroyed by exposure to excessive temperature.

A conventional whipstock consists of a long, tapered wedge of steel that is concave on one side to hold and guide a bit against the side of the hole. This tool is used in extremely hot holes or holes that are difficult to sidetrack. The disadvantage of the whipstock is that it must be accurately positioned and cemented; therefore, using it is more time consuming and more expensive.

Cost constraints during drilling operations often led to the choice of low-cost procedures, with low potential of success. The failures of several low-cost procedures during this rework led to a higher overall cost of the operations than would have resulted from choosing procedures with higher chances of success.

A locked bottom-hole assembly is formed by placing stabilizers every few feet behind the drill bit. This produces a stiff assembly that tends to progress in a straight line. Where the existing bore deviates abruptly from a straight line, such as at the dogleg near 6,200 ft, a locked bottom-hole assembly may kick-out from the existing bore in a straight-line extension of the bore, above the deviation. This would initiate a sidetrack from the existing hole.

Sidetracking the State 2-14 Well. The initial approach to sidetracking the State 2-14 well was to start the sidetrack above the dogleg at 6,200 ft. This would eliminate the dogleg problem for the next liner installation.

A cement plug was set from 6,036 to 6,480 ft with 360 ft^3 of cement. Three samples of the cement were taken during the cementing operation and each indicated that a good, hard cement plug had been set.

Four mud motors, one locked bottom-hole assembly, and two whipstock runs were made in attempting to sidetrack the hole. A brief summary of the results follows.

a. *Run No. 1 Using a Mud Motor*. Since mud return temperatures were low (about 115 °F or 46 °C) and injection of 5,000 bbl of cold water was assumed to have cooled the wellbore, a PDM was chosen for the first run, because it has higher torque for a lower flow of mud. It is also usually easier to start than a turbine motor, but has lower tolerance to high temperatures.

   To ensure that the PDM would stay cool, it was staged into the hole. That is, circulation was established at 2,000-ft (610 m) intervals, while tripping into the hole.

   After tagging the cement plug, the plug was drilled out from 6,036 to 6,058 ft before running a survey to orient the tool. The orientation shots took about an hour, during which time the mud was not circulated. After orientation shots, the mud motor would not start.

   The PDM was then pulled-out of the hole and checked. The bit shaft could be turned by hand (which is normally impossible); therefore, the failure of this PDM was initially judged to be a sheared coupling between the power shaft and the bit shaft. However, later inspection showed that the elastomer stator had disintegrated, probably from excessive heat, and drilling fluid had washed the stator away.

b. *Run No. 2 Using a Mud Motor*. A second PDM was staged into the hole. While a directional survey was being completed, one of the rig engines failed, causing complete power failure. The PDM was on bottom, without circulation, for 1-1/2 hours before it could be pulled from the hole. Upon retrieval, the PDM was tested and appeared to be in good condition. However, after repair of the rig engines, the PDM was tested again before running into the hole, and it would not run.

c. *Run No. 3 Using a Mud Motor*. The first turbine motor was picked up and tested before staging-in the hole. The motor was run to 6,063 ft (1,848 m), where an hour was required to survey for orienting the tool. After surveying, the motor would not start, and it was pulled from the hole. Inspection at the surface revealed that the elastomer thrust bearing was shattered, probably by thermal exposure.

d. *Run No. 4 Using a Mud Motor*. A second turbine motor was tested at the surface and then run to the bottom of the hole as fast as possible without staging. Since heating appeared to be the problem, the faster transit was expected to alleviate the problem. Nevertheless, the motor failed to start, and it was pulled from the hole.

e. *Run Using a Locked Bottom-Hole Assembly*. After the mud-motor failures, an attempt was made to effect a sidetrack in the 5-degree dogleg at about 6,200 ft, using a locked bottom-hole assembly. Such a stiff assembly will often sidetrack when it encounters a dogleg; however, this attempt was not only unsuccessful but also ended up drilling out the cement plug. This necessitated setting another cement plug before using a whipstock.

f. *Run No. 1 Using a Whipstock*. A whipstock tool was run in the hole. The tool was pulled from the hole before attempting a sidetrack and a bit run was made to clean out 17 ft of fill.

g. *Run No. 2 Using a Whipstock*. The whipstock was set at 6,536 ft, and a 6-in. pilot hole was drilled to 6,547 ft . This was followed by an 8-1/2 in. hole opener to 6,547 ft. An 8-1/2 in. bit was then used to drill from 6,547 ft to 6,630 ft.

While drilling-out the cement plug, the cement appeared to be relatively soft. However, cutting samples during the whipstock operation indicated hard cement, mixed with formation cuttings; this suggested that some kick-off from the original hole was accomplished. During the drilling operation, the cuttings began to grade more toward cement. Apparently, the bit had wandered back into the original hole. Eventually, the bit penetrated the bottom of the cement plug. At a depth of 7,180 ft an obstruction (probably stabilizer blades pushed aside during drilling of the well) was reached and, after an additional day of milling, DOE directed Bechtel to stop drilling and prepare for a flow test of accessible zones (6,100 - 7,100 ft and deeper zones).

Review of the Sidetracking Attempts. Temperature measurements taken shortly after the PDM runs, using a maximum recording thermometer, showed a temperature of 302 °F at 6,000 ft (150 °C at 1,829 m). Failure of the PDMs was attributed to thermal stress on elastomer components.

The cause of failure of the turbine motors was not immediately evident. One early hypothesis held that the motors may have become blocked by debris, since mud screens had not been used. However, a subsequent report by the subcontractor (Eastman), completed after the motors were disassembled and inspected, indicated that this was not the case. Rather, failure occurred from destruction of the radial and thrust bearings due to thermal stress. This result was surprising, since turbine motors had been used during the initial drilling of the State 2-14 well, where greater temperatures (>300°C) were encountered. The drilling contractor's reports showed that both mud pumps were run at 110 strokes per minute, which implies approximately 550 gpm (35 L/s) flow. This should have been ample to run and cool the turbine motors. However, subsequent examination of computer-printout sheets from the mud logging firm showed that the average pump speed during the first turbine-motor run was about 100 strokes per minute for 250 gpm (16 L/s) mud flow, and that average pump speed was about 120 strokes per minute, producing 300 gpm (19 L/s), during the second turbine-motor run. These flow rates were insufficient to start the turbine motors and were barely enough (at 300 gpm or 19 L/s) to sustain motor operation once started.

Conclusions. The PDMs did not operate because excessive temperature caused the elastomer stators to disintegrate.

Failure of the turbine motors was caused by insufficient fluid flow to operate and cool the motors. Inadequate cooling caused failure of the radial and thrust bearings.

Drilling with a whipstock achieved some kick-off, as indicated by formation cuttings in the returns, but the bit may have never completely exited the original hole, as shown by the presence of some cement in the cuttings.

6.2.4 Bit Record

A total of 10 bits were used in reworking the well: five mill-tooth and five button bits. Three of the mill-tooth bits were 8-1/2 in. diameter, and they were used on the mud motors for sidetracking the hole, for drilling cement and cleaning out fill. Two 6-in. diameter mill-tooth bits drilled the pilot hole during attempts to sidetrack using a whipstock.

The five button bits were used in attempts to drill a new hole. The original hole was drilled primarily with API 537 (medium-soft) bits, which showed wear on the cone, indicating that a longer-tooth (soft) bit could have been used, with a resulting increase in penetration rates. The button bits used for the rework were API 437 (soft-formation) bits. Because little new hole was drilled (and most of that was on junk), no conclusions can be made concerning the suitability of the soft formation bits.

6.2.5 Drilling Fluids Program

Fresh water was used primarily for cooling the well, and brine from the brine pond, with density of 9.2 lb/gal (1.10 kg/L), was used for killing the well.

A fresh-water gel mud with Kenseal was used for drilling. Mud weight and funnel viscosity were maintained at 8.7 lb/gal (1.04 kg/L) and 38 sec/qt, respectively.

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

A solids-control system similar to that used for the original hole was used to maintain a mud of low-weight and solids-content. Mud chillers were used to maintain return-mud temperature well below flash point.

6.2.6 Short Flow Test

A short flow test was conducted on August 31, 1987, after terminating the rework activities, to ensure that State 2-14 could be used for the long-term flow test and by the Idaho National Engineering Laboratory as the production well for an injection experiment planned in combination with the Imperial 1-13 well.

The State 2-14 well was flowed for 12 hours, averaging about 569,000 lbm/hr of total flow (steam and liquid combined). 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 discussion of the short flow test of the State 2-14 well is included in Section 9.

7.0 COMMERCIAL GEOLOGY AND LOGGING

7.1 INTRODUCTION

GeothermEx, Inc., Richmond, California, provided commercial geologic services for the SSSDP, including the sampling and interpretation of cuttings and completion of a lithologic log for core and cuttings for well State 2-14. Exlog/Smith provided on-site mud logging services. The descriptions of geologic setting and lithology that follow are an edited version of the GeothermEx, Inc. (1986) report (listed in Appendix A).

7.2 GEOLOGIC SETTING

Well State 2-14 is located on the southeastern shore of the Salton Sea in the SE quarter of Section 14, T. 11 S., R. 13 E. (Figure 7.1). This is an area of intense seismic activity, recent earth movements, and high heat flow. Temperatures of 337°C were measured in the River Ranch #1 well, 0.8 km southeast of the SSSDP. The State 2-14 well is located 3 km NE of the high-temperature anomaly shown by Younker, et al. (1982). From this study, the temperature at 10,000 ft can be estimated as only 350°C, much less than the 380°C found in the hotest wells of the Salton Sea field. Temperature gradients decrease rapidly away from the axis of the geothermal system. The Salton Buttes, a chain of Quaternary rhyolite domes, lie 2 km to the northwest of the Project Area. The Salton Buttes area is a postulated "spreading center," a zone of crustal extension into which new molten material is being emplaced.

The Salton Trough is a Late Tertiary-Quaternary, sediment-filled extension of the Gulf of California rift, extending 300 km from the head of the Gulf to San Gorgonio Pass (Figure 7.1). The trough contains the Imperial and Mexicali Valleys, the Coachella Valley, and the Salton Sea. The delta of the Colorado River crosses the trough from Yuma, Arizona, isolating the northwest part from the Gulf of California. This closed, sedimentary basin, northwest of the delta crest, is known as the Salton Basin. The Salton Trough is bounded by mountain ranges that consist mainly of Mesozoic and older plutonic, metasedimentary and metavolcanic rocks, locally overlain by Cenozoic lavas.

7.2.1 Sedimentary History

Sedimentation in the Salton Trough has been dominated throughout Late Tertiary history by deposition in the Colorado River delta. The sediments are a complex section comprised of intertonguing deposits of continental, marine, deltaic, and lacustrine origin. Detailed stratigraphic relationships within the sedimentary section are poorly-known, due to the lack of useful fossils and the rapid facies-changes that occur in this environment. The main lithologies in the axial part of the basin are claystone, siltstone, and sandstone. The deepest well in the basin, Wilson No.1, drilled to 4,097 m, 10 km southeast of Brawley, penetrated a sequence of fine sandstone to siltstone, similar to modern Colorado River sediments (Muffler and Doe, 1968). Coarse clastic material occurs in great proportion toward the basin margins and southward toward the delta crest.

Maximum marine submergence occurred during the Pliocene. In mid-Pleistocene, probably during low sea levels that characterized glacial epochs, the delta built across the trough, isolating the Salton Basin from the Gulf of California (Van DeKamp, 1973). At that time, the northern Salton Trough became a sub-sea level, enclosed basin.

