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THE AHUACHAPAN GEOTHERMAL PROJECT: A TECHNICAL AND ECONOMIC ASSESSMENT

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TABLE OF CONTENTS

TABLE OF CONTENTS
(Continued)

LIST OF FIGURES

LIST OF TABLES

SUMMARY

In 1975, Ahuachapan Unit 1 began generating 30 MW of electricity from geothermal energy. Unit 2 began producing an additional 30 MW, one year later. Both units are base-loaded and achieved an average capacity factor of 76% in 1977. No significant operating problems have been encountered.

Geothermal energy is an economic and reliable source of electricity generation in El Salvador. In 1977 geothermal energy from Ahuachapan produced 32% of the electricity generated in El Salvador. Geothermal energy is competitive with hydroelectric power, the principal other indigenous energy source. Both geothermal and hydroelectric power costs are significantly lower than the marginal cost (energy supply cost) of electricity from oil. Capacity expansion plans call for additional hydroelectric and geothermal power plants. If expansion plans are achieved, El Salvador will be independent of petroleum for electricity generation by 1985.

If the Ahuachapan reservoir were located in the U.S., it would probably produce power at costs which would be competitive with new nuclear or coal fired plants and with The Geysers geothermal field. The Ahuachapan reservoir is shallow, 600-1400 meters below the surface. The wells are highly productive averaging 6 MWe. The reservoir temperature is about 240°C. Steam is separated at the wellhead at 160°C.

The Ahuachapan power plants use flashed (wet) steam in contrast with dry (superheated) steam at The Geysers. Although no existing U.S. geothermal plants use flashed steam, the proposed power plants at Roosevelt Hot Springs, Utah, and Valles Caldera, New Mexico, plan to use flashed steam. Flashed steam technology is not new technology. Existing geothermal power plants in Mexico, New Zealand and Japan also use flashed steam. The New Zealand plants have been in operation since 1958. Ahuachapan Unit 3 is planned to use a "double flash" cycle. This will increase the efficiency of utilization by extracting more energy from the geothermal fluid.

Electricity generation and transmission in El Salvador is performed by the Comision Ejecutiva Hidroelectrica Del Rio Lempa (CEL), a governmental commission. Assuming governmental financing at 10%, power is produced at

Ahuachapan for 21 mills/kWh. Without financing charges, the cost of power is only 8 mills/kWh. The actual financing of Ahuachapan was partly through foreign loans and a local bond issue at 6% to 8% interest and partly through the internal funds of CEL.

The Ahuachapan development has provided definitive economic and technical feasibility data which permits definition and comparison of the economic viability of using geothermal energy in a specific electric power generation system which is representative of U.S. conditions. The project has successfully demonstrated flashed steam technology and provided technical and cost data for determining reliable methods of assessing reservoir capacities, well stimulation, and utilization technology.

INTRODUCTION

Rising energy prices and potential shortages of fossil fuels have spurred increased interest in geothermal energy throughout the world. In the past, geothermal energy development was severely limited by competition from low-priced, well-accepted alternatives. Now, with these alternatives in short supply, geothermal energy has become economically competitive in many locations.

Over a short time El Salvador has become the nation most reliant on geothermal energy for electricity generation and plans to increase its geothermal capacity. In 1977, the 60 MWe Ahuachapan geothermal power plant constituted 14% of El Salvador's installed electric generating capacity and supplied about one-third of the electricity produced in the country. An additional 35 MWe is under construction at Ahuachapan. Besides Ahuachapan, there is good potential for geothermal energy production at four other sites: Berlin, Chinameca and San Vicente, which may each produce 100 MW eventually, and Chipilapa which may support 50 MW. The locations of the prospective geothermal sites, together with the existing power plants, both geothermal and conventional, are shown in Figure 1.

The Ahuachapan plant is very important to the economy of El Salvador. In this report we will examine the economic and technical factors involved in using geothermal energy at Ahuachapan. We will evaluate the experience at Ahuachapan in relation to conditions prevailing in El Salvador and to conditions prevailing in the U.S.

This report is based on information provided by Gustavo Cuellar, Superintendent of Geothermal Studies, Comision Ejecutiva Hidroelectrica Del Rio Lempa (CEL) and his associates. CEL operates the geothermal plant at Ahuachapan. This report concentrates on economic and cost-related information. Additional technical data is summarized in other references cited later. The information in this report was obtained during a June 1978 visit to El Salvador by C. H. Bloomster, R. DiPippo, J. T. Kuwada and R. Reeber, Department of Energy, Division of Geothermal Energy.

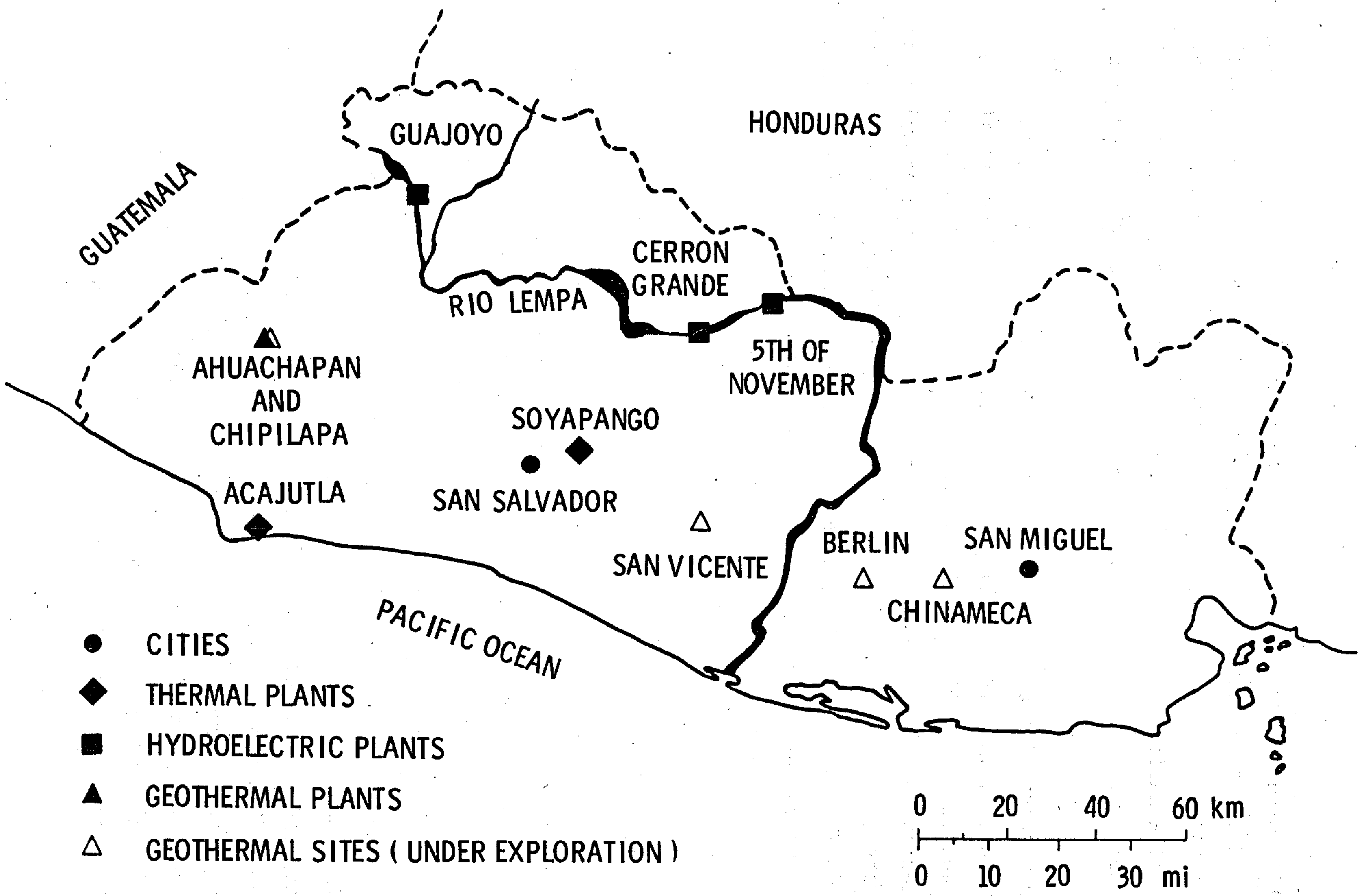

FIGURE 1. Map of El Salvador Showing Geothermal Sites and Existing Power Plants

THE AHUACHAPAN GEOTHERMAL PROJECT[a]

The first explorations of the subsurface of the mudholes in Ahuachapan were made in 1957 with the help of the Geological Service of the Ministry of Public Works.

The objective pursued by the Comision Ejecutive Hidroelectrica Del Rio Lempa (CEL) was to establish the possibility of using the hot vapors from the subsoil, as had been done in Italy, New Zealand, the U.S., and other countries, to produce electrical energy.

TECHNICAL ASSISTANCE

In 1965 the Government of El Salvador and the Special Fund of the United Nations signed a technical assistance agreement to study the Geothermal Project, which represented progress in using indigenous natural resources in the national electrical development.

The support for financing the investigations was $0.9 million from the Special Fund of the United Nations and $0.6 million from CEL.

DRILLING

To determine the geothermal site with the most possibilities of exploration, Loffland Brothers, Inc. signed a contract in 1968 to drill deep geothermal wells: 3 in Ahuachapan, 1 in San Vicente and 1 in Usulutan. The opinion of the experts was that the area of the mudholes of Ahuachapan offered better prospects for success.

STUDIES

The technical contractors to the Special Fund of the United Nations performed important studies: (1) Geological studies, from surface geology to aerial photography to obtain morphological and geotechnical maps, that

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[a] Translated from "Planta Geotermica De Ahuachapan". Comision Ejecutiva Hidroelectrica Del Rio Lempa, San Salvador, El Salvador, C.A., 1976.

permitted them to detect fractures in the earth's crust or zones that showed alterations of the original thermal gradient; (2) geophysical studies, which used gravimetric analyses, magnetic measurements, thermal measurements, seismicity and electrical resistivity, to determine the structure of the subsurface, density, etc.; (3) geochemical studies, which consisted of samples of water and gases, with their analyses to correlate the chemical composition of the underground fluids with the possibility of success.

SECOND STAGE

The year 1969 was the start of the second stage of the geothermal project, assigning the following portions of the technical assistance agreement: CEL, $1.0 million and Special Fund of the U.N., $0.9 million.

Loffland Brothers, Inc., drilled in 1970 by means of a new contract, 8 geothermal wells of great depth at Ahuachapan, with the objective of getting more information about the vapor reserves in the area.

FEASIBILITY

In May 1971, the feasibility study on construction of a geothermal power plant was finished, performed by the firm "Kingston, Reynolds, Thom and Allardice", in association with Kennedy and Donkin, of Great Britain, and the Ministry of Public Works of New Zealand.

CONCLUSIONS

The study of the consulting firms determined the following: (1) the technical and economic feasibility of constructing a geothermal power plant of 30,000 kW at Ahuachapan; (2) the estimated cost of the work; (3) the energy production cost for utilization of the hot subsurface vapors; (4) the alternatives of a canal to the sea and reinjection to solve the problem of the residual water from the geothermal wells.

WORK PERFORMED

Technical assistance services related to the construction stage were contracted to the Italian firm ELC Electroconsult S.P.A. From 1972 to 1976, the following main jobs were performed:

Prosecution of the studies of the geothermal area of Ahuachapan to complete the available scientific information.
Drilling of 9 wells, by contract with the French firm Foramines S.A., to guarantee vapor reserves for the geothermal plant.
Bidding on the jobs and awarding the respective contracts.
Exploratory drilling in the area of Los Toles and Chipilapa.

Contractors

The supplies of equipment and the construction of the civil works of the geothermal plant were performed by the following firms:

1. First and second turbogenerator units of 30,000 kW each, by Mitsubishi Corporation of Japan.
2. Electrical and mechanical equipment, by Gruppo Industrie Eletro Meccanique Per Impianti All' Estero of Italy.
3. Construction of the civil work (plant building, cooling tower, lab, etc.) and equipment mounting of units 1a and 2a, by Sociedad Venezolana de Electrificacion C.A., associated with the national firm Siman S.A.
4. The 115 kW line from Ahuachapan-Santa Ana to Sadelmi-Cogepi, associated with the national firm CELSA.
5. Cranes for the machine house and lab, by Boetticher and Navarro of Spain.
6. Gathering pipes to carry the vapor from the geothermal wells to the central generator, were contracted to William Press and Son of Great Britain and Mitsubishi Corporation.
7. Canal to the sea: first span of 29 km, built by the national firms: Siman S.A. and Lecha Palomo; second span of 36 km, by Siman S.A.; third span, 21 km, by Molina Cuenca Associates.

