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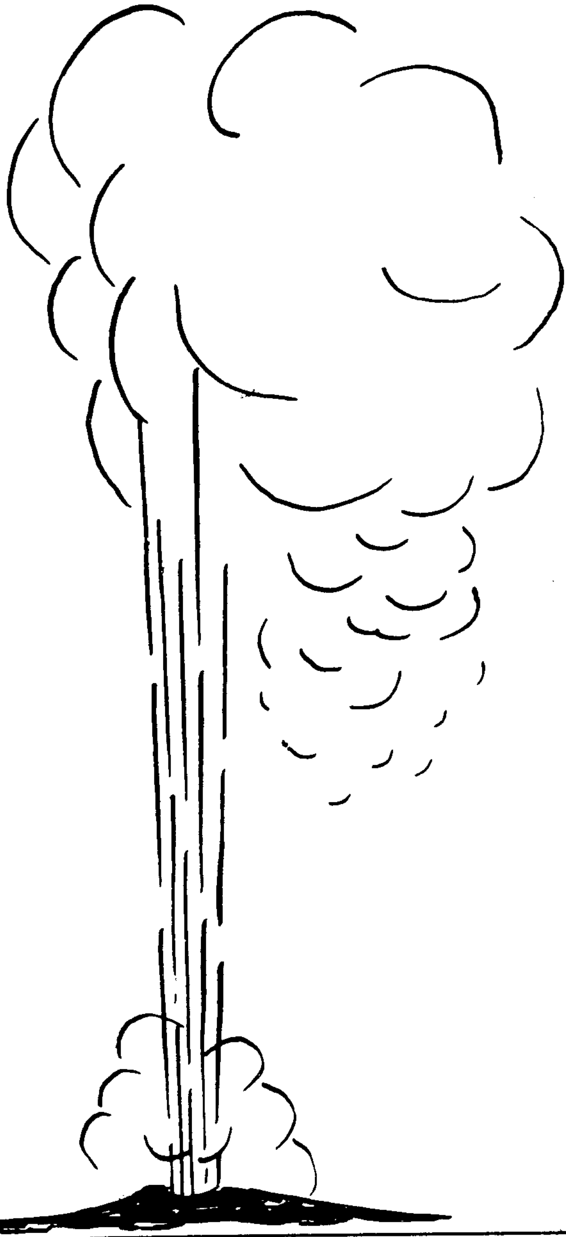

GEOTHERMAL POWER PLANTS OF MEXICO AND CENTRAL AMERICA: A TECHNICAL SURVEY OF EXISTING AND PLANNED INSTALLATIONS

By
Ronald DiPippo

July 1978

Work Performed Under Contract No. EY-76-S-02-4051

Brown University
Division of Engineering
Providence, Rhode Island

U. S. DEPARTMENT OF ENERGY
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Abstract

In this report, the fifth in a series describing the geothermal power plants of the world [DiPippo, 1978(A), 1978(B), 1978(C) and 1978(D)], we focus on the countries of Mexico and of Central America. The geothermal plants are located in areas of recent and active volcanism; the resources are of the liquid-dominated type. The report contains details about the plants located at Cerro Prieto in Mexico and at Ahuachapán in El Salvador. In both cases, attention is paid to the geologic nature of the fields, the well programs, geofluid characteristics, energy conversion systems, materials of construction, effluent handling systems, economic factors and plant operating experience. Exploration and development activities are described for other promising geothermal areas in Mexico and El Salvador, along with those in the countries of Costa Rica, Nicaragua, Guatemala, Honduras and Panama.

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Part I. Mexico

1. Historical role of geothermal energy in Mexico

The first exploration for sources of geothermal energy in Mexico took place in 1955 west of the city of Pachuca at Pathé. This geothermal field is situated along the Neovolcanic axis which trends east-west across the country. This region consists of upper Tertiary and Quaternary basaltic, andesitic, rhyolitic and pyroclastic rocks [Alonso, 1975].

As of 1975, the total installed electric capacity of Mexico was 7500 MW with 48% being supplied by hydroelectric plants, 51% from oil and gas-fired thermal power plants, and the remaining 1% by coal and geothermal. It is unlikely that expansion in hydroelectric capacity will amount to more than about 12,000 MW. The discovery of extensive petroleum reserves in Mexico has allowed Mexico to become an exporter of crude oil and refined petroleum products. The proven reserves of crude oil, natural gas and condensate as of 1977 were 16 billion barrels, the probable reserves 31 billion barrels, and the potential reserves 120 billion barrels [Diaz Serrano, 1978]. Thus, Mexico's energy situation is extremely favorable for the next several decades, well into the 21st century.