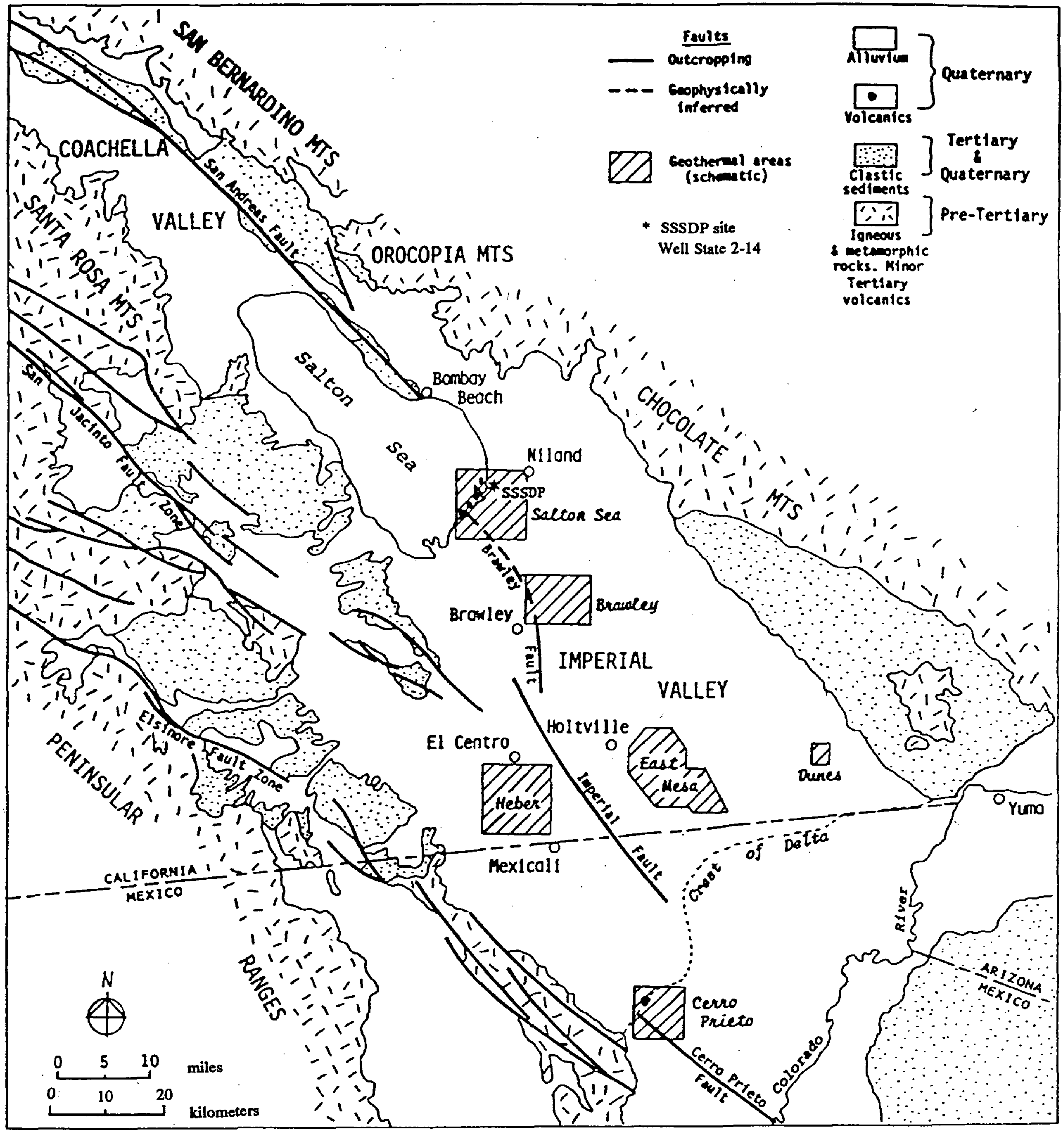


Figure 7.1 Location and Geologic Setting of the Salton Sea Geothermal System
(after Robinson, et al., 1976)

The Colorado River delta has alternately drained northward and southward. At times, its distributaries have emptied northward, filling the Salton Basin. When drainage has been to the south into the Gulf of California, lakes in the Salton Basin have shrunk. Currently, the Colorado River drains southward, and under natural conditions the Salton Sea would evaporate. Instead, the lake level is rising, in response to the current influx of irrigation water.

Holocene sedimentary rocks in the Salton Basin can be divided into three facies (Van DeKamp, 1973). A central lacustrine facies consists of mud and silt, which become coarser-grained toward the basin margins. Evaporites are common, and bedding is often disturbed by animal burrows. Fluctuations in lake level caused intertonguing of the lacustrine materials with coarser, basin-margin sediments. Meandering stream channels formed sand and silt deposits within the lacustrine muds. Alluvial fans and braided streams deposited boulders and gravels at the base of the surrounding mountains, but grain size decreases rapidly toward the center of the basin. These locally-derived sediments have compositions different from those deposited by the Colorado River. The most significant features of the Holocene sediments are the abrupt facies changes and variety of sedimentary environments present in small areas. These changes make correlating units difficult.

Before significant quantities of irrigation water began to enter the basin in 1901, the Salton Sea was a playa known as the Salton Sink. An uncontrolled diversion of the Colorado River in 1905-1907 raised the lake surface to -60 m, its highest modern level (Littlefield, 1966). The current lake level is about -70 m. Wave-cut terraces at elevations of +12 m were formed by Lake Cahuilla, the last natural basin-filling lake, which existed until about 300 years ago (Van DeKamp, 1973).

7.2.2 Quaternary Volcanism

Five small rhyolite domes, known as the Salton Buttes, are the only surface evidence of recent volcanism in the Salton Basin. The domes are aligned along a 7 km-long, northeasterly trend. From the southwest, they are: Obsidian Butte, Rock Hill, Red Island (2), and Mullet Island. Red Island is 2.9 km southwest of the SSSDP. Recent age dating by Friedman and Obradovich (1981) and Herzig and Jacobs (1991) indicates a range in age from 8,500 years to 2,400 years before present. Three of the domes are discharging minor amounts of gas from cracks and joints (Muffler and White, 1969). Basaltic rocks are not exposed at the surface, but occur as xenoliths in the domes and as dikes or sills encountered in State 2-14 and other wells.

7.2.3 Diagenesis, Metamorphism and Mineralization

Muffler and Doe (1968) identified the original, detrital mineralogy of the Colorado River sediments as predominantly quartz, calcite, dolomite, plagioclase feldspar, K-feldspar, montmorillonite, illite and kaolinite. Burial, heating, and mineralizing fluids cause pronounced changes in sediments deposited in the Salton Basin. The first detailed work on alteration was done by Muffler and White (1969). Some of these changes are visible, megascopically, while others are not; effects of these on the geothermal reservoir are of great importance.

Diagenesis. Diagenesis is a process whereby detrital minerals are altered in place, at relatively low temperatures. The diagenetic process grades into metamorphism, but the term is generally applied to reactions taking place under 200°C. Diagenesis is important in geothermal reservoirs, because one of its products is secondary cement, which binds the detrius and decreases the initial porosity of reservoir sands. In the Salton Basin, two main types of cement produce this "self-sealed caprock." Most important is calcite, which may be produced, along with chlorite, at temperatures as low as 125°C (Muffler and White, 1969). A second diagenetic cement is pyrite, produced by reduction of iron from iron-bearing detrital minerals (McKibben and Elders, 1985).

Temperatures in the 200-300°C range may destroy the diagenetic cement, producing secondary porosity in a "main reservoir" (McKibben and Elders, 1985). Pyrite cement breaks down and large pyrite porphyroblasts form in its place. Calcite cement is destroyed by decarbonation reactions, producing CO_2 gas.

Metamorphism. Deeply buried sediments in the Salton Basin belong to the greenschist metamorphic facies. In the Salton Sea field, the metamorphic process is better referred to as "metasomatism" or "hydrothermal metamorphism." Major changes in bulk-sediment composition occur by reaction with a hot, saline, metal-rich brine. The major effect of temperatures above about 300°C is the gradual sealing of pores by new minerals and by silica overgrowths (McDowell and Elders, 1983). One important metamorphic mineral in this regard is epidote, which forms at the expense of calcite, at about 290°C (Muffler and White, 1969; Younker et al., 1982)

Metamorphism also produces progressive changes in mineralogy. The metamorphic mineral assemblage in a well may reveal the highest rock-fluid equilibrium temperature reached. This may not be the present temperature. McDowell and Elders (1980) have described mineral assemblages found in Elmore No.1, 4.25 km south of State 2-14. The dolomite-ankerite zone is found at temperatures below 190°C. Minerals of the calcite-chlorite zone form between 190° and 325°C, and include calcite, quartz, epidote, pyrite, sphalerite and anhydrite. Biotite, quartz, epidote, actinolite, pyrite, anhydrite and sphalerite are found in the biotite zone, at temperatures of 325°-360°C. In the garnet zone, andradite garnet appears at temperatures greater than 360°C. No garnets were observed in State 2-14, but if present, these probably would not be discernible to the unaided eye.

Mineralization. Fracturing and vein-related mineralization are important in geothermal reservoirs because fractures are a "renewable" source of permeability. Deposition of vein minerals tends to seal fractures, but tectonic or hydraulic stresses can reactivate filled fractures, or open new ones. Below the depth at which epidote seals the pores in sandstones, fractures are the sole source of permeability.

McKibben and Elders (1985) have identified two main vein-filling assemblages in Magmamax No.2 and River Ranch No.1 wells. These are the "sulfide-carbonate-silicate" assemblage and the "hematite-silicate-sulfide-sulfate" assemblage. Their work suggests that the hematite-silicate-sulfide-sulfate is the younger, and is in equilibrium with the current geothermal brines at approximately 300°C. The first appearance of hematite in veins occurs between 3,075 and 3,600 ft (937-1,097 m) in Magmamax No.1, Magmamax No.2, River Ranch No.1, Sportsman No.1, IID No.1, and IID No.2 wells (McKibben and Elders, 1985). The first appearance of vein hematite in State 2-14 is at about 3,050 ft (930 m).

7.2.4 Tectonics

The Salton Trough occupies a unique position in the zone of transition between the divergent-plate margin of the East Pacific Rise and the strike-slip San Andreas Fault System on the continent. In the Gulf of California, short spreading centers are offset by right-stepping transform faults trending northwest. Lomnitz and others (1970) suggested that the tectonics of the Salton Trough could be viewed in the same context by assuming that the right-lateral faults were transforms, offsetting short spreading centers at Cerro Prieto and the Salton Buttes. Elders and others (1972) refined the model. They suggested that active spreading occurs in "tensional gaps" between offset segments of strike-slip faults. Such tensional gaps would be loci of volcanism, normal faulting and high heat flow. The Imperial Valley and Cerro Prieto lie between offset segments of major strike-slip faults (Figure 7.1), and it has been suggested that there are spreading centers at the Salton Buttes, Brawley, and Cerro Prieto.

Accurate geodetic surveying in the Imperial Valley began in 1934. Since then, there has been a total of about 2 m of right-lateral movement in the valley, and the valley floor has subsided by tens of centimeters (Elders et al., 1972). The southern Salton Basin has been the site of more small to moderate earthquakes than any other section of the San Andreas Fault System. Most of this activity has been on the Imperial, Brawley, and San Jacinto faults. Seismic activity has been conspicuously low eastward of the Imperial Fault (Hill et al., 1975). In addition to lack of seismicity, no surface evidence for movement on the San Andreas Fault is found southward of Bombay Beach (Sharp, 1982).

The proposed tensional gap between the San Andreas and Imperial Faults (Figure 7.1) is, in fact, a region of high heat flow and recent volcanism, and it is also the site of the greatest seismic activity in the Imperial Valley. Known as the Brawley Seismic Zone, this locus of seismicity trends N20°W across the gap. Most of the motion along the N20°W trend appears to be right-lateral strike-slip. Within the Brawley Seismic Zone, several short lineations trend northeastward, and involve normal faulting (Johnson and Hadley, 1975; Gilpin and Lee, 1978; Fuis et al., 1982). These northeast-trending zones may be sites of extension and intrusion. One of these northeast lineations passes under Red Hill and near State 2-14.

The Brawley Fault (Figure 7.1) is defined by seismicity and by ground breakage during recent earthquakes. Motion on the Brawley Fault is predominantly right-lateral. Accurate triangulation indicates that during the period 1934-1972, the benchmark on Red Hill moved 15 cm south-southeastward, relative to the benchmark on Obsidian Butte (Savage et al., 1974). Seismicity indicates that the northern end of the Brawley Fault passes approximately through Obsidian Butte (Gilpin and Lee, 1978).

Folding is also common in the Imperial Valley, with greatest deformation (for example, overturned folds) occuring near faults. Folded, Late Cenozoic rocks are found on the East and West Mesas. On the margins of the southern Salton Sea, Pleistocene rocks are uplifted and eroded. Former shorelines of Lake Cahuilla are also warped, indicating that folding has continued into recent times.

7.2.5 Geophysics

The Salton trough is characterized by a gravity high, despite its thick sedimentary fill. The low density fill in the upper part of the section is probably compensated by alteration and by intrusion of mafic rocks and depth. Seismic-refraction studies (Fuis et al., 1982) reveal a sedimentary trough, 10-16 km deep at its axis. The upper 6 km appears to be normal- to moderately-altered sedimentary rocks, overlying a "basement" of sedimentary rocks thoroughly altered to greenschist-facies assemblages. The whole sedimentary trough apparently overlies a "sub-basement" of mafic-intrusive rock.

A prominent magnetic high trends northwestward from Calipatria, with a superimposed northeast-trending anomaly in the vicinity of the Salton Buttes. Griscom and Muffler (1971) believe the northwest-trending magnetic high represents intrusive rocks buried at least 2 km, while the northeast trend represents shallower dikes and sills.