Financing

The geothermal plant at Ahuachapan was financed with a loan from the World Bank, a local bond issue and private resources of CEL. The total cost of the work with 2 generator units, including the canal to the sea, is estimated at $44 million, approximately. [The final construction cost increased to almost $50 million, see Table 5, p. 26][a].

Future Expansion

The initial capacity of 30,000 kW of the Geothermal Plant of Ahuachapan was augmented in 1976 by means of the addition of the second generating unit to a total of 60,000 kW. It is planned in the near future to install the third unit to attain the maximum plant capacity, estimated at 90,000 kW. [The third unit is now planned at 35 MW, increasing maximum plant capacity to 95 MW.]

CEL will continue and will expand the scope of their investigations to other geothermal areas, to establish the feasibility of constructing geothermal electric plants: (1) the zone north and northeast of the City of Ahuachapan; (2) Berlin, section of Usulutan; (Chinameca, section of San Miguel, and (4) in the section of San Vicente.

The expansion of the efforts of the geothermal investigation is founded in the politics of utilizing to the maximum the natural resources of the country to satisfy her growing energy needs without depending on fossil fuel imports.

[a] Brackets [] indicate translator's notes.

TECHNICAL CHARACTERISTICS OF THE AHUACHAPAN PROJECT

The Ahuachapan geothermal field is characterized as a liquid-dominated geothermal resource. The reservoir is shallow, ranging in depth from 600 to 1,400 meters; with a downhole temperature of 240°C (464°F). The total amount of dissolved solids averages about 18,400 ppm (1.84%), indicating a high grade resource. The Ahuachapan geothermal field powers two 30 MW power plants. The first unit was put into operation in June 1975 at Ahuachapan; the second, a duplicate of the first, began generating electricity a year later. Both units are rated at 30 MW, and are of the so-called "single-flash" type. Steam is separated at the wellhead and transported to the power plant. Construction is underway on Unit No. 3, a 35 MW, separated-steam/flash ("double-flash") plant.

The Ahuachapan geothermal resource was developed in four stages; exploration, resource inventory, feasibility, and utilization. The field development required about 5 years and an additional 3 years for the power plant construction for each 30 MW unit. Because of overlapping schedules, the second plant started up a year after the first plant.

The Ahuachapan geothermal field is located in the western portion of El Salvador, 18 km (11 mi) from the Rio Paz which forms the international boundary between El Salvador and Guatemala. The geothermal plant is on moderately sloping terrain on the northern side of the coastal volcanic mountain chain which extends the length of the country. An aerial view of the power plant and the bore field is shown in Figure 2.

GEOLOGICAL CHARACTERISTICS

Information gathered since 1965 when exploration and deep drilling began at Ahuachapan indicates that the geothermal formation consists essentially of the following layers:

brown tuff and pyroclastics (top 50 m)
andesites (next 50 m)
agglomerated tuff and pyroclastics (next 20 - 150 m)
andesites (next 50 - 100 m)

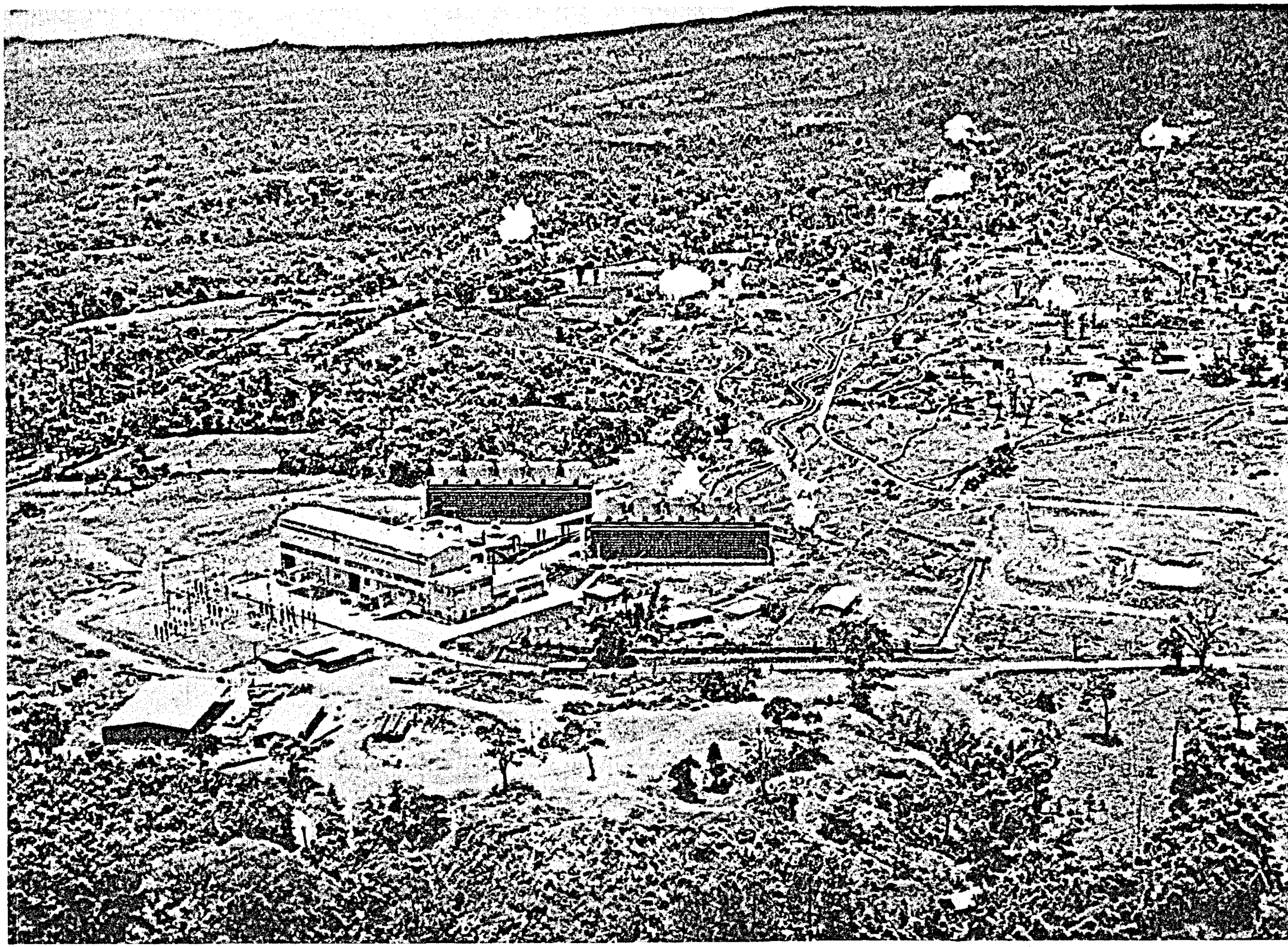

Figure 2. The Ahuachapan 60 MW Geothermal Power Plant and Borefield (CEL, 1976)

young agglomerates (next 100 - 250 m)
Ahuachapan andesites (next 10 - 300 m, absent in parts)
ancient agglomerates (basement rock)

The young agglomerates act as the reservoir cap; the Ahuachapan andesites serve as the aquifer. The permeability of the reservoir is created by fractures in an otherwise hard formation. There are three major faults which traverse the field trending north-northwest. The geofluid temperature is about 230°C in the reservoir. It is believed that the reservoir is recharged from a volcanic lake which lies to the south of the field.

An extensive study of the Ahuachapan field has been reported by Vides (1975).

WELL PROGRAMS AND GATHERING SYSTEM

A total of 28 wells have been completed at the time the material for this report was compiled. The plan is to complete only two additional wells at Ahuachapan. Table 1 contains a summary of information on the well completions. "Dual-purpose" wells such as AH-8 and -17 are producing wells that may also be used for reinjection. The arrangement of the wells is shown in Figure 3.

The drilling program for well AH-26 is shown in Figure 4. The well was completed in 49 days to a depth of 804 m (2,638 ft); the penetration rate averaged about 2 m/h (6.6 ft/h). Drilling mud was used until the aquifer was reached at about 400 m (1,312 ft); drilling proceeded with water to the full depth of the well.

The layout of the production and reinjection wells as well as the location of the power house are shown in Figure 5. The area to the south of the plant is the site of numerous surface thermal manifestations such as steam vents, hot springs, boiling pools and mud pools. The separation between the wells is not less than about 150 m (490 ft). Over the entire field, the average spacing is roughly 23 ha (57 acres) per well, although in the main, central portion of the field the wells are more densely spaced, 11 ha (28 acres) per well. The pipelines are shown schematically in Figure 5

TABLE 1. Well Information at Ahuachapan (DiPippo, 1978)

Well No.	Elevation		Depth		Comments
	m	ft	m	ft	
AH-1	802.8	2634	1205	3954	Producer for Unit No. 1.
AH-2	808.0	2651	1200	3937	Reinjector for AH-4.
AH-3	855.5	2807	802	2631	Collapsed during drilling.
AH-4	812.2	2665	640	2100	Producer for Unit No. 1.
AH-5	789.5	2590	952	3124	Producer for Unit No. 2.
AH-6	783.0	2569	591	1939	Producer for Unit No. 1.
AH-7	804.8	2641	950	3117	Producer for Unit No. 1.
AH-8	811.0	2661	988	3242	Dual-Purpose, Reinjector for AH-7.
AH-9	871.3	2859	1424	4672	Dry hole, beyond the field.
AH-10	723.8	2375	1524	5000	Dry hole, beyond the field.
AH-11	759.3	2491	943	3094	Dry hole, beyond the field.
AH-12	758.8	2490	1003	3291	Dry hole, beyond the field.
AH-13	859.6	2820	860	2822	Producer, on Stand-By.
AH-14	822.0	2697	1053	3455	Dry hole, but highest temperature.
AH-15	772.7	2535	704	2310	Dry hole, beyond the field.
AH-16	869.0	2851	1006	3301	Producer, on Stand-By.
AH-17	773.0	2536	1200	3937	Dual-Purpose; Reinjector for AH-6.
AH-18	926.3	3039	1256	4121	Newly drilled; not in equilibrium Yet.
AH-19	~880	~2887	(NA)	(NA)	Newly drilled.
AH-20	792.9	2602	600	1969	Producer for Unit No. 2.
AH-21	795.0	2608	849	2786	Producer for Unit No. 2.
AH-22	842.0	2763	660	2165	Producer for Unit No. 2.
AH-23	825.4	2708	924	3032	Producer, on Stand-By.
AH-24	783.1	2569	850	2789	Producer for Unit No. 1.
AH-25	798.5	2620	943	3094	Dry hole in middle of field.
AH-26	791.1	2596	804	2638	Producer for Unit No. 2.
AH-27	~830	2723	(NA)	(NA)	Producer, on Stand-By.
AH-28	(NA)	(NA)	--	--	To be sited and drilled.
AH-29	794.8	2608	1200	3937	Reinjector for AH-1.