Geothermal energy will, nevertheless, play an important role in meeting the growing demand for electricity in Mexico. There are over 130 geothermal regions in the country; these appear in 24 of the 32 states. The largest concentration of geothermal sites are in the states of Michoacán (22), Jalisco (16), Baja California (15) and Guanajuato (9). Owing to their wide geographic distribution and their potential as an inexpensive source of local power, these geothermal regions will be taken seriously into account in national plans to meet the expected future demand for electricity in Mexico.

2. Pathé

Mexico's first geothermal power plant was installed at Pathé, a geothermal field located in the municipality of Tecozaulta, in the State of Hidalgo, about 80 km (50 mi) north-northeast of Mexico City. The plant began operations in 1959; it is, however, no longer operational [Cuéllar, 1978].

The Pathé unit had a capacity of 3.5 MW. It employed a noncondensing turbine supplied with steam separated, most likely, from one well. Very little information exists on this plant in the literature. Figure 1 shows a view of the power house at Pathé and well No. 2 at the site [CFE, 1971].

3. Cerro Prieto

The major geothermal development in Mexico is taking place at Cerro Prieto in the State of Baja California, roughly 35 km (22 mi) south of the city of Mexicali and the international boundary between the United States and Mexico. The geothermal field is located between 114°50' and 115°48' west longitude and between 31°55' and 32°44' north latitude. The general location of the area is shown in Fig. 2 [CFE, 1971].

Since 1973 Cerro Prieto has been generating 75 MW of power on a highly reliable and economic basis. The plant recently has achieved the highest capacity factor of any power plant in Mexico. So successful has been the experience that construction is underway on an extension of the plant which will duplicate the two existing power units. The new units will bring the installed capacity to 150 MW in 1979. The full potential of the field is estimated to be at least 400 MW.

3.1. Geology

The Cerro Prieto geothermal field is located on a plain in the Mexicali-Imperial rift valley and covers an area of about 3000 ha (7400 acres). The most prominent feature of the flat, desert area is the volcano of Cerro Prieto ("Black Hill") which has an elevation of 260 m (853 ft), covers an area of 400 ha (988 acres), and which lies about 6 km (4 mi) west-northwest of the main geothermal steam production area [Reed, 1975]. The field is bounded on the west by the Sierra de los Cucapahs and contains numerous faults of the San Jacinto fault zone. These faults strike northwest and have resulted in considerable downthrows on the northeast side. This can be seen in Fig. 3, for example, where the vertical separation between the plutonic rock at the crest of the Sierra de los Cucapahs and the same type of rock beneath the geothermal field is about 5.5 km (18,000 ft).

Exploration studies, undertaken in the 1950's and motivated by the large number of surface manifestations of thermal activity, have revealed a good deal about the nature of the geothermal field. Figure 3 is a highly-simplified geologic cross-section of the field [after CFE, 1971]. The reservoir is capped by a layer of plastic, impermeable clays with a thickness of 600 - 700 m (1970 - 2300 ft) over the main portion of the field. These are sedimentary rocks and deltaic deposits of the Quaternary period which were deposited by the Colorado River [Paredes, 1975].

Underlying the cap clays is the main reservoir which was formed in the Tertiary period. Shales and sandstones possessing considerable porosity and permeability were deposited in a large graben as a result of intensive erosion of igneous granitic and metamorphic rocks. Basement faulting contributed to the permeability of this formation. The pores of these rocks became filled with water during the late Tertiary from the Colorado River. The aquifer is believed to consist of alternating layers of non-deltaic lutites and sandstones with the sandstones being saturated with connate water at a pressure in excess of the hydrostatic saturation pressure. The total thickness of the non-deltaic sediments is about 2 km (6500 ft).

The basement rock is granitic in nature and may be seen in large outcroppings in the Sierra de los Cucapahs. These are of the Mesozoic period, probably of the Cretaceous age.

3.2. Well programs and gathering system

Information on the drilling program and reservoir development at Cerro Prieto has been reported at various stages during the project [Dominquez and Vital, 1975; Guiza, 1975; Mercado, 1974, 1975(A) and 1976].