A contour map of electrical conductance (Kasameyer et al., 1984), based on resistivity surveys by Meidav and others (1976), shows a high-conductance (low-resistivity) zone, centered approximately on the Salton Buttes. Low resistivity often results from saturation of porous rocks by hot, saline brines.

7.2.6 Surface Manifestations of the Geothermal System

There are no surface manifestations for most of the geothermal fields in the Salton Trough. The Salton Sea and Cerro Prieto fields, however, are associated with Quaternary volcanoes, warm springs, and mud pots associated with CO_2 discharges.

Two areas of weak warm springs are aligned along northwest trends at the Salton Sea field. Major warm-spring activity was centered 1.5 km southeastward of Mullet Island, but is now submerged by the Salton Sea. The SSSDP is approximately on this trend, 3.2 km southeastward of Mullet Island. The second alignment is northeastward, between the SSSDP and Niland, on the projection of the San Andreas fault. Both of these thermal areas are thought to represent warm waters ascending along faults. Mud pots are common in the area, and numerous abandoned carbon dioxide wells are found less than 3 km north of State 2-14.

7.3 GEOLOGY OF WELL STATE 2-14

7.3.1 Introduction

Geologic knowledge of the Salton Sea geothermal system, as inferred from drilling of well State 2-14, is one of the principal results of this scientific drilling program. This information has been derived from careful study of cuttings, cores and geophysical logs.

The lithology and geologic relationships of well State 2-14 were interpreted as drilling progressed. Exlog/Smith collected and prepared cuttings samples and recorded mud-log information. GeothermEx, Inc. (1986) (Report N, Appendix A), examined cuttings and cores in the field and laboratory, using a hand lens (10x) and binocular microscope (30x). The stratigraphy, based on cuttings, was compared to a suite of geophysical logs covering the interval between 1,032 and 6,000 ft. The geophysical logs suggest that sandstone may be slightly underestimated in cuttings descriptions, and claystone slightly overestimated. Lithologic interpretations at depths greater than 6,000 ft are less reliable because few calibrated geophysical logs were obtained and because some useful information had not been recorded in the field. The summary of lithology that follows is abstracted from GeothermEx, Inc. (1986).

Herzig et al., (1988) present a similar interpretation of the lithostratigraphy of State 2-14 with illustrations of selected core samples and detailed examinations of selected intervals. Figure 7.2 from Herzig et al. presents the stratigraphy in appropriate detail for this report, and provides a comparison with the abstracted descriptions prepared by GeothermEx.

7.3.2 Summary of Lithology

Only two major sedimentary-rock intervals can be readily distinguished in the well section. The upper, consisting of poorly indurated clay, silt, and sand, extends from the surface to about 1,100 ft-depth. The detailed character of this interval is poorly known, due to limited sampling, lack of sample coherence, and the lack of geophysical-log coverage. The lower unit, extending from a depth of about 1,100 ft to total depth of the well, consists of an assemblage of alternating claystones, siltstones, and sandstones. Many depositional and soft-sediment deformational structures are found throughout this section, consistent with deposition in a deltaic environment. No major stratigraphic breaks were observed in this section. Some of the most notable lithologic changes observed are those associated with changes in the intensity of alteration. Alteration is superimposed on, and partly controlled by, pre-existing sedimentary features. The following subdivisions are based partly on variations in the original sedimentary rock, and partly on the character of the alteration.

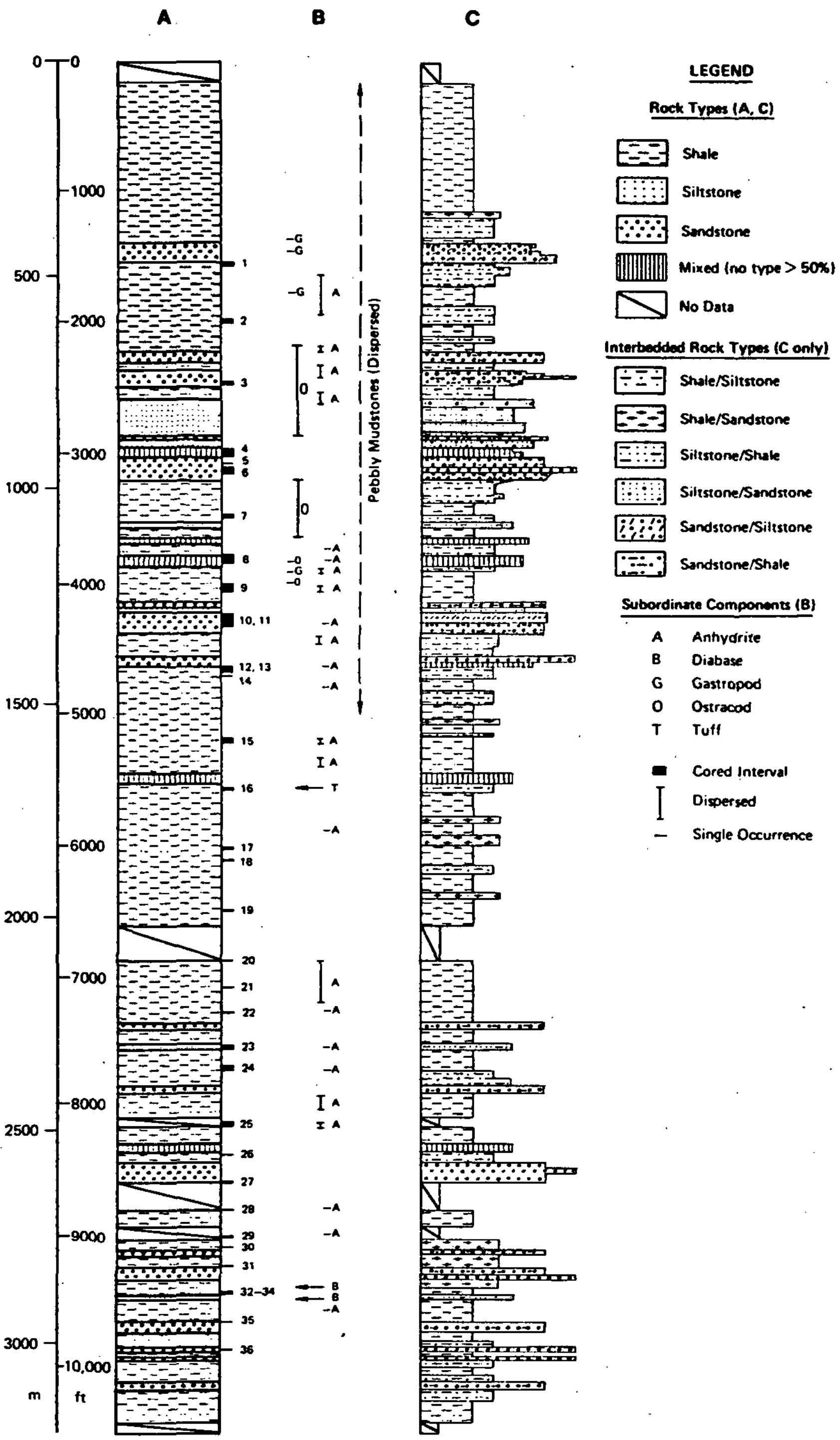


Figure 7.2 Lithostratigraphic Summary for Sedimentary Rocks in the State 2-14 Borehole
Based on cored intervals, cuttings, and spontaneous potential and gamma ray logs (380-1830 m). Below a depth of 1830 m, the column is based only on the cored intervals and cuttings. (A) Generalized column showing the dominant rock types. (B) Cored intervals and subordinate components. (C) Blocky weathering profile emphasizing contrasts in sedimentary rock lithologies. (from Herzig et al., JGR v. 93, B11, 1988, copyright by the American Geophysical Union).

180-1,100 ft: Clay, gray in color and calcareous. Occasional fragments of organic material and gastropod fossils. The clays are interbedded with minor fine sands and silts. Sediments in this interval appear to be equivalent to the Holocene lacustrine facies in the center of the basin.

The effects of lithification were reflected in the drilling rate. In soft clays, higher in the hole, the drilling rate often exceeded 400 ft/hr. By 900 ft-depth, clays were compacted into claystones, and the drilling rate dropped to less than 100 ft/hr.

1,100-2,630 ft: Lithology changed from lacustrine clays to siltstones and sandstones more characteristic of a fluvial-deltaic environment. The dominant lithology in cores 2 and 3 was calcareous medium-gray claystone. Sandstone comprised 27 ft of the 30-ft length of core 3. The sandstone was calcareous and only slightly porous, apparently forming part of the "self-sealed caprock."

Minor veins were nearly vertical and less than 3 mm thick. Veins were either filled with calcite or had calcite on vein walls, with sphalerite, galena, and pyrite in the center. The pit-volume indicator was not operational until after the 13-5/8-inch casing point at 3,515 ft-depth, but fluid losses were minor.

2,630-3,220 ft: Geophysical logs showed a change from claystone to siltstone, or silty claystone, at 2,600 ft-depth, and a distinct drilling break occurred at about the same depth. An increase in alteration accompanied the lithologic change. Siltstones and silty claystones changed from gray to grayish green or green. Green siltstones were less calcareous than the gray. The color change was probably due to formation of matrix chlorite, too fine to be visible under the binocular microscope. Sandstones tended to be more friable than at shallower depths, apparently due to partial dissolution of calcite cement.

Traces of epidote were first seen in sandstones at 2,790 ft-depth, while vein-epidote first appeared at 2,760 ft-depth. Depth to the first appearance of epidote in the Salton Sea field varies, from 2,660 ft in Magmamax No. 2 to 3,830 ft in Sportsman No. 1 (Younker et al., 1982). This altered zone marked the first appearance of major vein fillings. Vein filling at depths less than 2,630 ft were minor, and consisted of calcite ± sulfides. Vein fillings at greater than the remaining 2,630 ft-depth were more abundant, and in addition to calcite and sulfides, contained euhedral epidote, quartz, and specular hematite. Most veins were less than 1/2 inch (1 cm) thick, with attitudes from vertical to steeply inclined. Commonly, the walls of the veins were epidote-lined, with calcite and sometimes sulfides, hemitite, or quartz in the center. This zoning may indicate reactivation of the fractures.

Alteration was most developed in sandstones, with the calcite matrix partly dissolved and replaced by chlorite, epidote and sulfides. Apparently, mineralizing fluids, rising along fractures, had greater access to the sand layers, due to secondary porosity.

3,220-4,430 ft: This interval marked a return to non-permeable rocks, accompanied by a decrease in alteration. In core 6 at 3,156 ft, a dark-gray claystone was separated from a green siltstone by a 37-ft thick sand layer. Geophysical logs showed a significant decrease in sand-silt content at depths varying from 3,220 to 3,250 ft. Claystone was the most common lithology in the cuttings, with subordinate siltstones and sandstones. Core 8 contained a 10-ft sandstone layer, but most beds were less than 1-ft thick. Sedimentary structures were common and easily recognizable in the cores.

Claystones and siltstones were calcareous and medium gray. Sandstones were tan to pale gray, with well developed calcite cement. Yellow-green patches in the matrix suggest alteration to epidote. Fracture filling was scarce in the cuttings. Rare calcite ± sulfide veins less than 1/4 inch (6 mm) thick were found in cores. Attitudes of the veins ranged from near-vertical to horizontal. Minor vein epidote appeared in cores 10 and 11.

Circulation losses were nearly nil. The only measurable loss coincided with a sand layer at 4,150 ft-depth. The lack of permeability reflects the scarcity of sandstone, the well-developed matrix cement, and the absence of fracturing.

4,430-5,150 ft: Basic lithology of the cuttings remained the same as above; claystone with subordinate siltstone and fine sandstone. Geophysical logs showed interbedded claystone and siltstone, with a thick sandstone layer between 5,050 and 5,150 ft-depths. The maximum thickness of sandstone seen in cores was 6 ft. There was a marked increase of vein filling and associated alteration in comparison to the previous interval.

Claystone cuttings were light greenish-gray, and slightly calcareous to non-calcareous. Sandstones were non-calcareous to slightly calcareous. Matrix alteration to epidote varied from partial to complete. Sandstones cut by veins showed the greatest alteration.

Fracture filling was found in all cuttings samples, and high-angle veins were pervasive in cores. Vein mineralogy was variable. Mineralogies included: (a) epidote + calcite + specular hematitie ± chalcopyrite; (b) epidote + calcite; and (c) specular hematite, alone. Most veins were less than 0.2 in. (5 mm) wide, with some up to 1 in. (2.5 cm) wide. Veins that appeared to be pure hematite cut epidote-bearing veins.