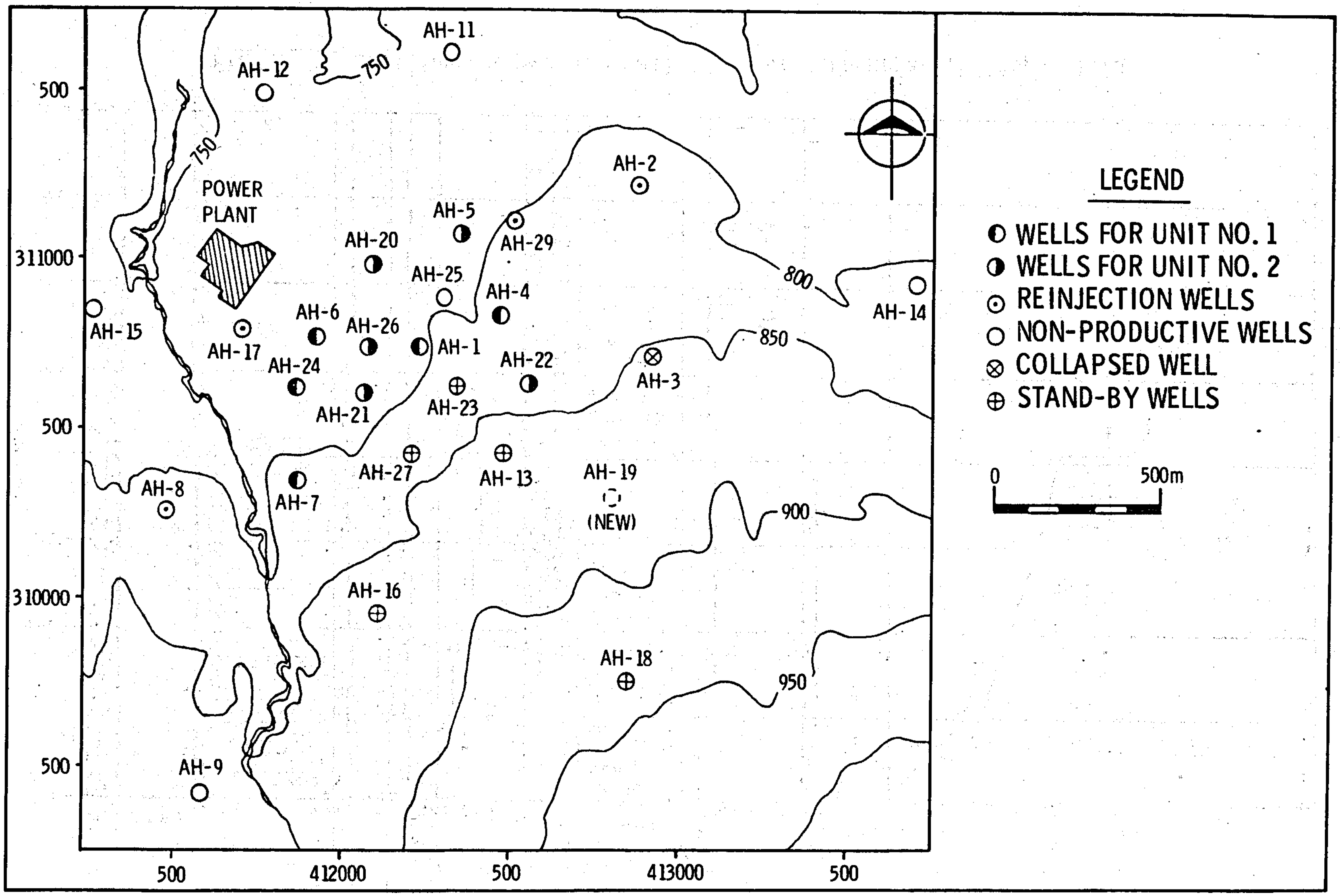

FIGURE 3. Well Arrangement at Ahuachapan Geothermal Field (DiPippo, 1978)

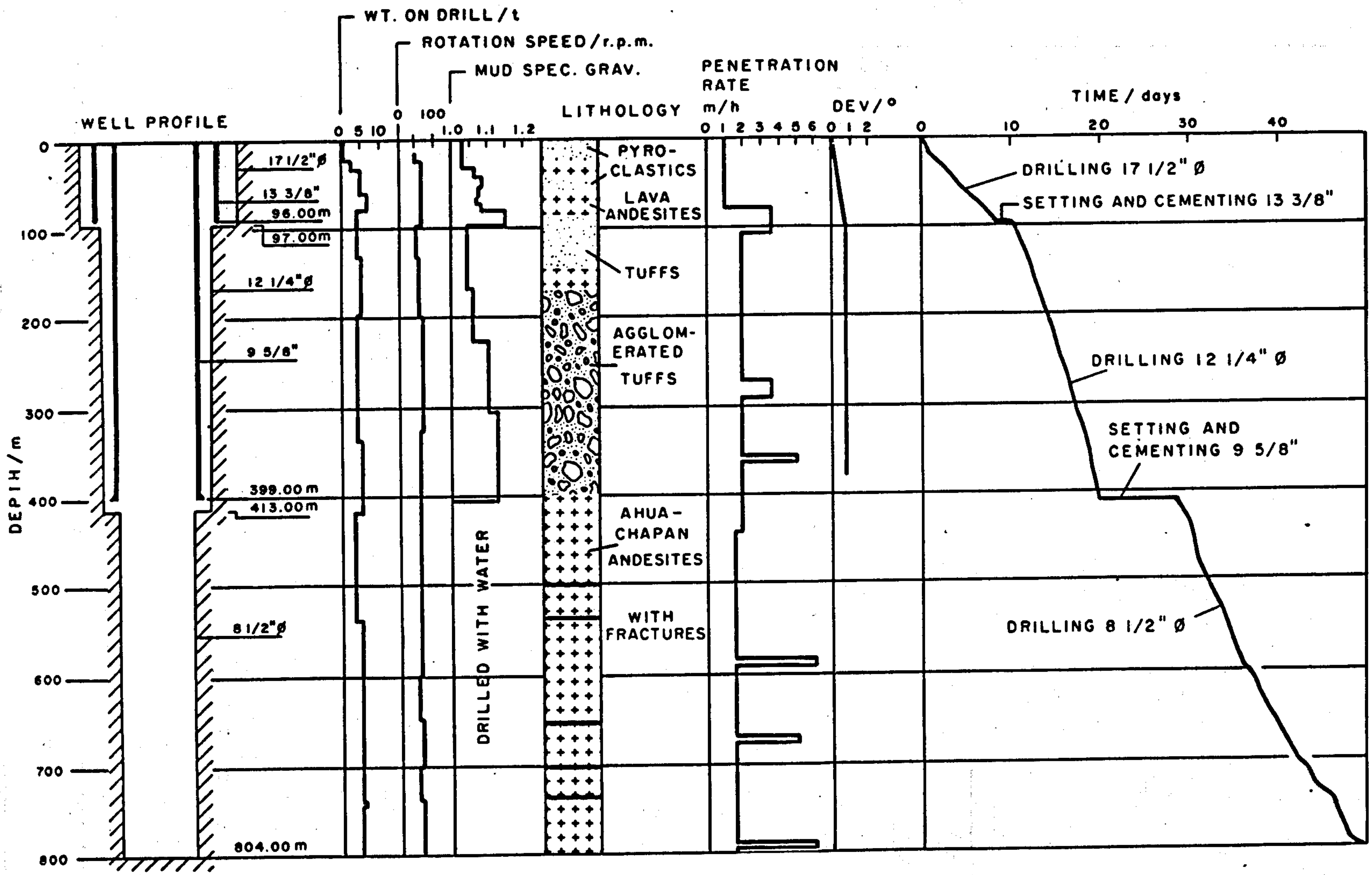

FIGURE 4. Drilling Program for Well AH-26 at Ahuachapan (DiPippo, 1978)

and do not depict the actual configurations which include numerous bends to compensate for thermal expansion. (See Figure 2.) The true lengths and diameters of the various steam and liquid reinjection lines are given in Table 2.

WELL PRODUCTIVITY AND GEOFLUID CHARACTERISTICS

Table 3 gives production data on the ten wells which supply Units No. 1 and 2. The wellhead separator pressure, liquid flow rate, steam flow rate and total flow rate are listed for two time periods, October 1976 and April 1978. The average wellhead quality was about 17% in April 1978, whereas it was nearly 19% in October 1976. The power potential of well AH-4 is 17 MW, but only 13 MW is being extracted owing to a flow limitation imposed by the size of the wellhead separator.

The total amount of dissolved solids in the liquid at the wells averages about 18,400 ppm or 1.84%. The principal constituents are chloride (10,430 ppm), sodium (5,690 ppm) and potassium (950 ppm). Noncondensable gases amount to only 0.05% by weight of the total well flow, or about 0.2% by weight of the steam flow. Detailed information on all impurities in the geofluid have been reported elsewhere (Cuellar, 1975; DiPippo, 1978; Einarsson, et al., 1975).

ENERGY CONVERSION SYSTEMS

There are two main power units and one auxiliary power unit presently installed at Ahuachapan, and a third unit is under construction. In the following sections we will describe some of the important technical features and list the operating conditions or design specifications for each of these units.

AUXILIARY TURBO-GENERATOR UNIT

A 1.1 MW, condensing geothermal steam unit is used for station start-up from cold conditions. The unit is completely self-contained, requiring neither an external power source nor cooling water. Power is generated

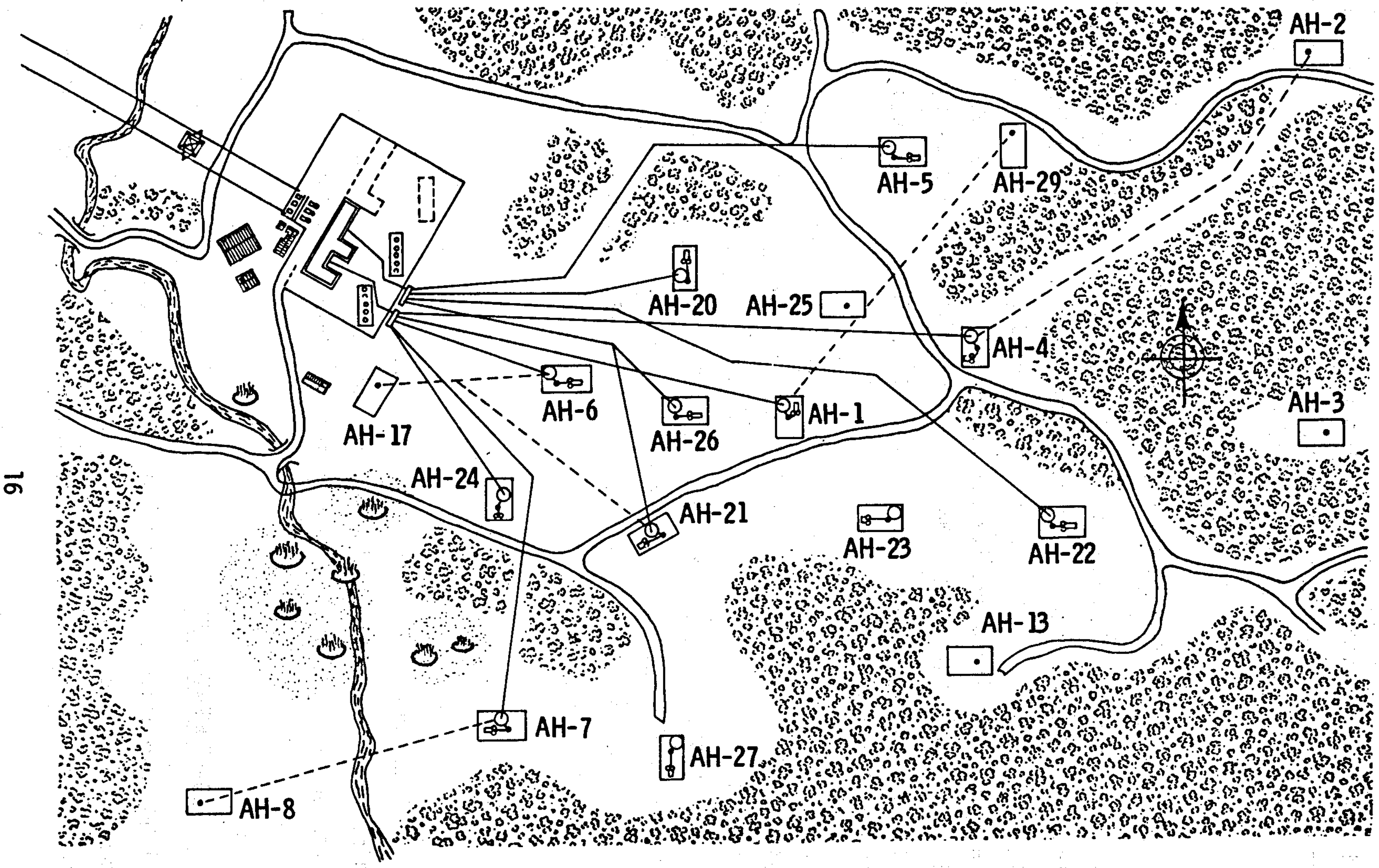

FIGURE 5. Layout of Production and Reinjection Wells for Units No. 1 and 2 at Ahuachapan (DiPippo, 1978)

TABLE 2. Lengths and Diameters of Steam Transmission Lines and Liquid Reinjection Lines at Ahuachapan

Unit No.	Well No.	Pipe Diameter		Length: Wellhead-Receiver	
		mm	in	m	ft
1	AH-1	406	16	560	1840
1	AH-4	508	20	820	2690
1	AH-6	406	16	280	920
1	AH-7	305	12	695	2280
1	AH-24	305	12	303	995
2	AH-5	305	12	740	2430
2	AH-20	406	16	420	1380
2	AH-21	406 (1)	16	256	840
2	AH-22	508	20	900	2955
2	AH-26	406 (1)	16	100	330
Reinj.	AH-2R	305	12	600	1970
Reinj.	AH-8R	305	12	350	1150
Reinj.	AH-17R (2)	305	12	250	820
Reinj.	AH-29R	305	12	500	1640

(1) Joined into a 508 mm (20 in) line which runs 470 m (1540 ft).