Small drilling breaks at depths of 4,470 to 4,490 ft and 5,020 to 5,080 ft coincided with fractured intervals. In spite of evidence for pervasive fracturing, circulation losses were never greater than 6 bbl/hr. An injection test was conducted on the interval 3,515 to 4,710 ft, with no evidence of significant permeability. Apparently, the fractures are tightly sealed with vein minerals.

5,150-6,100 ft: This section consisted of slightly altered sediments. Claystones usually comprised more than 70 percent of the cuttings. On geophysical logs, sandstones were subordinate and present in beds less than 20-ft thick. A major sandy interval extended from 5,450 to 5,590 ft. Claystones were light-gray to greenish-gray, and slightly calcareous. Sandstones showed more alteration, and were greenish-yellow and non-calcareous to slightly calcareous.

A 1-ft thick layer of light gray, very fine grained material at 5,590 to 5,591 ft in core 16 was tentatively identified as an airfall tuff (J. Mehegan, personal communication). This was later confirmed by Herzig and Mehegan (1988), and may be a valuable stratigraphic marker within the basin.

Vein filling was scarce in cores. Most veins were less than 0.1 in. (22 mm) thick, and consisted of: (a) epidote + hematite; (b) epidote + calcite; (c) calcite alone; and (d) epidote alone. Cuttings from 5,450 to 5,470 ft-depths had up to 10 percent epidote vein-filling material. Some of the epidote appeared to have grown into open vugs.

Circulation losses were low. Penetration rates were constant at about 20 ft/hr, with a pronounced break to 80 ft/hr at 5,450 ft-depth. Although epidote from this depth has grown into open vugs, the effect of the vugs on permeability was minor.

6,100-6,620 ft: Cuttings from this interval were usually 70 to 100 percent hard, lithified claystones. Samples were medium gray to greenish gray, and slightly calcareous to non-calcareous. Sandstones were friable and usually non-calcareous. The matrix of most sandstones was variably altered to yellow-green epidote, and some contained euhedral epidote crystals in the matrix.

Cuttings from the interval 6,110 to 6,130 ft were as much as 40 percent open-textured, monomineralic masses of euhedral epidote. After the first flow test, pieces of the same material, 0.75 in. (2 cm) in diameter, were found 300 ft (100 m) beyond the end of the blooie line. This was the only porous interval between the flow-test depth of 6,227 ft and the bottom of the 9-5/8 in. casing at 6,000 ft-depth. The flow undoubtedly came from this epidote-rich zone.

Some circulation losses continued to 6,620 ft-depth. Drilling breaks and minor zones of epidote veining indicated that additional fractures were present.

6,620-6,880 ft: No returns. Core 19 consisted of gray claystone and non-calcareous sandstone. Both were cut by high-angle fractures filled with epidote + quartz ± chalcopyrite and pyrite. Circulation loss at the top of the interval was due to fractures between 6,635 and 6,650 ft- depths. An abrupt drilling break, from 30 ft/hr to 100 ft/hr and back to 30 ft/hr, coincided with the lost-circulation zone.

6,880-8,090 ft: Cuttings were more than 90 percent claystones and silty claystones, except for the sandy interval between 7,380 to 7,410 ft-depths. Vein filling was common between 7,730 and 7,900 ft-depths, and consisted of epidote ± sulfide ± calcite ± fibrous-white mineral that appeared to be anhydrite. Cores 20 to 24 consisted almost entirely of argillaceous claystone, with high-angle fractures filled with epidote and other minerals.

Fluid losses were variable. Loss rates of 80 bbl/hr between 7,000 and 7,110 ft-depths may have been to the 6,635 to 6,650-ft lost-circulation zone. Lesser fluid losses may have been associated with vein fillings at about 7,300 ft-depth.

8,090-8,160 ft: No returns. Circulation was lost at the drilling break at 8,090 ft-depth. The zone was not flow tested.

8,160-8,597 ft: Lithologies in the upper part of this interval were predominantly metamorphosed claystones, gray to greenish-gray and non-calcareous. Sandstones increased below the 8,280 ft-depth, and are fine grained, non-calcareous and non-porous. Several fracture-filling mineral assemblages were found in the cuttings and in cores 25 through 27.

Mud losses were intermittant and variable, and were not associated with sand beds or increased vein filling. Complete loss of circulation accompanied a drilling break at 8,580 ft-depth.

8,597-8,800 ft: No returns. Mud losses were probably in a zone of rapid drilling between 8,580 and 8,825 ft-depths.

8,800-8,920 ft: Sample depths are questionable. The interval appeared to be mostly metamorphosed claystones, with subordinate, fine sandstones. Fracture filling was minor. Increases in drilling rate at depths of 8,830 and 8,880 ft may have represented short, fractured intervals.

8,920-9,050 ft: No samples received by GeothermEx. Lithology unknown.

9,050-9,250 ft: Predominantly metamorphosed claystones. A pronounced interval of fracture filling from 9,080(?) to 9,110 ft-depth was composed of euhedral epidote with subordinate quartz. Drilling rates were high and variable from 9,095 to 9,125 ft-depths, and probably represented the main fractured interval. Fragments of vein material in samples from 9,125 to 9,250 ft-depths probably were also from this interval. Partial fluid losses occurred in the interval.

9,250-9,440 ft: The proportion of sandstone increased greatly, to approximately 50 percent sandstone and 50 percent claystone. The sandstones were hard, epidotized and non-porous. Mud losses were variable in the interval, and show no correlation with sandstone content and vein mineralogy. The well was flowing, probably from one of the shallower fracture zones, during a trip from 9,254 ft-depth.

9,440-9,580 ft: Mafic-intrusive rocks. Comparison of cores, cuttings and drilling rates indicated two intrusive bodies: one at 9,443 to 9,450 ft-depths, and another at 9,505 to 9,520 ft-depths. Both were cut by high-angle veinlets of epidote + sulfide + quartz + dark green, prismatic actinolite(?). This was the first appearance of actinolite, indicating a temperature of at least 340°C (McDowell and Elders, 1980). A fibrous white mineral, which may have been tremolite, appeared at a shallower depth (7,870 ft), but could not be identified with certainty.

9,580-10,460 ft: The sequence continued to be predominantly metamorphosed claystones with beds of epidotized sandstone. Loss of circulation was abrupt and total at 10,465 ft-depth, and no lithologic information was available from 10,460 feet to the total depth of 10,564 ft.

7.3.3 Metamorphism and Vein Fillings

Many mineralogical and textural changes were observed indirectly in this well. The most obvious change was the increase in hardness accompanying lithification and metamorphism. The drilling rate in clays at 500 ft-depth was as high as 400 ft/hr, while in claystones at 1,000 ft-depth, it was 100 ft/hr. In argillites (the low-grade metamorphic equivalents of claystones) at 10,000 ft-depth, drilling proceeded at 10 ft/hr or less.

The appearance of claystones changes relatively little because of their original fine-grain size. With depth, claystones become harder, greener in color, and less calcareous. A dull sheen develops on broken surfaces from the growth of micas. Sandstones become dense, hard, non-porous and non-calcareous. Growth of epidote in the matrix gives sandstones a yellow-green color. Overgrowths of silica and other minerals, and the development of matrix epidote, reduce porosity.

Prograde metamorphic effects are overprinted by vein-related alteration. Sediments are more altered when crossed by veins, and more permeable rocks show a higher degree of alteration. Vein mineralogy is complex in State 2-14. There are two general vein associations: (a) calcite ± sulfides (sphalerite, galena, chalcopyrite, pyrite, bornite(?), pyrrhotite) ± epidote; and (b) epidote + hematite ± sulfides ± calcite ± quartz ± anhydrite. The first seems to correspond to the sulfide-carbonate-silicate association of McKibben and Elders (1985). The second is probably equivalent to the hematitie-silicate-sulfide-sulfate association. Where samples are available, production zones seem to be associated with hematite-silicate-sulfide-sulfate veins.

7.3.4 Structure

The generally thin veins seen in cores dip at high angles, consistent with extension and normal faulting. No inferences about orientation of the stress field are defensible without oriented cores. Some cores show brecciated zones, but these appear to be slump breccias, formed in the original sedimentary environment.

Bedding dips are relatively low, usually less than 25°. The consistently low overall inclination, however, indicates that the tectonic component of dip is low. There is a slight tendency for dip to increase with depth, from less than 20° at shallow depths to about 35° at 9,000 ft-depth. This increase is consistent with the location of State 2-14, in a subsiding sedimentary basin. The general structural regime indicated in State 2-14 is one of extension and subsidence, but without extreme tectonic deformation. The correlations discussed below support this conclusion.

Preliminary correlations were made between the geophysical logs of State 2-14 (to 6,000 ft-depth) and those available from the nearby wells: River Ranch No. 1, Hudson No. 1, Sportsman No. 1 and IID No. 1. State 2-14 was used for the type section. Correlation was best with River Ranch No. 1, the nearest well, while no reliable correlations were established with IID No. 1.

Given the rapid thickening and thinning of sedimentary units in a deltaic environment, it is not surprising that correlation with more distant wells was poor. Major lithologic breaks correlate, however, with varying degrees of certainty between State 2-14 and River Ranch No. 1, Hudson No. l, and Sportsman No. 1. They show that stratigraphic markers in State 2-14 are approximately 100 ft higher than in River Ranch No. 1; 70 ft higher than in Sportsman No. 1; and 170-200 ft higher than in Hudson No. l. These variations could be due to thickening and thinning of beds. The data do not require faults to correlate between wells. Some faulting may be present, but the data do not suggest large vertical offsets.

The altered zone from 2,630 to 3,160 ft-depths in State 2-14 seemed to correlate with a similar zone of alteration and production at about 2,900 to 3,800 ft-depths in River Ranch No. 1. The significance of this correlation is questionable, and there was no correlation between deeper production zones in these wells. Given that fluid entries in State 2-14 come from high-angle fractures, with unpredictable distribution, it is unlikely that production zones would correlate with other wells. Intergranular porosity in the "main reservoir" could be correlative, but the significance in State 2-14 is unclear.

7.3.5 Interpretation of Reservoir Characteristics

Most discussions of the Salton Sea field divide the geothermal reservoir into three vertical sections: (a) the cap rock; (b) the main reservoir; and (c) the altered reservoir (McKibben and Elders, 1985; Younker et al., 1982; Tewhey, 1977). The cap rock is divided into a "depostional cap," composed of impermeable lacustrine clays, and a "self-sealed cap," sealed with diagenetic cement. The cap may be from 1,100 to 1,900 ft thick, depending mainly on the thickness assigned to the self-sealed cap.

The main reservoir is also referred to as the "slightly altered reservoir" or the "'unaltered reservoir." Permeability results from variations in the amount of calcite cement. The main reservoir is thought to extend down to about 3,000 ft-depth. Below about 3,000 ft, intergranular permeability is destroyed by metamorphic minerals. In the altered reservoir, permeability results entirely from fracturing.

Below the depositional cap, the cap-rock zones are often shown as thick, laterally continuous layers, parallel to isotherms. The zones cut across sedimentary units that are correlatable over distances of several km (Younker et al., 1982). Several features of the idealized reservoir model were found in State 2-14. Lacustrine clays formed a depositional cap 1,100 ft thick, and no significant sand layers were encountered until 1,380 ft-depth.

Sandstones in core No. l appeared to be well-cemented, calcareous and non-permeable, and could be described as part of a "self-sealed cap." The next sand layer cored was from 2,448 to 2,456 ft depth, in core No. 3. While still hard and calcareous, it readily absorbed water. In the altered interval, 2,600 to 3,220 ft-depths, some sandstones were noticeably softer and more friable, and contained epidote in the matrix. Dissolution of calcite cement must have been a gradational process, and it was impossible to make fine distinctions in the field. It appeared that some degree of secondary porosity was being developed by dissolution of calcite. Only one sandstone layer, at 4,155 to 4,200 ft-depths on geophysical logs, correlated with measured lost circulation. Without continuous records of fluid loss above 3,515 ft-depth, no further conclusions may be drawn. Apparently, below 4,200 ft-depth, all circulation losses were fracture related.

All production came from steeply dipping fracture zones, probably less than 20 ft thick, and partially filled with epidote ± other minerals. McKibben and Elders (1985) inferred that the hematite-silicate-sulfide-sulfate vein association was in equilibrium with modern geothermal brines. Association of circulation losses with this type of vein, and textural evidence from samples, appears to confirm this.

The major departure of State 2-14 from the idealized reservoir model was in the distribution of alteration. The idealized model involves concentric zones of steadily increasing metamorphic grade, oriented parallel to isotherms. In State 2-14, at least one zone of increased alteration occurred between sequences of less altered rock. It appears that permeability, as well as temperature, controls metamorphism. In State 2-14, sandstones were more altered than claystones, and claystones associated with sandstones were more altered than those that were not.