(2) Values given are for the connection between AH-6 and AH-17R; there is a 254 mm (10 in) line from AH-21 to the line joining AH-6 and AH-17R.

Table 3

Characteristics of well production for units No. 1 and 2

Well No.	October 1976				April 1978			
	P[1]	$\dot{m}_\ell$	$\dot{m}_v$	$\dot{m}_t$	P[1]	$\dot{m}_\ell$	$\dot{m}_v$	$\dot{m}_t$
Unit No. 1	kPa	kg/s	kg/s	kg/s	kPa	kg/s	kg/s	kg/s
AH-1	665.3	81.70	13.20	94.90	670.3	76.39	14.16	90.55
AH-4	699.4	102.97	23.66	126.63	660.2	131.73	23.69	155.42
AH-6	670.5	44.97	17.65	62.62	651.1	61.80	15.18	76.98
AH-7	660.5	53.89	9.17	63.06	591.5	44.32	6.94	51.26
AH-24	—	—	—	—	602.0	54.01	7.82	61.83
Totals		283.53	63.68	347.21		368.25	67.79	436.04
Unit No. 2								
AH-5	631.2	47.72	6.15	53.87	601.8	55.09	7.69	62.78
AH-20	626.3	44.72	10.74	55.46	611.6	48.67	14.87	63.54
AH-21	650.9	81.29	12.51	93.80	655.8	59.63	12.50	72.13
AH-22	635.3	54.24	16.47	70.71	591.2	48.48	13.66	62.14
AH-26	640.9	19.55	12.37	31.92	601.7	19.44	10.26	29.70
Totals		247.52	58.24	305.76		231.31	58.98	290.29
Plant totals		531.05	121.92	652.97		599.56	126.77	726.33

(1) Pressure at wellhead separator

from a single Curtis stage fed with separated steam; the lubricating oil is air-cooled. All mechanical, electrical and control elements are mounted on a single platform. The technical particulars may be found in Table 4.

POWER UNITS NO. 1 AND 2

The two main power units are essentially identical. They are of the separated-steam, or so-called "single-flash" variety. A simplified flow diagram is shown in Figure 6. Each unit employs a 5-stage, double-flow turbine with impulse-reaction blading, mounted in a single housing, and develops 30 MW. Each turbine exhausts to a low-level, direct-contact condenser equipped with a slanted barometric pipe. This arrangement assures a negligible pressure loss between the condenser and the turbine exhaust hood, as well as ease of accessibility to condenser auxiliary equipment such as the circulating pumps, water treatment facilities, gas extraction devices, etc., which are located in the yard adjacent to the power house. The non-condensable gases are drawn from the gas cooler section of the condenser, through a 2-stage, steam ejector with inter- and after-coolers, and discharged to the atmosphere via stacks atop the power house. Two sets of extraction systems are installed on each unit for redundancy. The cooling towers are of the cross-flow, mechanically induced-draft type, with 5 cells each. Redwood is used for packing.

Steam pipes within the plant are made of 316 stainless steel; circulating water is carried in 304 stainless steel pipes. The turbine blades are of 13% Cr alloy steel with stellite inserts to prevent erosion.

The operating characteristics for both units are given in Table 4. The geothermal energy resource utilization efficiency, η, may be defined as the ratio of the actual work output of the plant to the ideal (maximum) thermodynamic available work of the geofluid at the wellhead, relative to the ambient sink condition. Using the data from Table 3 for April 1978, an output of 60 MW (combined for both units), and a sink temperature of 22°C (the design wet bulb temperature), one finds that $\eta = 37\%$ for Units No. 1 and 2. The overall steam consumption is about 7.6 Mg/MW·h.

TABLE 4. Technical Specifications for Energy Conversion Systems

	Unit No. 1 and 2	Unit No. 3	Auxiliary Unit
Year of Start-Up	1975, 1976	1980	1975
Turbine data:			
Type	Single-cylinder, double-flow, impulse, 5 x 2	Single-cylinder, double-flow, dual-admission, impulse-reaction, (3, 4) x 2	Single-cylinder, one Curtis stage, non-condensing, geared
Rated capacity, MW	30, each	35	1.1
Maximum capacity, MW	35, each	40	1.3
Speed, rpm	3600	3600	7129/1800
Main steam pressure, kPa	558.9	548.1	552.9
Secondary steam pressure, kPa	(None)	150.0	(None)
Main steam temperature, °C	156.1	155.3	156.0
Secondary steam temperature, °C	(None)	111.4	(None)
Exhaust pressure, kPa	8.33	8.33	96.2
Main steam flow rate, Mg/h	230, each	171	21
Secondary steam flow rate, Mg/h	(None)	145	(None)
Last-stage blade height, mm	520	565	(N.A.)
Condenser data:			
Type	Low-level, direct-contact type with slanted barometric pipe		(None)
Cooling water temperature, °C	27.0	27.0	-
Outlet water temperature, °C	40.3	40.3	-
Cooling water flow rate, Gg/h	8.65	12.26	-

TABLE 4. Technical Specifications for Energy Conversion Systems (Continued)

	Unit No. 1 and 2	Unit No. 3	Auxiliary Unit
Gas extractor data:			
Type	Two-stage, steam jet ejector with inter- and after-condenser		(None)
Suction pressure	7.84 kPa	(N.A.)	-
Gas capacity	11,700 m^3/h, each	(N.A.)	-
Steam consumption	4.1 Mg/h, each	(N.A.)	-
Cooling tower data:			
Type	Cross-flow, mechanical induced-draft with vertical axial fans		(None)
Number of cells	5, each	5	-
Design wet-bulb temp.	22°C	22°C	-
Fan motor power	80 kW/fan	80 kW/fan	-

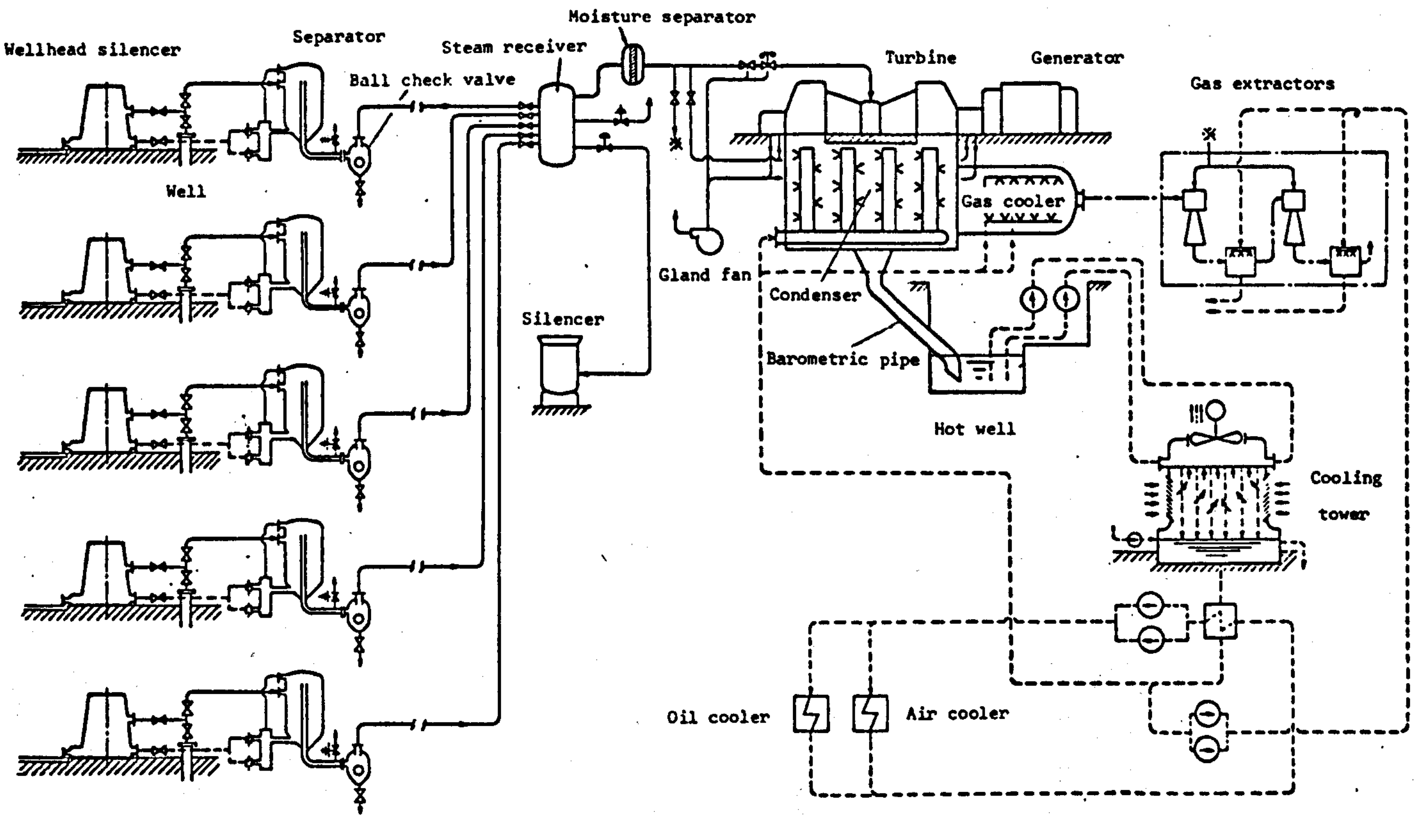

FIGURE 6. Flow Diagram for Units No. 1 and 2 at Ahuachapan (after MHI, 1977)

POWER UNIT NO. 3

Originally it was planned that the third unit would be a 30 MW, low-pressure (LP) unit that would have used steam flashed from separated bore liquid from Units 1 and 2. As the field became more developed and confidence in the steam supply grew, it was decided instead to install a dual-pressure unit of 35 MW capacity to be supplied with medium-pressure (MP) steam from 3 new wells together with low-pressure (LP) steam generated from flashed liquid.

A highly simplified flow diagram for Unit 3 is shown in Figure 7. The broken lines represent hot water from eight wellhead separators. The liquid will be flashed in two horizontal flash tanks, producing LP steam (solid lines) which is added to the turbine at the pass-in section. The MP steam (heavy lines) is scrubbed before entering the first stage of the turbine. Provision is made to flash a portion of the MP steam down to the LP section if necessary. Auxiliary steam (thin lines) will be used for turbine gland seals, steam ejectors for gland steam, and noncondensable gas removal.

The turbine will be of the dual-admission, double-flow type in a single housing, with an MP section consisting of three stages of essentially impulse blading followed by an LP section of four impulse-reaction stages. The generator will be air-cooled, rated at 40,000 kVA, 13.6 kV at 60 Hz with a 0.875 (lagging) power factor. Table 4 lists the technical specifications for this unit. Construction is underway and completion is expected toward the end of 1979.

The geothermal resource utilization efficiency for the third unit will be about 42%, based on design specifications. Since all three units will be inter-related, the overall plant utilization efficiency, for the three units, will be approximately 43%, assuming that the 13 wells which will supply the full plant have the same average conditions of temperature, pressure, and flow rate as the 10 wells now serving Units No. 1 and 2.

Additional information relative to the design of the plant, the materials of construction and the methods of disposal of the waste liquid have been reported elsewhere (Cruz, et al., 1978; DiPippo, 1978; Einarsson, et al., 1975).

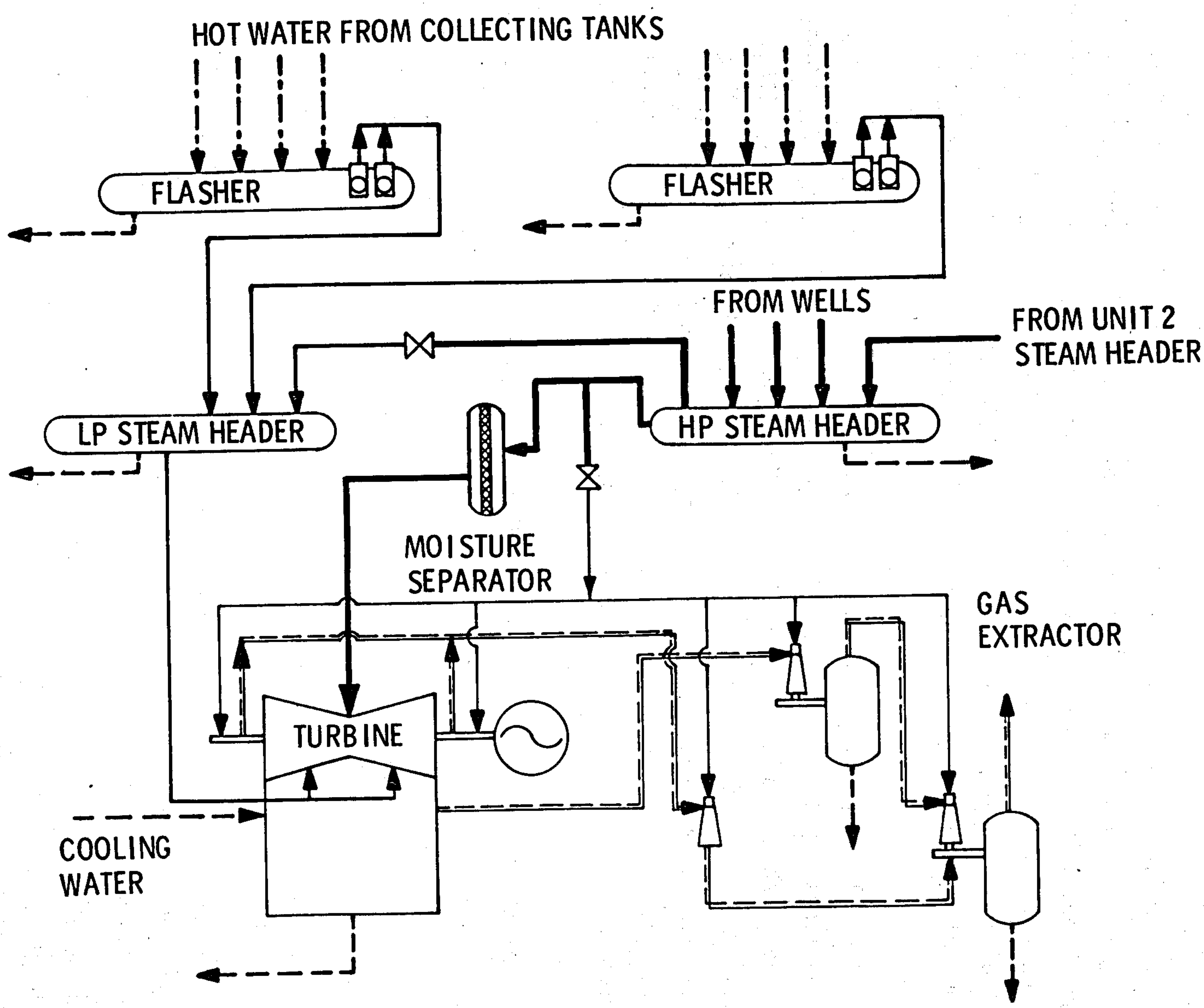

FIGURE 7. Simplified Flow Diagram for Unit No. 3 at Ahuachapan (after Fuji, 1977)

ECONOMIC FACTORS RELATED TO THE DEVELOPMENT AND UTILIZATION OF GEOTHERMAL ENERGY IN EL SALVADOR

FIELD DEVELOPMENT AND POWER PLANT CONSTRUCTION COSTS

Field development required about 5 years for the first unit. Power plant construction required about 3 years for each unit. The actual costs for Units 1 and 2, as reported by CEL, are shown in Table 5. The total cost for Unit 1 was $31.6 million. However, this cost included costs for site preparation, and other costs for common facilities and construction which also apply to Units 2 and 3. These costs will be allocated later to the other units. The incremental cost for Unit 2 was $18.0 million. The average cost of Units 1 and 2, therefore, is a better measure of the cost for each unit. All costs, both actual or anticipated, are expressed in current dollars* and, thus, include the impacts of inflation.

The anticipated costs for each unit, as reported by Cuellar in October 1975, are shown in Table 6. For Units 1 and 2, the anticipated and actual costs agreed quite closely, with the exception of the cost of the canal which was substantially higher than anticipated. The latest cost estimate for Unit 3 is substantially higher than the 1975 projection. This is caused by inflation and by increasing the power plant size to 35 MW from 30 MW. Field development, power plant construction, and the construction of the canal were carried out through separate contracts with a large number of firms. Details of these construction contracts and their rate of progress was not provided.

The cost of wells for Units 1 and 2 is based on 8 wells for each unit, 5 producing wells and 3 nonproducing. To date, 28 wells have been drilled at Ahuachapan. One more producing well is required for Unit 3.

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* Current dollars are the actual dollars expended as distinguished from constant dollars. Constant dollars are current dollars adjusted by the rate of inflation to a reference year.

TABLE 5. Construction Costs for Ahuachapan Units 1 and 2

	Unit 1[a] ($ Millions)	Unit 2[b] ($ Millions)	Total ($ Millions)	Average ($ Millions)
Turbo Generator Including Condenser and Cooling Circuit Wellhead Equipment and Turbine Controls	3.42	5.21	8.63	4.32
Steam Gathering Lines, Including Supports, Insulation, and Drainage	0.54	0.99	1.53	0.77
Electrical Equipment, Transformers and Meters	0.79	0.61	1.40	0.70
Crane	0.09	-	0.09	0.05
Fire Fighting Equipment	0.13	0.07	0.20	0.10
Wells -- Drilling and Casing	3.20	3.20	6.40	3.20
Subtotal	8.17	10.08	18.25	9.13
Civil Works, Equipment Foundations, Site Preparation, Studies, Engineering, Administration, Canal, and Contingencies	23.39	7.95	31.34	15.67
TOTAL	31.56	18.03	49.59	24.80
$/kW	1052	601	826	826

(a) As of August 1975.

(b) As of August 1976.

TABLE 6. Anticipated Costs ($ Millions) for Ahuachapan Units 1, 2, and 3[a]

	1st Unit	2nd Unit	3rd Unit	Total
Turbo Generator	3.73	5.26	8.00	16.99
Steam Gathering Lines	0.66	0.90	1.95	3.51
Electrical Equipment	0.80	0.62	0.70	2.12
Auxiliary Equipment	0.23	0.08	0.11	0.42
Subtotal	5.42	6.86	10.76	23.04
Civil Works	2.66	2.60	3.10	8.36
Equipment Installation	0.86	1.14	1.25	3.25
Canal	10.00	--	--	10.00
Land and Site Preparation	0.12	0.08	--	0.20
Engineering	1.20	0.60	1.00	2.80
Administration	1.15	0.40	0.50	2.05
Studies	2.10	0.32	0.73	3.15
Contingencies	1.00	1.00	1.66	3.66
Subtotal	19.09	6.14	8.24	33.47
Total	24.51	13.00	19.00	56.51
Wells	2.49	3.00	1.00	6.49
GRAND TOTAL	27.00	16.00	20.00	63.00

(a) 1975 Estimate by Cuellar based on original plans for 30 MW for each unit. Unit 3 is now planned for 35 MW.

ENVIRONMENTAL CONTROL COSTS

The major cost for environmental control was the cost of constructing the canal for liquid waste disposal from Ahuachapan to the Pacific Ocean. The canal, 86 km in length by one meter square, cost $15.2 million to complete. Spreading this cost over the three units, the canal cost is $160/kW. Adding an estimated $2.0 million for the cost of the four reinjection wells and their pipelines brings the total capital cost for liquid waste disposal to $181/kW. The operating costs for liquid waste disposal system were not separated. However, since little equipment is involved, these costs should average less than 0.5 mills/kWh.

During construction of the canal, up to 70% of the waste water from Units 1 and 2 was reinjected. Since reinjection proved so successful, plans are to reinject all waste water from new geothermal developments. At Ahuachapan, reinjection is believed to help maintain reservoir pressures. After Unit 3 is in operation, 30% of the waste water will be reinjected and 70% will be discharged into the canal. The canal has, however, sufficient capacity to carry all of the waste water from all three units.

Reinjection currently carries a hidden penalty related to inefficient utilization of the available energy. The water is reinjected at 155°C. Since the costs of bringing the brine to the surface have already been absorbed by the steam, the residual energy in the water from the steam separator is available "free" at that point. This energy could be extracted through a second flash or through a binary fluid cycle. The energy available in the waste water from Units 1 and 2 could power a 20 MW plant. The second flash planned for Unit 3 will utilize about 13 MW of this residual energy.

We estimate that the incremental cost of generating electricity from the residual heat in the waste water would be about the same as the generating cost from the existing plants. The potential gain from utilizing this energy, of course, would be offset by any increased costs related to pressure drawdown, if the lower temperature water could not be reinjected. Earlier attempts to reinject water at lower temperatures were unsuccessful due to formation plugging. CEL plans research into reinjection at lower temperatures, but sufficient information is not now available to make an economic analysis of this trade-off.

OPERATING EXPERIENCE AND COSTS

Unit 1 began operating in June 1975 and Unit 2 began operating in June 1976. Operating difficulties have been relatively minor: failure of rupture discs, leaky valves, failure through erosion of an elbow in the cyclone separator, failure of the gland seals in the turbine, and failure of a transformer in Unit 2. The only equipment limitation is the steam separator for well AH-4 that limits capacity for that well to 13 MW from a potential of 17 MW.

The operating staff at Ahuachapan is 107 (Table 7). Operations are continuous. A scheduled outage of one month for each unit every other year is planned. The outages will occur during the rainy season when sufficient hydroelectric power is available. For comparison, a large (600-1000 MW) power station in the U.S. has about 100 employees.

TABLE 7. Operating Staff at Ahuachapan

Geothermal Field	
Maintenance	1 Engineer and 9 Mechanics
Instrumentation	1 Engineer and 7 Operators
Operations	1 Engineer and 6 Operators
Power Plant	5 Engineers and 77 Operators
TOTAL	107

Direct operating costs are under 2 mills/kWh (Table 8). After the initial startup periods, the capacity factor reached 76% in 1977 and is estimated at 80% for 1978. Continued operation at a high load factor is anticipated. About 2% of the electricity generated is used internally (the "house load" in utility parlance). The average annual cost per employee at Ahuachapan is $5,500. For a U.S. utility the average annual cost per power plant employee is on the order of $100,000.

TABLE 8. Operating Costs at Ahuachapan ($ 1000)

	1975	1976	1977	1978[a]
Direct Costs of Production	82	398	584	614
Allocated Overhead Costs	24	115	188	192
Total	106	513	772	806
Electrical Generation (Millions kWh Gross)	72	280	400	418
Operating Cost (Mills/kWh)	1.5	1.8	1.9	1.9
Capacity Factor (%)[b]	55[c]	71[c]	76	80

(a) Projected

(b) $\text{Capacity Factor} = \frac{\text{Total Generation in Kilowatt Hours}}{\text{Rated Capacity x 8760 Hours/Year}}$

(c) Based on available hours after plant startup.

At this point in time no replacement wells are planned since there has been no decline in productivity. It is unclear whether any reserve well capacity will be maintained. Currently, there are 4 extra production wells which will be used for Unit 3; one additional production well is still required for Unit 3. The need for spare wells and well replacement could increase costs later. For comparison, excess well capacity at The Geysers has been about 50%, excess well capacity at Cerro Prieto is about 30%, and most U.S. planning studies include at least 20% excess well capacity.

FINANCING

Financing for Units 1 and 2 was 60% external and 40% internal (Table 9). Financing included a loan from the World Bank, a local bond issue, and the private resources of CEL. The detailed breakdown on the internal financing was not available. The turboalternator for Unit 2 was financed in part (85%) by a $4.4 million, 8 year loan from Mitsubishi at 7.25% interest. Electrical equipment for Unit 2 was financed in part (90%) by a 10 year loan for $0.5 million at 7% from G.I.E. (Italy). The World Bank loan was $21.6 million

TABLE 9. Summary of Financing

Exploratory Drilling

1965 $1.6 Million
- $1.0 United Nations
- $0.6 CEL

Units 1 and 2

1969 $1.9 Million
- $1.0 CEL
- $0.9 United Nations

1972-76 $47.7 Million
- 60% External
- 40% Internal

Unit 3 (Planned Investment Schedule)
($ Millions)

Year	CEL	Internal Loans[a]	External Loans[b]	Total
1976	-	0.13	0.22	0.35
1977	-	0.70	1.71	2.41
1978	0.39	2.15	9.81	12.35
1979	0.37	2.90	12.22	15.49
1980	0.24	0.58	3.59	4.41
	1.00	6.46	27.55	35.01

(a) CEL Bond Issue

(b) World Bank

at 6.2%; the term of the loan is 20 years after an initial 4-1/2 year grace period. All loans are to be repayed in equal annual or semi-annual installments. Two local bond issues were at 7.25% and 8% interest, maturing in 1983 and 1991, respectively, but it is not known which part of these applied to the geothermal plant.