Several aspects of permeability probably have been involved. The greenish, altered rocks at 2,600-2,900 ft were somewhat siltier than those above and below. These also overlie a porous sandstone unit 320 ft thick, while sandstones in the unaltered zones were less than 50 ft thick. Finally, fracturing was much more common in the altered interval. There seems to be a complex interplay of permeability and temperature effects. Areas of intense alteration related to permeability appear to cut across the normal zonation metamorphism related to depth and temperature.

7.3.6 Summary of Possible Production Zones

Permeability in geothermal wells is controlled by lithology and fracturing. In the Salton Sea field, intergranular permeability is secondary, created by the dissolution of diagenetic cements from sandstones. Some sandstone cores from State 2-14 showed minor development of secondary porosity, but its effect on the reservoir as a whole is minimal. A continuous record of fluid losses was not kept for depths less than 3,515 ft. Below this depth, only minor fluid loss from 4,150 to 4,170 ft-depths clearly coincided with a sandy interval. Fractures tend to self-seal with epidote, calcite, and other minerals, but may be reopened by tectonic or hydraulic stresses. All major fluid-loss zones in the State 2-14 well are fracture related.

Recognition of possible production zones during the drilling process is very important, and several lines of evidence are used. These include: mineralogy, lost circulation, drilling rate, mud-return temperatures, mud resistivity, and dissolved gases (especially CO_2). GeothermEx identified several potential production zones, using a combination of these criteria.

2,619-3,160 ft: Vein filling, including some void spaces, was common in cuttings and cores. Drilling rates were variable; peaks at 2,850 and 2,890 ft-depths may represent fractures. The pit volume indicator was not operational, but fluid losses were minor. No changes were observed in resistivity, dissolved gases or mud temperature. No injectivity tests were performed because temperatures were deemed to be much cooler than in the River Ranch No. 1 well, and too low for production.

3,515-5,422 ft: An injectivity test was performed of this open interval after minor fluid loss was noted. Injectivity was nil.

5,450-5,460 ft: A sharp drilling break and the presence of euhedral epidote in cuttings suggested a fracture zone. No other evidence indicated possible production. The interval was not tested.

6,110-6,130 ft: Tested during the first flow test. Abundant vein-filling epidote in monominerallic, open-textured masses was found in cuttings. Fluid losses were significant, but not total. Mud resistivity showed a slight decrease. The difference between mud temperature out and mud temperature in showed a slight increase. There were no gas shows.

6,635-6,650 ft: Circulation loss was abrupt and total. A sharp drilling break indicated fractures. No changes in circulation, mud temperature, dissolved gases or mineralogy occurred before the loss. The interval was not tested.

8,090-8,100 ft: A gradual circulation loss became total at 8,090 ft-depth, coincident with a small drilling break. The amount of epidote vein-filling had been increasing prior to the loss. No changes in gas content, resistivity or mud temperature were observed prior to the loss. The well flowed several times between 8,126 and 8,133 ft-depths, and had to be killed. One cement plug was lost entirely at this depth. The interval was not tested.

8,580 ft: An abrupt and total circulation loss occurred at 8,580 ft-depth. Drilling was rapid between 8,575 and 8,625 ft-depths. Mud-logger reports show an increase in vein-filling epidote between 8,560 and 8,580 ft-depths, but this was not observed in the samples sent to GeothermEx. No gas or mud temperature anomalies were observed. Resistivity out decreased before loss of circulation. Regaining circulation after this fluid-loss zone was extremely difficult. The zone was not tested.

8,950 ft: An abrupt and total loss of circulation was coincident with a sharp drilling break at 8,950 ft-depth. Another drilling break occurred at 9,000 ft-depth. No cuttings or fluid were returned to the surface, and the zone was not tested.

9,095-9,125 ft: Samples sent to GeothermEx, including some that were mislabeled, show abundant epidote vein filling between 9,080(?) ft and 9,100 ft-depths. The drilling rate was high and variable from 9,095 ft to 9,125 ft-depths, with circulation losses beginning at 9,050 ft depth. The well flowed at 9,248 and 9,273 ft-depths; probably, at least partly, from this zone. No gas kicks or mud-temperature shifts occurred. Resistivity readings are missing from 9,030 to 9,100 ft-depths. When restored, resistivity out was extremely variable, but higher than at 6,227 ft-depth. The change in resistivity may have been the result of mud conditioning activities. This zone was not tested.

10,475 ft: No cuttings or fluids were returned. This zone was flow tested, but it appears that at least some of the production came from shallower zones, behind the 7-in. liner.

7.3.7 Evaluation of Permeability

Circulation losses are the best indicators of significant permeability. Total circulation loss is not a requirement, and losses were only partial at the first flow-test zone. Circulation losses must be interpreted with care. Fluid losses may occur up-hole, into zones that were temporarily plugged with LCM or cement.

Vein-filling minerals were abundant at 6,110 ft to 6,130 ft-depths, the depth of the first flow test, and in other loss zones. The important factor in vein permeability is the degree to which fractures are sealed by secondary minerals. Monominerallic masses of euhedral epidote crystals projecting into void spaces characterized the interval of the first flow test. Abrupt increases in drilling rate, especially when followed by a return to a lower rate, indicate fracture zones. These are often associated with circulation loss. The lack of a drilling break at 6,110 to 6,130 ft-depths was probably due to the directional drilling process. Mud-return temperatures showed a slight increase between 6,110 ft and 6,130 ft-depths. Temperature kicks are usually obscured by the use of mud coolers. This is especially true when more than one cooler is in operation.

Mud resistivity results were variable. Slight resistivity decreases occurred at 6,110 to 6,130 ft and at 8,580 ft-depths. A significant increase in resistivity at 9,100 ft-depth probably does not indicate a different brine at depth.

Carbon-dioxide trip gas was produced in varying amounts, with the greatest kicks below 8,000 ft-depth. Apparently, the heavy mud keeps CO_2 in solution until agitation or swabbing occurs during a trip.

7.4 MUD LOG

A commercial mud-logging service company, ExLog/Smith (R. F. Smith Corp.), monitored the drilling fluid and cuttings returns from 150 to 10,564 ft. In addition, the mud loggers monitored drilling fluid temperatures in and out, drilling rate, fluid loss and gain, and hydrogen sulfide, carbon dioxides and hydrocarbon levels. The data, including a lithologic log, are presented versus depth as the standard Geothermal Data Log, and is listed as Report O in Appendix A of this report.

7.5 DIRECTIONAL SURVEYS AND BOREHOLE DEVIATION

A single-shot magnetic survey instrument with a heat shield was used to measure hole inclination and deviation to a depth of 9,400 ft. Surveys were suspended between 6,577 and 7,116 ft and discontinued after 9,400 ft because of loss of circulation and differential sticking problems. Table 7.1 summarizes the single-shot survey results.

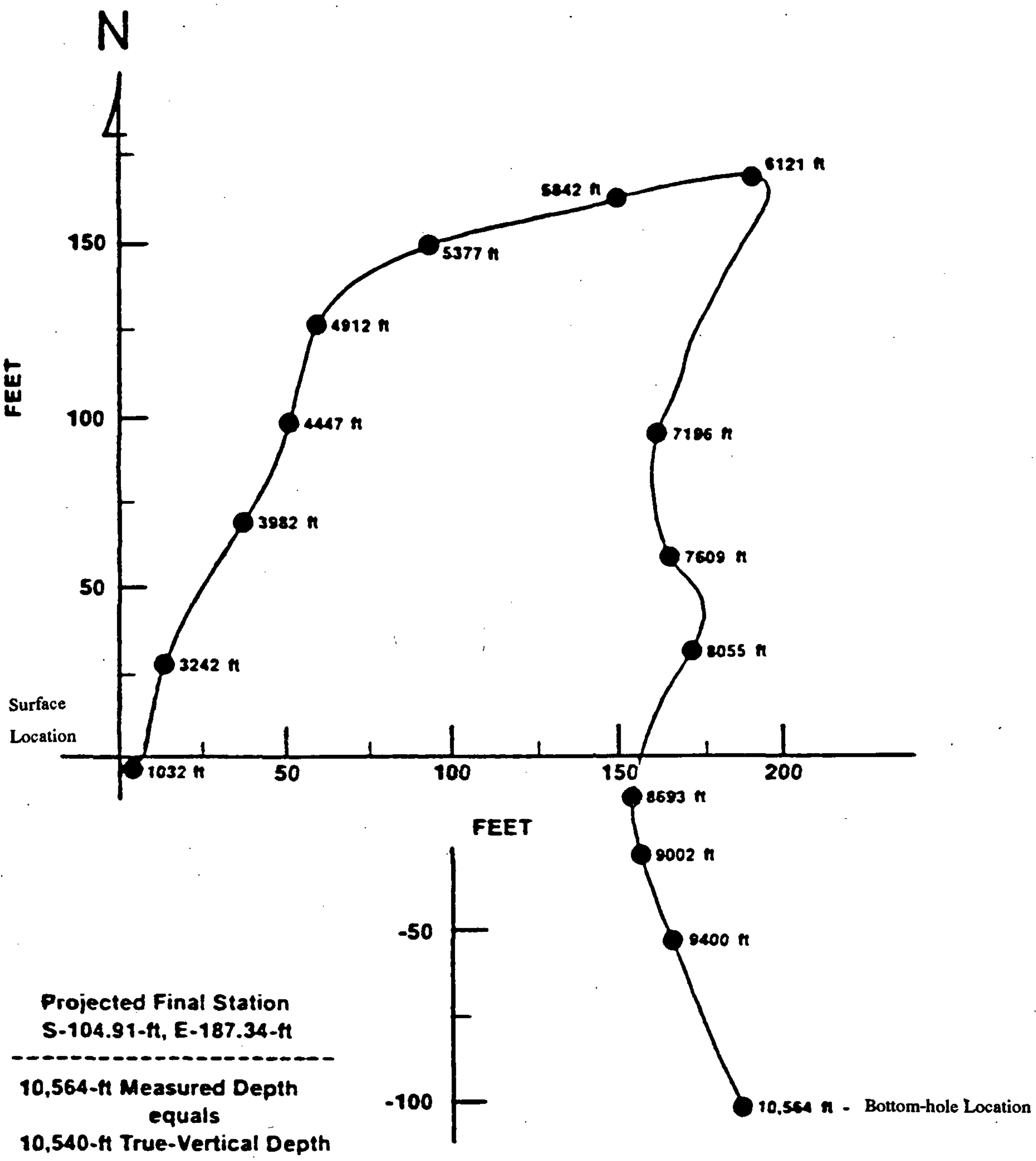
Table 7.1 SUMMARY OF SINGLE-SHOT DIRECTIONAL SURVEYS

Measured Depth (ft)	Angle (Degrees)	Direction	Remarks
485-1646	1/4	SE to NE	
2012-2970	1-1/4 to 2-1/4	N18E to N41E	
3192-4162	3 to 3-3/4	N15E to N38E	
4421-5228	4 to 4-3/4	N09E to N58E	
5336-5642	6-1/4 to 7-3/4	N73E to N76E	
5767-6121	6-1/4 to 8	N78E to S87E	Directional drill
6153-6577	3 to 5-1/2	S86E to S18E	6045-6316
6578-7115	---	---	No surveys
7116-7785	4-1/2 to 6-1/4	S02E to S47E	Directional drill
7849-8388	2-1/4 to 5	S02E to S40W	7734-8133
8450-9400	2-3/4 to 4-1/4	S13W to S27E	
9401-10564	---	---	No surveys

In addition to the single-shot surveys, Eastman Whipstock Company completed magnetic-multishot surveys at casing points and at total depth. Results are as follows:

Run No.	Interval	Remarks
1	3,515-1,000 ft	Tied into single-shot surveys at 1,000 ft
2	6,000-3,515 ft	Tied into run No. 1 and single-shot surveys to 9,400 ft
3	10,350-6,000 ft	Film destroyed by heat

Because of the destruction of film by heat in run No. 3, run No. 2 was tied into the single-shot surveys from 6,000 to 9,400 ft, then extrapolated to total depth, assuming the hole maintained the same angle and direction as the last survey. With this understanding, the final position of the hole at total depth (10,564 ft) is South 104.91 ft and East 187.34 ft from the surface location, with a true-vertical depth of 10,540 ft. The hole position, as interpreted from these surveys, is shown in Figure 7.3.



Projected Final Station
S-104.91-ft, E-187.34-ft

10,564-ft Measured Depth
equals
10,540-ft True-Vertical Depth

Figure 7.3 Well Deviation Horizontal Plot, Well State 2-14
(From Eastman Whipstock Co.)