TAXES, SUBSIDIES OR INCENTIVES

Since CEL is a quasi-governmental commission, it pays no taxes. There are also no subsidies or incentives provided for geothermal with the exception of low level funding to the university for exploration and to CEL for special studies of all kinds, both geothermal and nongeothermal.

MARKETING

CEL generates and transmits electricity for sale to seven distribution companies. In addition, CEL distributes some electricity directly to consumers through a rural electrification program. The average selling price in 1976 to all customers was 34 mills/kWh. The average selling price is quite uniform to the major customers. The sale of electricity is without regard to its source or transmission distance.

ELECTRICAL SYSTEM CHARACTERISTICS

Besides geothermal, electricity is generated from hydroelectric and oil-fired power plants and gas turbines (Table 10). The electrical demand, both peak and average, in El Salvador is projected to grow at the rate of 11%/year. Planned capacity additions to meet this growth are shown in Figure 8. The CEL system load factor averaged 44% in 1976 (Figure 9).

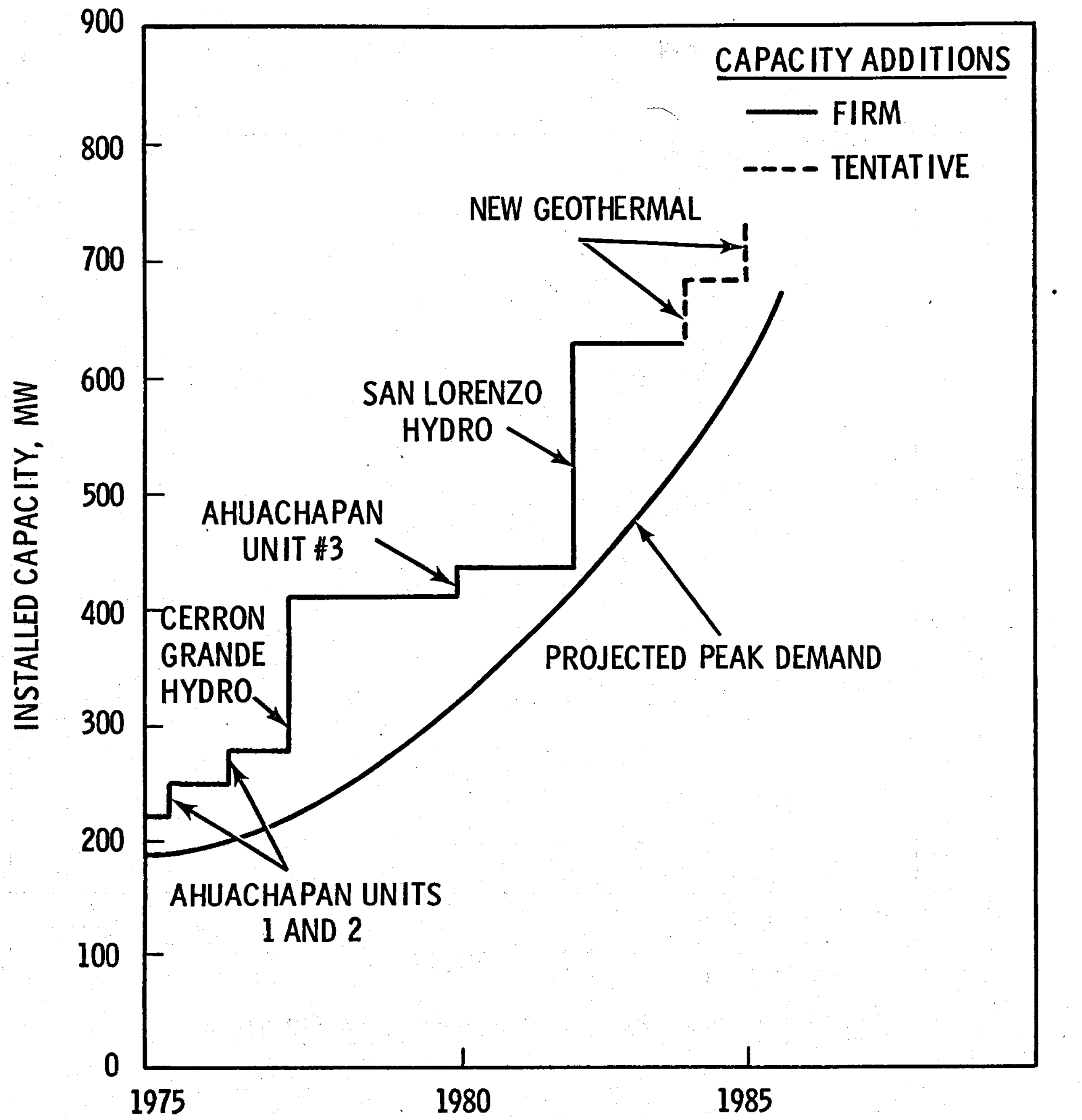

FIGURE 8. Electrical System Growth and Planned Capacity Additions in El Salvador

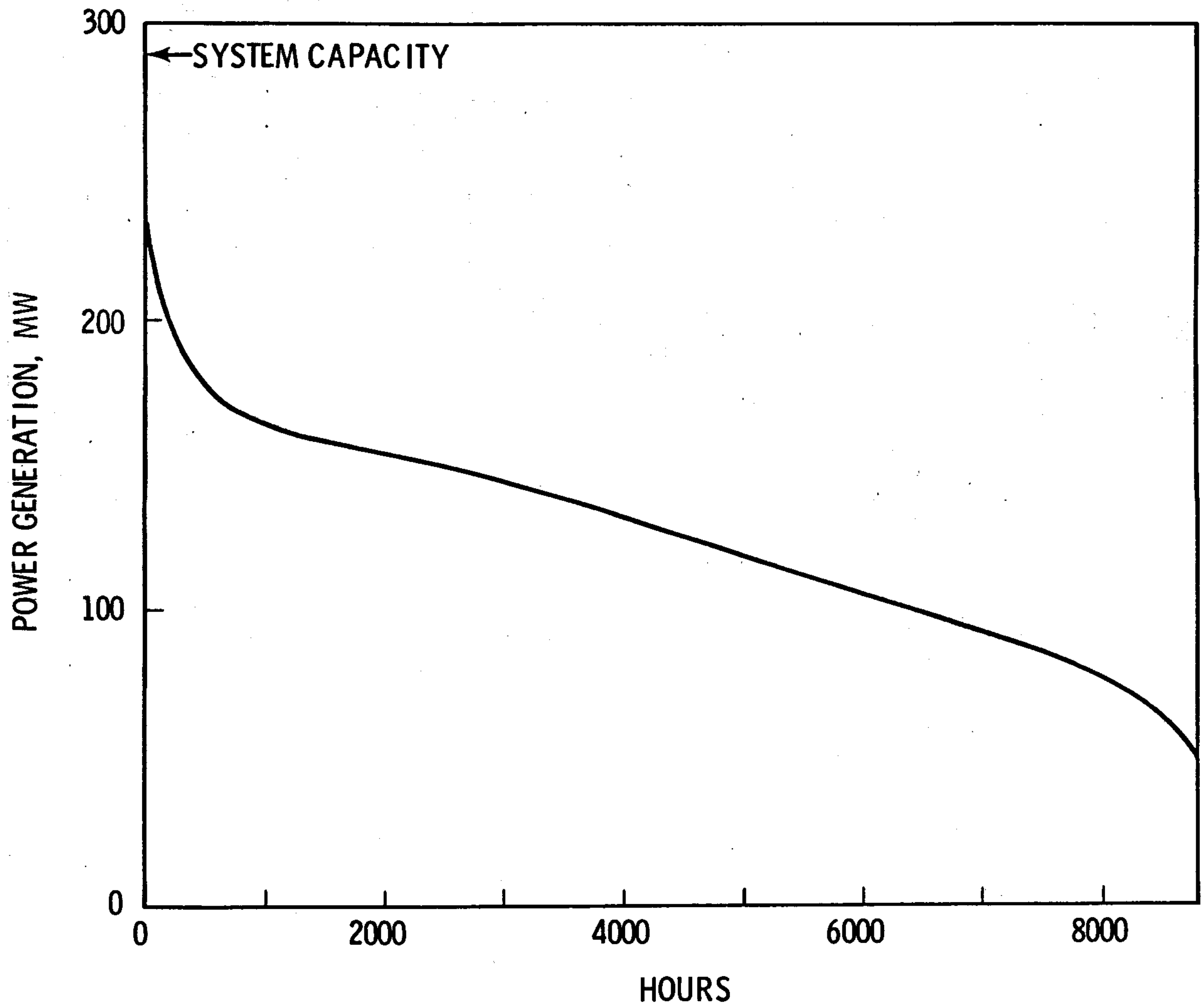

FIGURE 9. CEL Load Duration Curve (1976)

TABLE 10. Installed Capacity of CEL (1978)

Plant	Capacity (MW)	Totals (MW)
Hydroelectric		232
Cerron Grande No. 1 and 2	135	
Plant of November 5th	82	
Guajoyo	15	
Thermal		128
Acajutla	63	
Gas Turbines @ Acajutla	6.6	
Soyapango (Gas Turbine)	58.6	
Geothermal		60
Ahuachapan No. 1 and 2	60	
TOTAL Installed Capacity		420

New generating capacity additions to 1990 are expected to be geothermal and hydroelectric. If these resources become exhausted, CEL expects to turn to solar, nuclear, or importation of electricity through interties with other Central American countries.

Transmission distances in El Salvador are relatively short. San Salvador, the major load center, is less than 100 km from all generating stations.

COST ANALYSIS

The cost of power from Ahuachapan is calculated below under several different assumptions. Under assumptions reflecting government or municipal utility financing, the cost of power is shown to range from 8 to 21 mills/kWh for discount rates from 0% to 10%. Under assumptions reflecting typical investor-owned utility conditions in the U.S., the cost of power is shown to range from 18 to 27 mills/kWh. However, under consistent sets of assumptions, geothermal energy is closely competitive with hydroelectric power in El Salvador. Both geothermal and hydroelectric power costs are significantly lower than the marginal cost (fuel only) of oil generation. If the Ahuachapan plants were built in the U.S., they would be competitive with both new nuclear and new coal plants. The Ahuachapan plants would also be competitive with new plants at The Geysers.

CASH FLOW AT AHUACHAPAN

Based on the information provided by CEL, our reconstruction of the past and projected cash flow at Ahuachapan is shown in Table 11. The construction costs are in current dollars. The historic and projected operating costs are in constant 1977 dollars. The field development and construction costs were converted into constant 1977 dollars (Table 12). The U.S. Consumer Price Index is used as the deflator. The currency of El Salvador has been pegged to the U.S. dollar at the rate of 2.5 colones (¢) to the dollar.

COSTS UNDER GOVERNMENT FINANCING CONDITIONS

Based on the preceding cash flow, we determined the cost of power generation at Ahuachapan for three discount rates: 0, 5, and 10% (Table 13). Most of the debt financing for Ahuachapan was at 6% to 8% interest. Since subsequent inflation has been in this range, the real cost of debt financing to date has been near zero. If these rates of inflation continued over the life of the project, the real cost of power from Ahuachapan, in constant 1977 dollars, would be only 8 mills/kWh. For economic feasibility studies, the World Bank recommended to CEL a 10% discount rate. Municipal utility financing costs in the U.S. are historically in the 5% to 7% range. No taxes are included in this analysis which reflects typical government or municipal utility financing conditions.

COSTS UNDER PRIVATE UTILITY FINANCING

We also determined the cost of power generation under conditions which would be representative of U.S. investor-owned utilities (Table 14). For this we used two fixed charge rates, 11% and 17%, which cover the range experienced by U.S. utilities over the last 20 years. The fixed charge rate includes provisions for return on capital investment, recovery of capital investment, income taxes, and property taxes and insurance. The fixed charge

TABLE 11. Historic and Projected Life Cycle Cash Flow for the Ahuachapan Geothermal Project

Year	Capitalized Costs ($ Millions)	Operating Expenses ($ Millions)	Power Generation (Millions kWh)	Remarks
1965	1.6			Exploratory Drilling
1970	1.9			Deep Drilling
1972	3.1			Field Development and
1973	6.2			Construction for Units
1974	13.0			1 and 2
1975	12.3	0.1	72	
1976	15.4	0.5	279	Completion of Unit 2,
1977	2.4	0.8	400	Completion of Disposal
1978	12.3	0.8	418	Canal, and Field Development
1979	15.4	1.0	418	and Construction for
1980	4.4	1.0	494	Unit 3
1981		1.0	662	
.	.	.	.	
.	.	.	.	
.	.	.	.	
1999		1.0	662	Unit 1 Shut Down
2000		0.8	453	Unit 2 Shut Down
2001		0.5	264	
.		.	.	
.		.	.	
2004		0.5	264	Unit 3 Shut Down

TABLE 12. Field Development and Construction Costs for Ahuachapan in Constant 1977 Dollars

Year	Current ($)	Constant (1977 $)
1965	1.6	3.1
1970	1.9	3.0
1972	3.1	4.5
1973	6.2	8.4
1974	13.0	16.0
1975	12.3	14.0
1976	15.4	16.4
1977	2.4	2.4
1978	12.3	11.5
1979	15.4	13.4
1980	4.4	3.6[a]

[a] Projected inflation at 7% from 1977 through 1980.

TABLE 13. Cost of Power at Ahuachapan for 3 Discount Rates

Discount Rate %	0	5	10
Capital Cost ($ Millions)[a]	96.3	105.5	118.0
Operating Cost ($ Millions)[a]	31.6	18.2	12.1
TOTAL	127.9	123.7	130.1
Cost of Power (Mills/kWh)[b]	7.9	13.2	21.0

[a] Present value (1977 $)

[b] Average busbar cost in constant 1977 $.

rate, when multiplied by the capital investment, yields the annualized payment required to cover these costs. A fixed charge rate of 11% corresponds to a weighted average (debt plus equity) cost of capital of about 5%; a fixed charge rate of 17% corresponds to an average cost of capital of about 10%.

The current average cost of capital for U.S. utilities is about 10% at existing market rates. However, under recent rates of inflation, the real cost of capital, in constant dollars, is less than 5%. The average cost of capital to U.S. utilities was near 5% in the 1950's and early 60's.

TABLE 14. Cost of Power at Ahuachapan Under Financial Conditions Typical of U.S. Investor-Owned Utilities

Fixed Charge Rate (%)	11	17
Annualized Capital Cost ($/kW)	111	171
Annualized Capital Cost (Mills/kWh)	16	25
Operating Cost (Mills/kWh)	2	2
TOTAL (Mills/kWh)[a]	18	27

(a) Average busbar cost in constant 1977 $

COMPARISON BETWEEN THE COSTS OF HYDROELECTRIC AND GEOTHERMAL POWER IN EL SALVADOR

El Salvador, being a small country with only one large river, has a limited potential (up to 700 MW) for additional hydroelectric power. Under the current resource assessment, the potential capacity for new geothermal power is about 400 MW. However, in contrast with hydro, continued exploration may uncover substantial new geothermal energy.

In El Salvador, the cost of new hydroelectric plants is estimated at $900/kW and the cost of new geothermal plants is estimated at $1000/kW. The hydroelectric plant is assumed to have a 50 year life compared to 25 years for geothermal. Since the 2 mills/kWh operating cost at Ahuachapan includes both the reservoir and the power plant, we will assume the operating cost for a hydroelectric power plant would be 1.5 mills/kWh under a similar load factor. The operating staff and, hence, the annual operating costs are assumed to be fixed so that the unit operating cost will vary with the load factor. Under these assumptions, we calculated the costs of power (Table 15) from each energy source at two load factors and two discount rates.

TABLE 15. Comparative Cost of Power for Hydroelectric and Geothermal Power Plants in El Salvador

Discount Rate (%)	5		10	
Load Factor (%)	80	50	80	50
COST OF POWER				
Hydroelectric (Mills/kWh)	8.5	13.6	14.5	23.1
Geothermal (Mills/kWh)	12.1	18.4	17.7	28.4

Hydroelectric power is lower in cost than geothermal power at a constant load factor. However, the experience in El Salvador has been that in the dry season low river flows have limited the hydroelectric output from existing dams, leading to 50% to 60% annual load factors. Under this condition, the cost of power is less from base-loaded geothermal plants than from hydroelectric plants operating at a load factor under 50%.

UNITED STATES COMPARISONS

The Ahuachapan geothermal field is a superior liquid-dominated resource in terms of resource temperature, chemistry, depth and well productivity. A comparable resource has yet to be discovered in the United States. High temperature liquid-dominated geothermal reservoirs were discovered in the Salton Sea area of the Imperial Valley in California almost two decades ago, but these brines are characterized by high salinity, severe corrosion, and saltation which has deterred commercialization. Many moderately hot geothermal reservoirs, comparable in temperature to Ahuachapan, have been discovered in Northeastern California and Northwestern Nevada, e.g., Casa Diablo, Brady Hot Springs, and Beowawe. However, these geothermal reservoirs reside in shale and limestone formations and therefore contain high equilibrium concentrations of bicarbonate which precipitate in the wellbore and cause plugging if the wells are produced by flashing. Again, these wells have defied commercialization, awaiting the development of reliable pumping systems and conversion cycles such as the binary fluid power cycle.

GEOTHERMAL RESOURCE DEVELOPMENT

The high temperature, low salinity, shallow depth, and high permeability of the Ahuachapan geothermal reservoir are extremely favorable to its development for power generation. If such a comparable resource were discovered in the United States, it would have seen development. While the dry steam fields of The Geysers exemplify the best in geothermal resources and, therefore, experienced early exploitation, the Ahuachapan resource comes close to being the ideal flash steam resource.

Flash steam conversion technology was being developed in New Zealand during the same period that the dry steam power plants were being developed at The Geysers. The degree of technological development for both types of plants is adequate for commercialization, providing the resource is "clean" and of high temperature.

The development of flash steam plants has lagged in the U.S. because suitable liquid-dominated resources have not been found. Only recently is there indication that methodology is being developed which will assure continuous and reliable delivery of the troublesome brines, which characterize the majority of geothermal reservoirs discovered so far in the U.S.

Historically, a geothermal resource in the United States has been developed by an energy finder-supplier such as an oil company or a private venture capital group established specifically for this purpose. The finder either has or retains expertise in geology, geophysics, etc. required to locate, test, and evaluate geothermal reservoirs for commercial utilization. Mining and energy supply (oil) companies have the organization, technical experience in the pertinent sciences and a natural interest in this field. The exploration and geothermal development of an Ahuachapan type resource would probably be carried out by such firms to the point of energy supply to a power generation facility.

In the U.S., the power generation facilities are normally designed and constructed by a utility company which purchases the geothermal energy from the developer-supplier, operates the power plant and markets the electric power on its system.

Other methods of resource development are possible. For instance, a finder-supplier may develop the resource, and build the power plant facility and sell the energy generated to a utility. Or a small utility may elect to develop the resource and design and operate the plant as a total effort on its own or in a combined effort with an energy firm. For a resource as attractive as Ahuachapan but with a limited reservoir capacity, the latter approaches may find favor as a resource development program.

Financing for resource development and power plant facilities has been on a private enterprise basis for current operating facilities in the U.S. Federal funds, tax credits, and loan guarantees are now available to stimulate geothermal resource development. A number of geothermal projects have been announced recently which will utilize flash steam technology. It is significant to note that the majority of these projects will be privately financed, and a few will be utilizing steam from high salinity brines. Furthermore, these projects have been announced ahead of any U.S. demonstrations of flash steam power conversion technology. This fact further substantiates the observation that it has not been flash steam conversion technology which has slowed its development in the U.S., but rather the lack of knowledge and confidence in resource assessment and deliverability.

SCHEDULE FOR DEVELOPMENT

The total resource exploration and development program including plant construction will require about five to eight years regardless of the approach or method employed for resource development and utilization. The exploration process will require at least two years to complete. The resource and facility development will usually require an additional three years. A work schedule is presented in Figures 10 and 11. Figure 10 pertains to the exploratory phase and Figure 11 illustrates the time required for resource and facility development. However, two major factors will influence the proposed schedule: (1) time required to complete the permitting process, and (2) time required to negotiate with a utility to develop a power generation facility.

Specific permits and approvals required for geothermal resource development include air quality control, water quality control, environmental analysis, and land use. An environmental impact study must be completed, filed and approved prior to final approval of the project. The permitting process can delay a geothermal project by two years or more.

The time required for negotiating a commitment with a utility may present a major delay. The utility will not commit to a project until it is confident that the investment is recoverable. The utility must, therefore, be confident that the reservoir will provide the required energy over the normal life span of a power plant, prior to making any financial commitment. The time required for reservoir reliability to be established can greatly influence a resource and facility development. The time involved for this element of the program may be reduced if a federal loan or loan guarantee can be effected. This will reduce the financial risks involved in developing a geothermal resource and will tend to reduce the time required. While the loan guarantees do not eliminate the required financial commitment, they do provide insurance against the loss of the majority of the financial commitment by the developing team.

COMPARISON WITH U.S. COSTS

In order to provide comparisons under U.S. conditions, we adopted two approaches: (1) we simulated the operating conditions at Ahuachapan Units 1 and 2 using the GEOCOST model (Bloomster, et al., 1975), and (2) Kuwada and Russell made an independent estimate of the cost of constructing the Ahuachapan plant in the U.S. From our analyses the Ahuachapan geothermal plant generates power for a cost of 8 to 21 mills/kWh under government financing for discount rates from 0% to 10%. Under assumptions reflecting