7.6 OTHER WELL LOGS

Logs run for well-diagnostic purposes included the cement bond, temperature, and the casing caliper profile logs. A cement bond log was run in both the 13-3/8 in. and 9-5/8 in. casing to evaluate the respective cement jobs. The temperature log was run in conjunction with the last cement bond log, in an attempt to better define the cement top, without success. The casing caliper profile log was run to evaluate wear in the 9-5/8 in. casing. A list of logs and logging intervals are recorded below:

Date	Type of Log	Logging Company	Logged Interval (ft) From	To
11/17/85	Cement Bond Log	Schlumberger	3,523	30
12/18/85	Cement Bond Log	Schlumberger	5,696	190
12/18/85	Temperature Log	Schlumberger	5,670	50
03/3-/86	Casing Profile Caliper	Dia-Log	6,000	Surface

A broad suite of geophysical logs were run to assist in interpretation of the geology and evaluation of the geothermal system. These are described in a later section of this report.

7.7 REFERENCES

Bechtel National Inc., 1987, Salton Sea Scientific Drilling Program — Drilling and Engineering Program: (Draft) Final Report, 98 p.

Elders, W.A, Rex, R.W., Meidav, T., Robinson, P.T., and Blehler, S., 1972, Crustal spreading in southern California: Science, v. 178, pp. 15-24.

Friedman, I., and Obradovich, J., 1981, Obsidian hydration dating of volcanic events: Quaternary Research, v. 16, pp. 37-47.

Fuis, G.S., Mooney, W.D., Healey, J.H., McMechan, G.A., and Lutter, W.J., 1982, Crustal structure of the Imperial Valley region: U.S. Geol. Surv. Prof. Paper 1254, pp. 25-49.

GeothermEx, Inc., 1986, Salton Sea Scientific Drilling Program — geologic interpretation of Well State 2-14: Tech. rept. for Bechtel National, Inc., June, 156 p.

Gilpin, B., and Lee, T., 1978, A microearthquake study in the Salton Sea geothermal area, California: Bull. Seis. Soc. of Am., v. 68, pp. 441-450.

Griscom, A., and Muffler, L.J.P., 1971, Aeromagnetic map and interpretation of the Salton Sea geothermal area, California: U.S. Geol. Surv. Geophysical Invest. Map GP-754.

Herzig, C.T., Mehegan, J.M., and Stelting, C.E., 1988, Lithostratigraphy of the State 2-14 Borehole: Salton Sea Scientific Drilling Project: J. Geophys. Res. v. 93, no. B11, pp. 12,969 - 12,980.

Herzig, C.T., and Jacobs, D.C., 1991, Late Cenozoic basaltic magmatism in the Salton Trough: in The Diversity of Mineral and Energy Resources of Southern California, Field Trip Guidebook for Soc. Econ. Geol. Annual Meeting 1991, p. 104-116.

Hill, D.P., Mowinckel, P., and Peake, Z.G., 1975, Earthquakes, active faults and geothermal areas in the Imperial Valley, California: Science, v. 188, pp. 1306-1308.

Johnson, C.E, and Hadley, D.M., 1976, Tectonic implications of the Brawley earthquake swarm, Imperial Valley, California, 1975: Bull. Seis. Soc. of Am., v. 66, pp. 1133-1144.

Johnson, C.E, and Hill, D.P., 1982, Seismicity of the Imperial Valley: U.S. Geol. Surv. Prof. Paper 1254, pp. 15-23.

Kasameyer, P.W., Younker, L.W., and Hanson, J.M., 1984, Development and application of a hydrothermal model for the Salton Sea geothermal field, California: Geol. Soc. Am. Bull., v. 95, No. 10, pp. 1242-1252.

Lachenbruch, A.J., Sass, J.H., and Galanis, S.P., 1985, Heat flow in southernmost California and the origin of the Salton Trough: J. Geophys. Res., v. 90, pp. 6709-6736.

Littlefield, W.M., 1966, Hydrology and physiography of the Salton Sea, California: U.S. Geol. Surv. Hydrologic Investigations Atlas HA-222.

Lomnitz, C., Mooser, F., Allen, C.R., Brune, J.N., and Thatcher, W., 1970, Seismicity and tectonics of the Northern Gulf of California region, Mexico — preliminary results: Geofisica Internacional, v. 10, pp. 37-48.

McDowell, S., and Elders, W.A., 1980, Authigenic layer silicate minerals in borehole Elmore 1, Salton Sea Geothermal Field, California: Contrib. Mineral. Petrol., v. 74, pp. 293-310.

McDowell, S., and Elders, W.A., 1983, Allogenic layer silicate minerals in borehole Elmore #1, Salton Sea Geothermal Field, California: Am. Mineralogist, v. 68, pp. 1146- 1159.

McEuen, R.B., Mase, C.W., and Loomis, W.E., 1977, Geothermal tectonics of the Imperial Valley as deduced from earthquake occurrence data: Geothermal Resource Council Trans., v. 1, pp. 211-213.

McKibben, M., and Elders, W.A., 1985, Fe-Zn-Cu-Pb mineralization in the Salton Sea geothermal system, Imperial Valley, California: Economic Geol., v. 80, pp. 539-559.

Meidav, T., West, R., Katzenstein, A., and Rotstein, Y., 1976, An electrical resistivity survey of the Salton Sea geothermal field, Imperial Valley, California: Lawrence Livermore National Lab. Pub. UCRL-13690.

Muffler, L.J.P., and Doe, B., 1968, Composition and mean age of detritus of the Colorado River delta in the Salton Trough, southeastern California: J. Sed. Pet., v. 38, No. 2, pp. 384-399.

Muffler, L.J.P., and White, D.E., 1969, Active metamorphism of Upper Cenozoic sediments in the Salton Sea geothermal field and the Salton Trough, southeastern California: Geol. Soc. Am. Bull., v. 80, pp. 157-182.

Robinson, P.T., Elders, W.A., and Muffler, L.J.P., 1976, Quaternary volcanism in the Salton Sea geothermal-field, Imperial Valley, California: Geol. Soc. Am. Bull., v. 87, pp. 347-360.

Savage, J.C., et al., 1974, Possible fault slip on the Brawley Fault, Imperial Valley, California: Bull. Seis. Soc. Am., v. 74, pp. 713-716.

Sharp, R.V., 1976, Surface faulting in Imperial Valley during the earthquake swarm of January-February, 1975: Bull. Seis. Soc. Am., v. 66, pp. 1145-1154.

Sharp, R.V., 1982, Tectonic setting of the Imperial Valley region: U.S. Geol. Surv. Prof. Paper 1254, pp. 5-14.

Tewhey, J.D., 1977, Geologic characteristics of a portion of the Salton Seat Geothermal Field: Geothermal Resource Council Trans., v. 1, pp. 291-293.

Van De Kamp, P.C., 1973, Holocene continental sedimentation in the Salton Basin, California: a reconnaissance: Geol. Soc. Am. Bull., v. 84, No. 3., pp. 827-848.

Younker, L., Kasameyer, P.W., and Tewhey, J.D., 1982, Geological, geophysical and thermal characteristics of the Salton Sea Geothermal Field, California: J. Volc. and Geoth. Res., v. 12, pp. 221-258.

8.0 RESEARCH LOGS AND BOREHOLE STUDIES

8.1 INTRODUCTION

Well State 2-14 provided a unique opportunity to investigate the physical properties of sediments in a high-temperature environment, deep within the Salton Trough. A broad suite of conventional, geophysical well logs was obtained in the upper part of the borehole, but *in situ* temperatures greater than 300°C and the inability to cool parts of the borehole by circulation limited the suite of logs run at depths greater than 6,000 ft. Schlumberger Well Services obtained a standard log suite using conventional oil-field equipment, while the U.S. Geological Survey obtained both conventional and specialized logs using equipment modified to withstand geothermal reservoir conditions. Table 8.1, modified from Paillet and Morin (1988), summarizes the logging program completed for the State 2-14 borehole.

Most of the conventional logging equipment was incapable of operating in the corrosive geothermal fluids, at temperatures greater than 150°C. Commercial logging at depths greater than 5,900 ft was limited to a single run, using a deep-induction and self-potential logging tool combination, to a depth of about 8,806 ft.

The U. S. Geological Survey obtained uncalibrated neutron, natural gamma, and temperature logs to almost total depth. Acoustic televiewer and acoustic full-waveform logs were obtained from selected depth intervals greater than 5900 ft. Rig time limitations and deteriorating hole conditions limited the use of televiewer and acoustic full-waveform logs (Paillet and Morin, 1988).

8.2 LOG INTERPRETATION

Geophysical-log interpretation was not a specific task for DOE contractors. However, GeothermEx, Inc. (1986) and Herzig et al. (1988) integrated log interpretation into their lithostratigraphic studies. The detailed interpretation of temperature logs is reported by Sass et al. (1988). The U.S. Geological Survey was responsible for geophysical-log interpretation, and this has been reported in detail by Paillet et al. (1986). An overview of principal results are also reported by Paillet and Morin (1988). Some of the more important results of these studies are summarized below.

General lithology logs constructed from recovered cuttings and core appeared consistant with geophysical logs, even though the State 2-14 borehole encountered more fine-grained, clay-rich sediments than other Salton Sea boreholes. The very low frequency of sandstones in the State 2-14 borehole significantly complicates geophysical-log interpretation, using the sandstone-shale resistivity criteria given by Muramoto and Elders (1984).

Inspection of the geophysical logs indicates significant correlation between geophysical logs presented by Paillet et al. (1986), and lithology logs given by Mehegan et al. (1986).

Paillet and Morin (1988) show that, in the interval 3,940 - 4,760 ft, large resistivities and low porosities and acoustic-transit times correspond to large sandstone fractions on the lithology log, whereas small resistivities and larger porosities and acoustic-transit times correspond to large claystone fractions. Departures from this correlation represent the dependence of geophysical measurements to rock properties, other than clay-mineral content, and on details not reflected by the lithology log. At depths greater than 4,920 ft, the alteration of clay minerals apparently accounts for the poor correlation between geophysical and lithologic logs.

Table 8.1 Summary of Geophysical Logs, Dates, and Depth Intervals Over Which Logs Were Run In the State 2-14 Borehole

Commercial Log Type	Date Logged	Depth Range (ft)
SCHLUMBERGER WELL SERVICES		
Deep induction, spontaneous potential, natural gamma, nuclear porosity, compensated gamma-gamma (density)	Nov. 4, 1985	1,032-3,000
Caliper, acoustic transit time	Nov. 5, 1985	1,035-3,000
Deep induction, spontaneous potential, natural gamma, acoustic transit time	Nov. 13, 1985	2,900-3,520
Nuclear porosity, compensated gamma-gamma (density)	Nov. 13, 1985	2,900-3,494
Caliper	Nov. 13, 1985	1,032-3,524
Deep induction, spontaneous potential, natural gamma, nuclear porosity, compensated gamma-gamma (density)	Dec. 9, 1985	3,520-5,987
Caliper and acoustic-transit time	Dec. 9, 1985	3,520-5,980
Deep induction, spontaneous potential	Mar. 10, 1986	6,020-8,806
U.S. GEOLOGICAL SURVEY		
Temperature, natural gamma	Nov. 5, 1985	1,032-3,000
Temperature(2), caliper(2), acoustic televiewer, acoustic-transit time(2)	Nov. 6, 1985	1,032-3,000
Full-waveform acoustic, temperature(2), natural gamma, gamma spectral	Nov. 7, 1985	1,032-3,000
Temperature, caliper	Dec. 4, 1985	1,032-3,000
Temperature	Dec. 9, 1985	3,513-6,000
Temperature, caliper, acoustic televiewer, natural gamma	Dec. 10, 1985	3,513-6,000
Gamma spectral, single-point resistance, acoustic-transit time, full-waveform acoustic (2), caliper, temperature	Dec. 11, 1985	3,513-6,000
Caliper, neutron	Dec. 12, 1985	3,513-6,000
Temperature	Dec. 23, 1985	3,513-6,000
Temperature	Dec. 29, 1985	3,513-6,000
Temperature	Feb. 15, 1986	6,000-10,000
Temperature	Mar. 8, 1986	1,032-10,003
Temperature	Mar. 12, 1986	6,000-10,000
Acoustic televiewer	Mar. 12, 1986	5,994-6,601
Full-waveform acoustic	Mar. 13, 1986	6,000-7,001
Natural gamma, neutron	Mar. 29, 1986	6,000-10,000
Temperature	Mar. 27, 1986	1,032-10,003
Temperature	Mar. 31, 1986	1,032-10,003
Temperature	Apr. 7, 1986	1,032-10,003

Changes in transit time on the acoustic log seem to correlate with changes in lithology, but the recorded values appear too low for indurated shales and sandstones. The large borehole diameters and viscous drilling mud significantly attenuated the acoustic signal generated by the tools and complicated interpretation. Full-waveform logs were also affected by these factors.

The natural gamma log, usually considered to be a good indicator of lithology, did not correlate well with lithology in much of the borehole (Paillet and Morin, 1988). In the upper part of the borehole, this was related to the lack of good lithology contrasts, where there were few clean sandstones. At greater depths, hydrothrmal alteration may have acted to redistribute natural isotopes, obscuring the initial correlation between sediment-type and natural radioactivity.

Paillet and Morin (1988) illustrate a good correlation between the Spontaneous-Potential (SP) log and lithology for the depth interval 3,940 to 4,920 ft. Above this interval, the limited occurrence of sandstone and a small water-quality contrast between formation waters and drilling mud results in little variation in the SP log. The low porosity and electrical conductivity typical of the high-claystone fraction below 4,920 ft-depth, probably indicative of significant alteration of clay minerals, results in poor correlation between the SP log with the lithology log at depths greater than 4,920 ft.

8.3 INTERPRETATION OVERVIEW

Previous authors (Ershaghi et al., 1979; Muramoto and Elders, 1984) have observed that the depth trends in geophysical-log values in the Imperial Valley are affected by changes in clay mineral properties, resulting from hydrothermal alteration of sediments, as well as by compaction and increasing confining pressure. In well State 2-14, the lithology developed from cuttings correlates with most geophysical logs, but correlations are strong for only some intervals of the borehole. Qualitative and quantitative interpretation of most logs is hampered by borehole conditions, the relative absence of "clean" sandstones and good lithology contrasts, and the effects of hydrothermal alteration at depth. The trend of increasing alteration is evident as a general increase in deep-induction resistivity with depth. For a more complete discussion of the geophysical-log interpretation of well State 2-14, the reader is referred to Paillet, et al. (1986) and Paillet and Morin (1988).

8.4 TEMPERATURE-LOG INTERPRETATION

Temperature logs were recorded during breaks in drilling and both during and after flow tests for well State 2-14 (Table 8.1). The logs completed during the active drilling phase were used to assist in identifying zones of fluid loss or gain and to estimate reservoir temperatures. Additional logs recorded from April 8 to October 24, 1986, and on July 31, 1987, were used to estimate equilibrium reservoir temperatures and heat flow (Sass, et al., 1988).

Figure 8.1 from Paillet and Morin (1988) shows a composite temperature log of the State 2-14 borehole indicating the temperature at various times during drilling. Figure 8.2 from Sass, et al. (1988) shows the interpreted equilibrium temperature log obtained by extrapolation of the previous logs. The temperature profiles reflect the history of the drilling and testing program, and could be misleading without supplemental information. The temperatures were measured with a platinum resistance thermometer (RTD), attached to four conductors of a logging cable, or with modified oil-field, downhole-recording devices (Kuster gauges), that employ mechanical transducers. All of the temperature data presented by Sass, et al.(1988), were obtained with platinum RTDs deployed either in a conventional mode (surface readout) or in a downhole recording, digital "memory" tool. The log of April 1, 1986 (Figure 8.2), was begun immediately upon cessation of the injection of

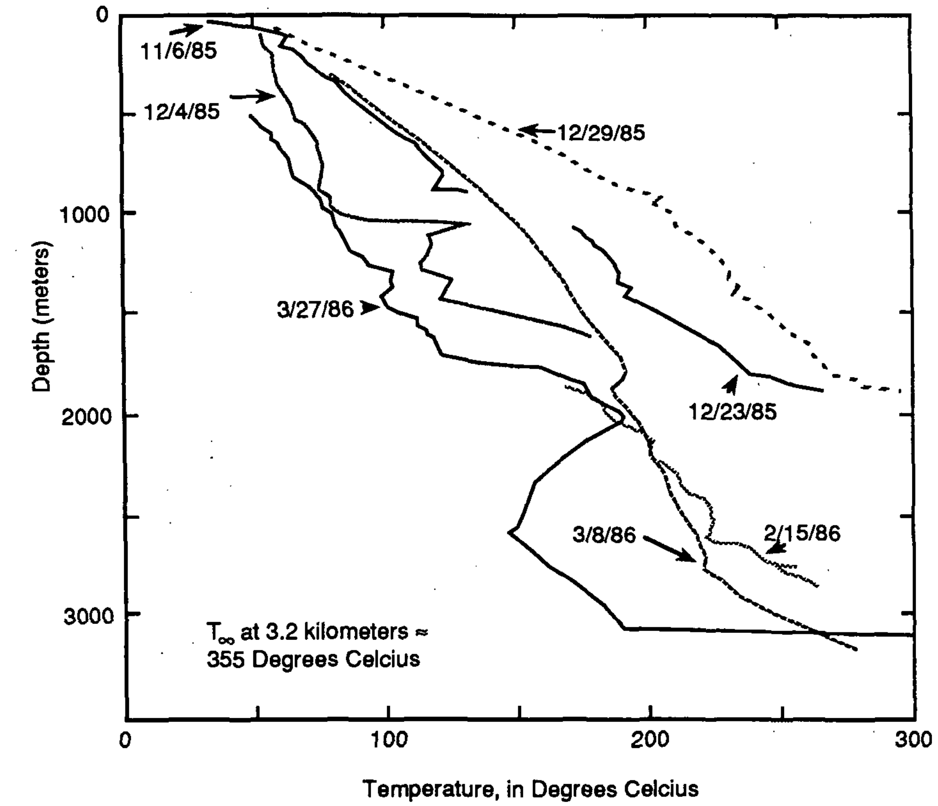


Figure 8.1 **Summary of Temperature Logs Taken While Drilling State 2-14** (from Paillet and Morin, JGR v.93, Bll, 1988, published by the American Geophysical Union).

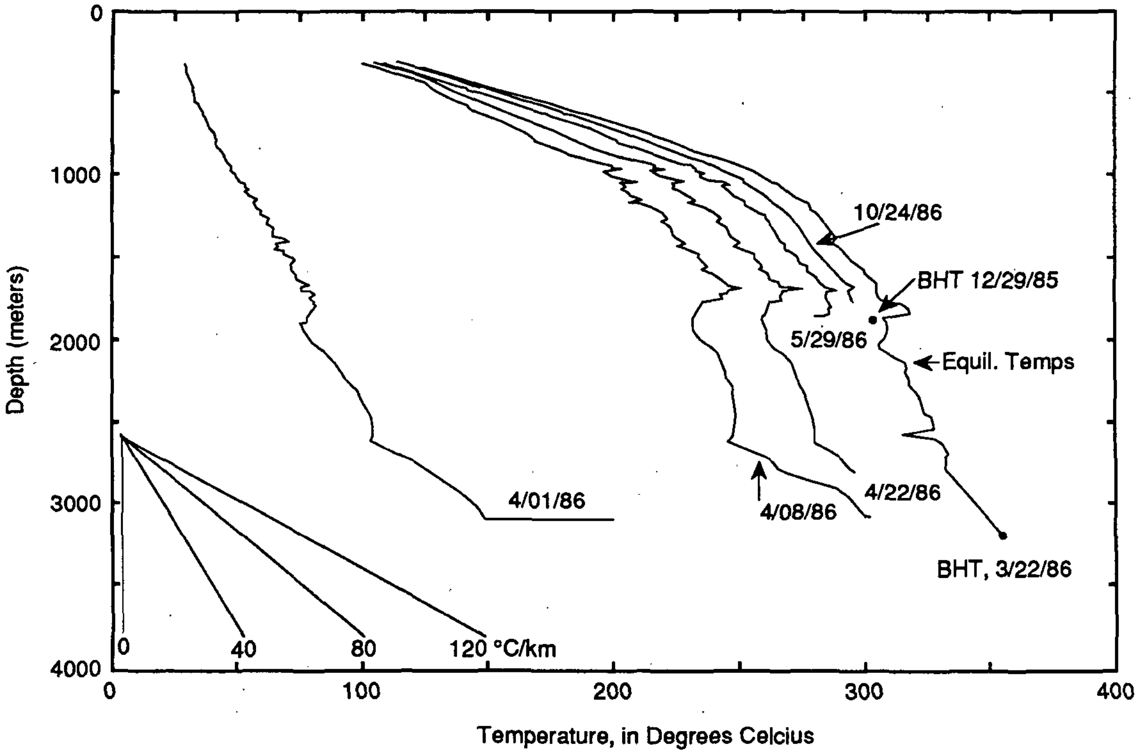


Figure 8.2 **Temperature Log Summary; March-October 1986, State 2-14** (from Sass et al., JGR v.93, Bll, 1988, published by the American Geophysical Union).

nearly $10^4 m^3$ of cooled brine (from an earlier flow test) and irrigation water. A pronounced temperature reversal occurs just beneath the 9-5/8 in. casing at a depth of about 6,000 ft. This was the depth of the first production zone tested in December 1985, and it appears cooler because it accepted a large amount of (cooled) injected fluid. The strong reversal at about 8,500 ft indicates a very permeable zone (Sass et al., 1988). A sharp increase in temperature at the base of the 7-in. liner (10,148 ft.) shows that very little, if any, fluid was injected below the 7-in. liner, and that most of the injected fluid flowed around the bottom of the liner, up the annulus, and entered the formation at various depths, mostly around 6,070 and 8,596 ft.

Sass et al. (1988) used four logs recorded from April 8 to October 24, 1986, to estimate equilibrium temperatures in the upper 5,900 ft. A profile obtained on July 31, 1987, to 3,215 ft showed reasonable agreement between 980 and 1,640 ft, but divergence from the "equilibrium" temperatures at depth. The July 31, 1987, profile was considered to be the best estimate of formation temperatures in the upper 3,300 ft of the well, and that data set was used in estimating the conductive heat flux. Principal conclusions from the work of Sass et al. (1988) are:

a) Best estimates of formation temperature below 3,300 ft are 305°+/-5°C at about 6,200 ft and 355°C +/-10°C at 10,400 ft;

b) A low-permeability overlying strata on the thermal system extends to a depth of more than 2,950 ft in the State 2-14 well;

c) Thermal gradients decrease from about 250°C/km in the upper few hundred meters to just below 200°C/km near the base of the conductive cap;

d) The heat flux decreases systematically below 984 ft and averages about 350 mWm^{-2};

e) One interpretation, consistent with fluid-inclusion data, is that the rocks in this part of the field were once several tens of degrees Celsius hotter than present;

f) Several other wells in the Salton Sea field are hotter than State 2-14 at comparable depths.

8.5 DOWNHOLE EXPERIMENTS SUMMARY

A number of downhole experiments were conducted during both the first flow test at 6,120 ft and the second test at 10,564 ft. Experiments on the first flow test were limited to temperature and pressure surveys and downhole sampling. Studies during the second flow test included, in addition to the foregoing, spinner, vertical seismic profiling and downhole gravity surveys, and the Bethke fluid-inclusion experiment. Several sampling attempts or survey efforts were unsuccessful for mechanical, environmental or other reasons. A listing of downhole experiments and comments is presented in Table 8.2.

Results of these studies have been published in various organizational reports and technical journals or are included as reports submitted to Bechtel (Appendix A). Important results that contribute materially to understanding the Salton Sea geology and geothermal system are referenced elsewhere in this report.

Table 8.2
DOWNHOLE EXPERIMENTS

Date	Depth (ft)	Experiments	Comments/Results
First Flow Test - 6200 feet			
12/30/85	6,200	Kuster T/P*	Logged during flow and buildup, after shut in. Well bottom-hole temp. (BHT) 305 +/- 5°C.
12/31/85	6,200	LANL/Sandia downhole fluid sampler	Two attempts: first failed due to brine flashing upon entry into sample bottle and clogging port. Second failed due to malfunction of battery system.
Second Flow Test - 10,564 ft			
03/21/86	0-5,000	Kuster spinner and pressure	Spinner failed at 5,000 ft
03/21/86	0-10,000	Kuster T/P	baseline error on temp. chart.
03/22/86	0-10,400	Kuster T/P	BHT 350 +/-10°C.
03/22-23/86	10,400	First run, LANL/Sandia downhole fluid sampler	No sample due to seal failure; motor flooded and it shorted out.
03/23/86	10,400	Second LANL/Sandia sampler	No sample due to seal failure.
03/23/86	10,400	First run, Leutert downhole fluid sampler	Failure due to LCM clogging bullnose.
03/23/86	10,200	Second Leutert	Clock stopped; canister did not close.
03/23/86	10,200	Third Leutert	O-rings on sampler bottle failed.
03/23-24/86		USGS Bethke fluid inclusion	Wireline broke leaving tool in bottom of hole. One fishing attempt with no recovery.
03/25/86	10,200	Third LANL/Sandia	Sample bottle returned empty.
03/25/86	10,200	Fourth LANL/Sandia	Recovered 1.5 liters liquid and 0.5 liter gas sample.