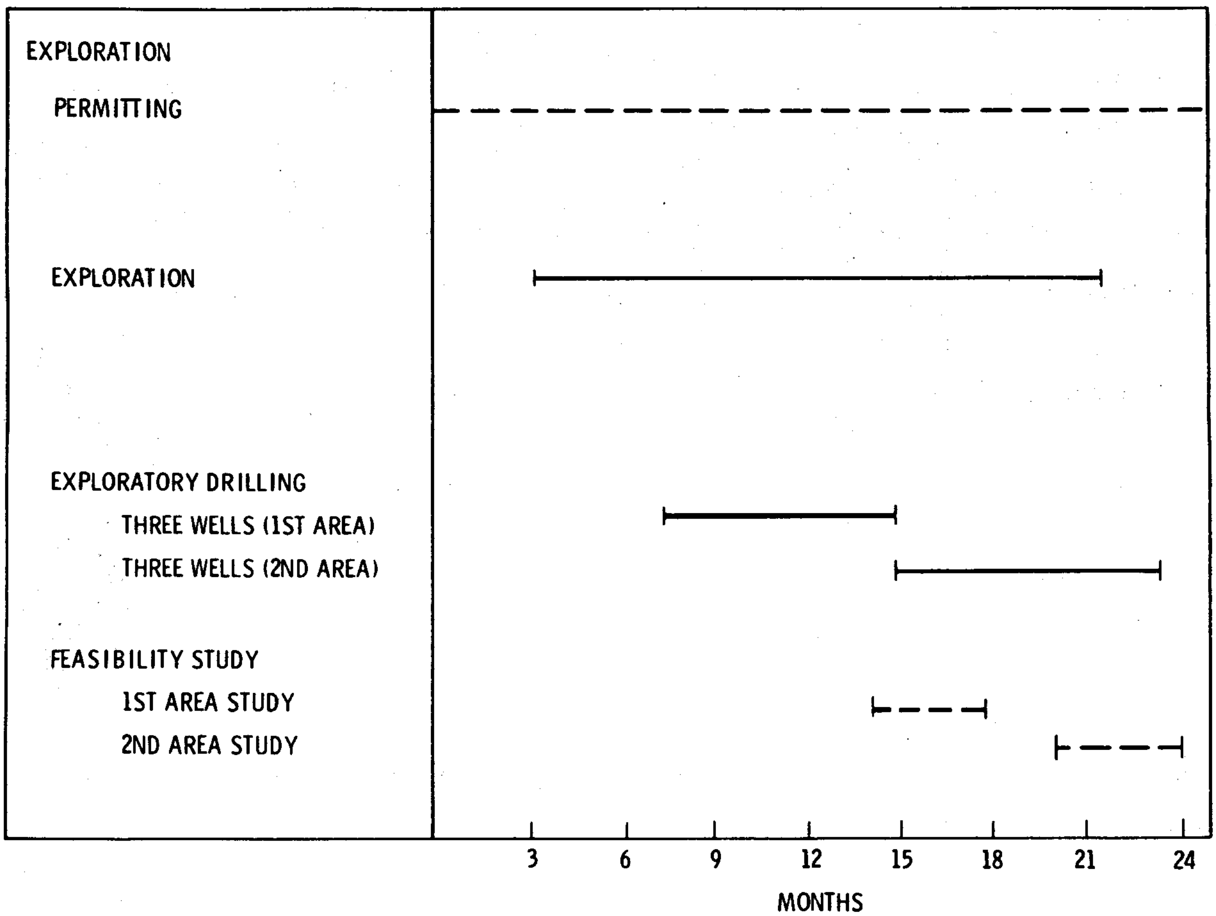

FIGURE 10. Exploratory Phase of Geothermal Development

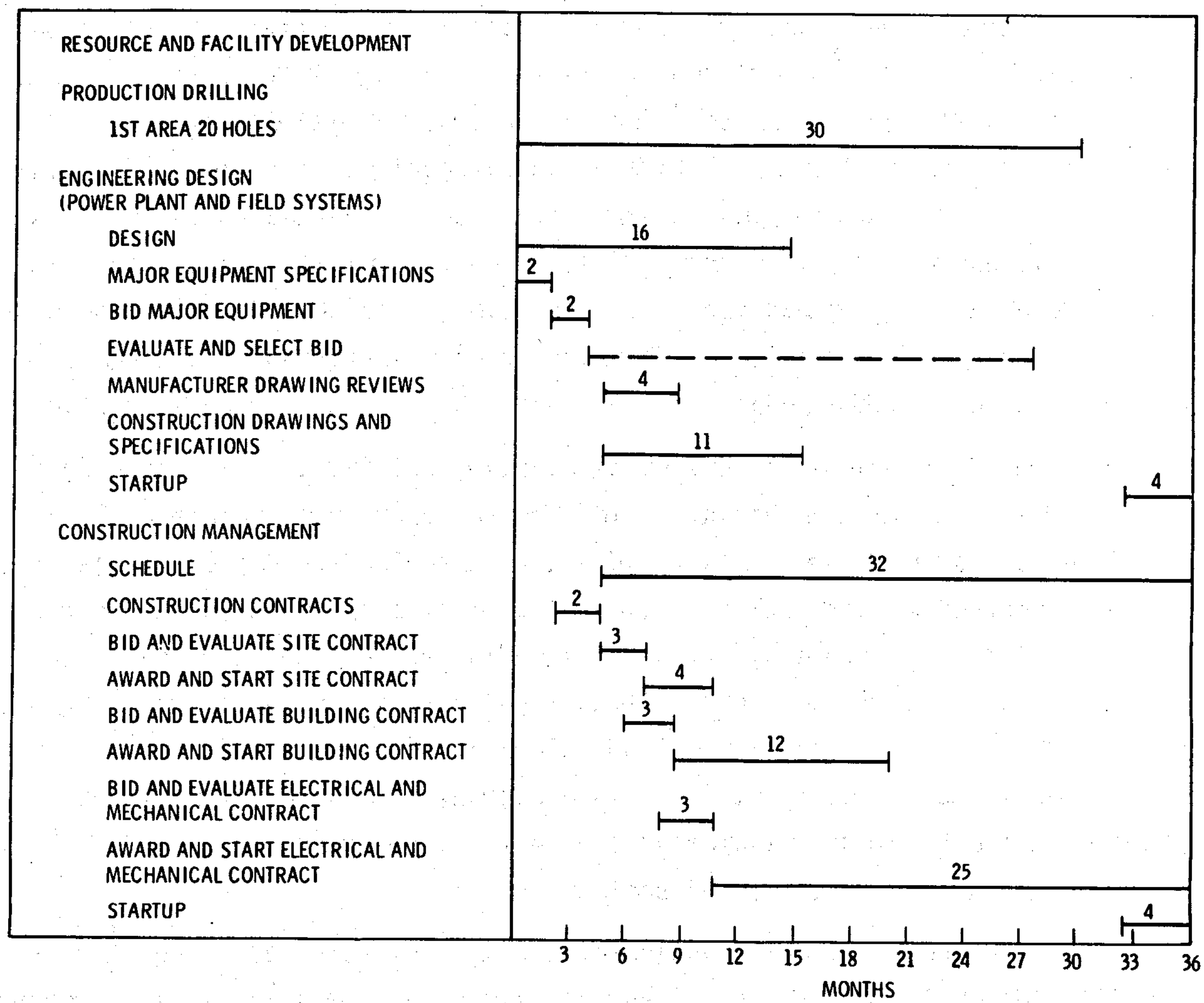

FIGURE 11. Resource Development and Utilization -- 100 MW Facility

typical investor-owned utility conditions in the United States and using similar cost information, the cost of power would range from 18 to 27 mills/kWh. These costs appear to be competitive with new hydroelectric, nuclear, and coal-fired power plants in the U.S.

The cost distribution for the power plant and reservoir, as estimated by GEOCOST, is shown in Table 16. Table 16 is for one 30 MW unit. Costs should be doubled for two units. For comparison, we have distributed the capital costs reported by CEL into similar categories (Table 17). The cost comparisons between power plant and reservoir should not be taken too rigidly, since they depend heavily on the allocation of the "civil works, etc." category. We used our judgment for this allocation since this distribution was not provided by CEL. Because of the site-specific nature of the canal and well costs, we used the Ahuachapan costs for these items in the simulation.

Field development costs are particularly sensitive to well depth; shallow reservoirs, like Ahuachapan, would lead to lower than average field development costs in the U.S. In the U.S., reinjection would probably be the preferred method of disposal. Thus, the costs of a canal would not be incurred, but additional reinjection wells would probably be required. However, because of the high receptivity of the formation used for reinjection, the added cost for reinjection wells would be probably more than offset by the savings in canal construction. In addition, the unit cost of the power plant in the U.S. might be somewhat lower if a large plant (e.g., 50 MW) which achieves some economies of scale were built.

Table 18 shows the distribution of the cost of power as calculated by GEOCOST under U.S. conditions. These conditions assume a large oil company operating the reservoir and a large utility operating the power plant. Taxes and financing assumptions are typical for these firms. Tax incentives include expensing intangible drilling costs, accelerated depreciation, and 10% investment tax credit. Table 18 does not include the recently enacted percentage depletion allowance for geothermal reservoirs. Percentage depletion would reduce the energy supply cost by about one mill/kWh. For the utility these financing and tax assumptions would approximate the 17% fixed charge rate previously used. For comparison, conventional power plants -- nuclear

TABLE 16. Distribution of Capital Costs From Simulation of Ahuachapan by GEOCOST Model

Account	Power Plant (30 MW)	($ 1000)	
1.0	Power Plant Components		
1.1	Piping, Insulation, and Tanks	401	
1.2	Crane	227	
1.3	Turbo Generator	3,329	
1.9	Miscellaneous Process Support Equipment	103	
1.10	Instrumentation and Controllers	266	
1.12	Electrical Support Equipment	138	
1.16	Condensers	900	
1.18	Buildings, Foundations, and Support Equipment	1,211	
1.19	Gas Ejectors (Steam Driven)	132	
1.20	Cooling Water Pump	153	
1.22	Cooling Tower Reinjection Pump	25	
1.23	Condensate Pump	114	
1.99	Subtotal 1.0	$ 6,999	
2.0	Heat Rejection System (Cooling Towers)		
2.1	Cooling Tower System (Forced Draft Wet)	488	
2.99	Subtotal 2.0	$ 488	
3.0	Switch Yard System		
3.99	Subtotal 3.0	$ 711	
5.0	Other Costs		
5.1	Indirect Field Cost	820	
5.2	Engineering and Design	1,082	
5.3	Contractors Fee	451	
5.4	Contingency Cost	1,804	
5.5	Environmental Impact Statement	250	
5.99	Subtotal 5.0	$ 4,407	
	TOTAL POWER PLANT COST	$ 12,605	$420/kW
Field Development			
Producing Wells		$ 2,000	
Nonproducing Wells		400	
Injection Wells		800	
Wellhead Equipment		620	
Transmission System		1,812	
Disposal System		492	
	TOTAL FIELD DEVELOPMENT COST	$ 6,126	$204/kW
	Canal	4,800	$160/kW
	GRAND TOTAL (Rounded)	$ 23,500	$784/kW

TABLE 17. Distribution of Actual Capital Costs for Units 1 and 2 at Ahuachapan

	$ Million	
Power Plant		
Turbo Generators, etc.	3.70	
Electrical Equipment	0.70	
Crane	0.05	
Fire Fighting Equipment	0.10	
Subtotal	4.55	
Allocation of Civil Works, etc. Category	8.15	
TOTAL	12.70	$423/kW
Reservoir		
Wellhead Equipment	0.62	
Steam Gathering Lines	0.77	
Wells	0.20	
Subtotal	4.59	
Allocation of Civil Works, etc. Category	3.72	
TOTAL	7.31	$244/kW
Canal	4.80	$160/kW
GRAND TOTAL	24.80	$827/kW

or coal -- coming on-line in 1977 would produce power at 20 to 25 mills/kWh under similar financing assumptions.

TABLE 18. Cost of Power from Ahuachapan Under U.S. Conditions as Simulated by GEOCOST Model

	Mills/kWh
Power Plant	
Capital Costs	9.4
Operating Costs	2.3
Energy Supply	10.4
Canal	3.6
	25.7

Kuwada and Russell made an independent estimate of the cost of constructing the Ahuachapan power plant in the U.S. Their estimated plant costs are about $100/kW greater than that generated by the model. A $100/kW difference in power plant cost estimate would increase the cost of electricity generation about 2 mills/kWh. They also point out that field developments costs in the U.S. will often times approximate 50% of the total project costs. Thus, Kuwada and Russell would estimate the combined power plant and field development costs in the U.S. at up to $750/kW. This would lead to a U.S. equivalent cost of power of about 25 mills/kWh. (Note that this estimate excludes the cost of the canal, which would probably not be used in U.S. developments.)

From the two estimates, the GEOCOST model and Kuwada and Russell, we would estimate the cost of power from developing a reservoir similar to Ahuachapan in the U.S. under private financing to range from 22 to 25 mills/kWh without the canal.

EFFECT OF THE WELL REPLACEMENT RATE ON THE COST OF POWER

One uncertainty in the preceding analyses is whether the existing wells will last the life of the power plant (25 years). We evaluated the sensitivity of power costs to shorter well life (Table 15). The impact of well replacement rate on power costs will be relatively small unless the frequency of well replacement is less than 5 years. We evaluated the impact for the three discount rates 0, 5, and 10% previously used. However, the incremental power costs were nearly identical for all three discount rates.

TABLE 19. Incremental Cost of Power Resulting From Shortened Well Life

Well Life (Years)	Incremental Cost (Mills/kWh)	Remarks
25	0	Reference Case
12.5	0.6	1 Complete Well Replacement
5	2.5	5 Complete Well Replacements

OBSTACLES TO U.S. GEOTHERMAL RESOURCE DEVELOPMENT

The problem of obtaining a financial commitment from the utilities has slowed the development of geothermal resources in the United States. The utilities must have confidence in long term resource deliverability. However, it is impossible for resource developers to provide the utility a positive "guarantee" and this has been a major contributing factor in delaying geothermal developments in the U.S. In the Imperial Valley, geothermal resources are being developed with private financing by the supplier. This demonstrates that private enterprise will provide venture capital for geothermal development under acceptable conditions.

VALUE OF AHUACHAPAN GEOTHERMAL PROJECT

The Ahuachapan development has provided definitive economic and technical feasibility data which permits definition and comparison of the economic viability of using geothermal energy in a specific electric power generation system which is representative of industry. The project has successfully demonstrated application of current technology and methodologies and provided data for determining reliable methods of assessing reservoir capacities, well stimulation, and utilization technology with cost. It has further provided a basis for an evaluation of the effect that economic considerations, such as tax incentives, government guaranteed loans, and direct government grants as temporary measures, may have in overcoming the initial uncertainties associated with the development and use of geothermal resources.

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