* T = temperature, P = pressure

Table 8.2 (Cont'd)

Date	Depth (ft)	Experiment	Comments/Results
03/25/86	10,200	Fifth LANL/Sandia	Bottle did not open.
03/25/86	10,200	LBL fluid sampler run	Recovered 1 liter, unpressurized fluid and no gas
03/27-29/86	50-5,650	LBL-Vertical Seismic Profile	Two good data sets with vibrators on drill pad and 1/2 mile off-pad. Third data set with tool in liner produced too much noise. Fourth run: tool shorted out.
03/30-31/86	6,000	LLNL downhole gravity	Recovered good data with gravimeter ascending hole from 6,000 ft

* T = temperature, P = pressure

8.6 REFERENCES

Bechtel National, Inc., March 1987, Salton Sea ScientificDrilling Program — Drilling and Engineering Program: (Draft) Final Report, Prepared for U.S. Department of Energy.

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.

Ershaghi, I., Phillips, L.B., Dougherty, E.L., Handy, L.L., and Mathews, M., 1979, Applications of oilfield well log interpretation to the Cerro Prieto geothermal field; Trans. SPWLA Annu. Logging Symp., v. 20, pp. 1 - 11.

Paillet, F.L., and Morin, R.H., 1988, Analysis of Geophysical Well Logs Obtained in the State 2-14 Borehole, Salton Sea Geothermal Area, California: J. Geophys. Res., Vol. 93, No. B11, pp. 12,981 - 12,994.

Paillet, F.L., ed., 1986, Preliminary Report on Geophysical Well-Logging Activity on The Salton Sea Scientific Drilling Project, Imperial Valley, California: U.S. Geol. Surv. Open-File Report 86-544.

GeothermEx, Inc., 1986, Salton Sea Scientific Drilling Program — geologic interpretation of well State 2-14: Tech. report for Bechtel National, Inc.

Herzig, C.T., Mehegan, J.M., and Stelting, C.E., 1988, Lithostratigraphy of the State 2-14 Borehole: Salton Sea Scientific Drilling Project: J. Geophys. Res., V. 93, No. B11, pp. 12,969 - 12,980.

Mehegan, J.M., Herzig, C.T., and Sullivan, R.M., 1986, SSSDP, California State 2-14 well, visual core descriptions, Vol. 1, Publ. UCR/IGPP-86/1, 221 pp., Univ. of Calif., Riverside.

Muramoto, F.S., and Elders, W.A., 1984, Correlation of Wireline Log Characteristics with Hydrothermal Alteration and Other Reservoir Properties of the Salton Sea and Westmoreland Geothermal Fields, Imperial Valley, California, USA; Los Alamos Natl. Lab. Rep., LA-10128-MS, 1984.

Sass, J.H., et al., 1988, Thermal Regine of the State 2-14 Well, Salton Sea Scientific Drilling Project: J. Geophys. Res., V. 93, No. B11, pp. 12,995 - 13,004.

Liner repair work of August 1986 reestablished tool access to approximately 8,005 ft (2,440 m) through the temporary installation of 793 ft (242 m) of 7-in. (17.8-cm) patch liner (5,728 to 6,521 ft; 1,746-1,988 m). Direct project costs of this first well remedial work exceeded $290,000.

In the first logging attempt following remedial work (October 22), a dewared Kuster tool encountered a soft bridge at 5,800 ft (1,768 m) and stopped at 5,810 ft (1,771 m). A sinker bar was worked to 6,717 ft (2,047 m), but the temperature tool was again stopped by a gel bridge, at 5,822 ft (1,775 m) on October 24. It was concluded that the liner was full of gel from 5,800 ft (1,768 m) to at least 8,000 ft (2,438 m) and logging attempts were discontinued. Bechtel suggested that during the final water displacement of mud in the August remedial work, the water may have flowed around the top of the replacement liner rather than down through it, and that mud located below 5,800 ft (1,768 m) was not circulated out. Alternatively, the mud may have migrated back up into the liner from the lower part of the well. The inability to run logging tools to the bottom of the well and the need for a flow test of deeper reservoir zones led to additional well rework which was performed in August 1987. The 7-in. temporary liner was retrieved with some difficulty, related to pulling the liner through the dogleg at about 6,200 ft (1,890 m). Four attempts to sidetrack the hole using mud motors failed because of the high temperature. One attempt to effect a sidetrack, using a locked bottom-hole assembly, drilled out the cement plug. After setting a new cement plug, a second run with a whipstock apparently wandered back into the original hole and encountered a major obstruction at a depth of 7,180 ft (2,188 m). At this point, Bechtel was directed by DOE to stop drilling and prepare for a flow test of accessible zones (6,100-7,100 ft; 1,859-2,164 m). This marked the greatest depth tested by all subsequent logging, except for temperature logging, although flow tests may have produced fluids from greater depths. The two well rework attempts were largely failures. The drilling techniques used were unable to regain access to the bottom of the hole. Direct project costs for the drilling contractor for the Phase 2 rework exceeded $330,000.

GEOSCIENCE

Geologic, mineralogic, permeability, and temperature data were obtained for most of the 10,564-ft (3,220-m) total depth of the hole, subject to lack of cuttings from lost-circulation zones, and were not seriously limited by loss of access to the hole due to the liner separation and subsequent hole obstruction. The obstruction did prevent controlled flow-testing of individual permeable zones and the acquisition of samples for fluid chemistry from known depths. Nonetheless, an impressive amount of geoscientific information was obtained from well State 2-14 and entered into the public domain.

Only two major sedimentary-rock intervals can be readily distinguished in the borehole. The upper, consisting of poorly indurated clay, silt, and sand, extends from the surface to about 1,100 ft (335 m) depth. The lower unit, extending from a depth of about 1,100 ft to total depth of the well, consists of an assemblage of alternating claystones, siltstones, and sandstones. These sediments were deposited in the continental basin of the Salton Trough, and are interpreted as the basinward facies of the Borrego and Brawley formations, which range from Pliocene to Pleistocene in age (Herzig et al.,1988). Lacustrine shale and siltstone are the dominant lithologies, but sandstones were deposited in lake margin, meander-channel fill, and lacustrine-delta environments.

Alteration generally increases with depth and is superimposed on, and partly controlled by, pre-existing sedimentary features. The rocks below about 2,760 ft (841 m) show evidence of greenschist facies metamorphism, with the first appearance of vein epidote noted at this depth. Alteration is enhanced along permeable zones, primarily the sandstone units. Two mafic intrusive bodies were intersected between 9,440 and 9,589 ft (1,963-2,923 m). Both were cut by high angle veinlets of epidote + sulfide + quartz + actinolite (?). The self-sealed cap rock extends to

The Colorado River delta has alternately drained northward and southward. At times, its distributaries have emptied northward, filling the Salton Basin. When drainage has been to the south into the Gulf of California, lakes in the Salton Basin have shrunk. Currently, the Colorado River drains southward, and under natural conditions the Salton Sea would evaporate. Instead, the lake level is rising, in response to the current influx of irrigation water.

Holocene sedimentary rocks in the Salton Basin can be divided into three facies (Van DeKamp, 1973). A central lacustrine facies consists of mud and silt, which become coarser-grained toward the basin margins. Evaporites are common, and bedding is often disturbed by animal burrows. Fluctuations in lake level caused intertonguing of the lacustrine materials with coarser, basin-margin sediments. Meandering stream channels formed sand and silt deposits within the lacustrine muds. Alluvial fans and braided streams deposited boulders and gravels at the base of the surrounding mountains, but grain size decreases rapidly toward the center of the basin. These locally-derived sediments have compositions different from those deposited by the Colorado River. The most significant features of the Holocene sediments are the abrupt facies changes and variety of sedimentary environments present in small areas. These changes make correlating units difficult.

Before significant quantities of irrigation water began to enter the basin in 1901, the Salton Sea was a playa known as the Salton Sink. An uncontrolled diversion of the Colorado River in 1905-1907 raised the lake surface to -60 m, its highest modern level (Littlefield, 1966). The current lake level is about -70 m. Wave-cut terraces at elevations of +12 m were formed by Lake Cahuilla, the last natural basin-filling lake, which existed until about 300 years ago (Van DeKamp, 1973).

7.2.2 Quaternary Volcanism

Four small rhyolite domes, known as the Salton Buttes, are the only surface evidence of recent volcanism in the Salton Basin. The domes are aligned along a 7 km-long, northeasterly trend. From the southwest, they are: Obsidian Butte, Rock Hill, Red Hill, and Mullet Island. Red Hill is 2.9 km southwest of the SSSDP. A K-Ar age of 16,000 years was obtained from samples of Obsidian Butte. Three of the domes are discharging minor amounts of gas from cracks and joints (Muffler and White, 1969). Basaltic rocks are not exposed at the surface, but occur as xenoliths in the domes and as dikes or sills encountered in State 2-14 and other wells.

7.2.3 Diagenesis, Metamorphism and Mineralization

Muffler and Doe (1968) identified the original, detrital mineralogy of the Colorado River sediments as predominantly quartz, calcite, dolomite, plagioclase feldspar, K-feldspar, montmorillonite, illite and kaolinite. Burial, heating, and mineralizing fluids cause pronounced changes in sediments deposited in the Salton Basin. The first detailed work on alteration was done by Muffler and White (1969). Some of these changes are visible, megascopically, while others are not; effects of these on the geothermal reservoir are of great importance.

Diagenesis. Diagenesis is a process whereby detrital minerals are altered in place, at relatively low temperatures. The diagenetic process grades into metamorphism, but the term is generally applied to reactions taking place under 200°C. Diagenesis is important in geothermal reservoirs, because one of its products is secondary cement, which binds the detrius and decreases the initial porosity of reservoir sands. In the Salton Basin, two main types of cement produce this "self-sealed caprock." Most important is calcite, which may be produced, along with chlorite, at temperatures as low as 125°C (Muffler and White, 1969). A second diagenetic cement is pyrite, produced by reduction of iron from iron-bearing detrital minerals (McKibben and Elders, 1985).

7.6 OTHER WELL LOGS

Logs run for well-diagnostic purposes included the cement bond, temperature, and the casing caliper profile logs. A cement bond log was run in both the 13-3/8 in. and 9-5/8 in. casing to evaluate the respective cement jobs. The temperature log was run in conjunction with the last cement bond log, in an attempt to better define the cement top, without success. The casing caliper profile log was run to evaluate wear in the 9-5/8 in. casing. A list of logs and logging intervals are recorded below:

Date	Type of Log	Logging Company	Logged Interval (ft) From	To
11/17/85	Cement Bond Log	Schlumberger	3,523	30
12/18/85	Cement Bond Log	Schlumberger	5,696	190
12/18/85	Temperature Log	Schlumberger	5,670	50
03/3-/86	Casing Profile Caliper	Dia-Log	6,000	Surface

A broad suite of geophysical logs were run to assist in interpretation of the geology and evaluation of the geothermal system. These are described in a later section of this report.

7.7 REFERENCES

Bechtel National Inc., 1987, Salton Sea Scientific Drilling Program — Drilling and Engineering Program: (Draft) Final Report, 98 p.

Elders, W.A, Rex, R.W., Meidav, T., Robinson, P.T., and Blehler, S., 1972, Crustal spreading in southern California: Science, v. 178, pp. 15-24.

Fuis, G.S., Mooney, W.D., Healey, J.H., McMechan, G.A., and Lutter, W.J., 1982, Crustal structure of the Imperial Valley region: U.S. Geol. Surv. Prof. Paper 1254, pp. 25-49.

GeothermEx, Inc., 1986, Salton Sea Scientific Drilling Program — geologic interpretation of Well State 2-14: Tech. rept. for Bechtel National, Inc., June, 156 p.

Gilpin, B., and Lee, T., 1978, A microearthquake study in the Salton Sea geothermal area, California: Bull. Seis. Soc. of Am., v. 68, pp. 441-450.

Griscom, A., and Muffler, L.J.P., 1971, Aeromagnetic map and interpretation of the Salton Sea geothermal area, California: U.S. Geol. Surv. Geophysical Invest. Map GP-754.

Herzig, C.T., Mehegan, J.M., and Stelting, C.E., 1988, Lithostratigraphy of the State 2-14 Borehole: Salton Sea Scientific Drilling Project: J. Geophys. Res. v. 93, no. B11, pp. 12,969 - 12,980.

Hill, D.P., Mowinckel, P., and Peake, Z.G., 1975, Earthquakes, active faults and geothermal areas in the Imperial Valley, California: Science, v. 188, pp. 1306-1308.