A total of 41 wells had been drilled through 1974. These include exploration wells, step-out wells and deep, production wells. The locations of these wells are shown in Fig. 4 which also gives the site of the power plant and the evaporation pond. Eighteen wells are connected to the two units of the power plant, nine for each unit. Of these 15-16 are needed to generate 75 MW, the others are held on stand-by reserve. Figure 5 shows the piping layout for the steam gathering system. There are four main steam gathering lines which run from the wells to the steam receivers at the power house. There are over 6 km (20,000 ft) of steam pipelines of diameters greater than 406 mm (16 in).

The wells are drilled with rigs rated for 2200 m (7200 ft) using draw works powered by two 250-hp engines. The drill string consists of FH 114 mm (4.5 in) drill pipe and 165 mm (6.5 in) drill collars. The drilling mud is of the bentonitic type, emulsified with 4 - 9% diesel oil, and having a density between 1.09 - 1.24 Mg/m^3 (68.05 - 77.41 lbm/ft^3). The mud has a solids content of 8 - 15% and a pH of 7.5 - 10.5 [Guiza, 1975].

The wells were completed during three periods: 1964-1967, 1967-1968 and 1972-1974, as follows:

1964-1967: M-5, -8, -9, -10, -15.
1967-1968: M-11, -13, -15A, -19A, -20, -21, -21A, -25, -26, -30, -35.
1972-1974: M-29, -31, -34, -38, -39.

From the first group, M-10 is not used, and M-15 needed extensive repairs and was replaced with a new well M-15A. From the second group, five wells suffered casing failures or other problems and needed to be repaired or replaced: M-13, -19A, -20, -21, -26. Wells M-13, -20 and -26 were successfully repaired, M-19A was plugged at the bottom to seal off a zone of cooler water, and M-21 was permanently sealed and replaced with M-21A. From the last group, only M-29 did not need repairs or rework. The causes of the problems included mechanical accidents during drilling, inadequate materials or materails incapable of withstanding the high temperatures and stresses encountered, and improper well development and stimulation techniques which subjected the casings to abrupt changes in conditions [Dominguez and Vital, 1975].

A schedule of gradual heating is now followed to avoid casing failure. The water in the well is allowed to reach its maximum temperature in not less than 15 days, during which period gases and steam produced are vented to the atmosphere. In this way the casing and the cement expand simultaneously, without excessive temperature differentials between the casing and the formation [Guiza, 1975].

The mean lifetime of a well at Cerro Prieto is considered to be fifteen (15) years; there are wells that are fourteen (14) years old and are still in good condition, producing steam [Mercado, 1976].

The casing profiles for the 18 wells which serve the two units are shown in Figs. 6 and 7.

The two-phase geofluid is processed conventionally in a Webre-type centrifugal separator, with the separated steam passing through a ball check valve before entering one of the four main steam transmission lines (see Fig. 8). The main steam is collected outside the power house in a set of receivers (see Fig. 9), and passes through a final stage of moisture separation (see Fig. 10) before entering the turbines.

From observations of pressure, temperature and flow measurements taken in the wells together with geochemical analyses of the fluid produced from the wells, it has been possible to determine the distribution and movement of hot water through relatively shallow layers (100 - 500 m (330 - 1640 ft)) from the southeast towards the northwest. Furthermore, hot fluid appears to be rising and flowing horizontally generally from the eastern and central portions of the field towards the western portion. The temperature gradient is most gradual in the eastern part of the field (in the vicinity of well M-53) where the magma intrusion is believed to lie at depth.

The reservoir is probably being recharged from two sources: (1) the highly pervious and saturated alluvial fans of the Sierra de los Cucapahs (see Fig. 3), and (2) meteoric water from the Colorado River. The first of these feeds the reservoir from the west, whereas the second delivers water from the east. The second source is relatively unimportant, however, since the field has only moderate permeability in the eastern region [Mercado, 1975(A)].

On the basis of these studies, it has been determined that future wells should be drilled to the following approximate depths, depending upon the location in the field: 800 - 1400 m (2625 - 4590 ft) for wells to the west of the power house, and 1400 - 2600 m (4590 - 8530 ft) for those to the east of the power house. The depth required to reach the aquifer increases from west to east across the field [Mercado, 1975(A)].

3.3. Geofluid characteristics

The liquid-dominated reservoir produces a mixture of liquid and vapor at the wellhead. The fluid in the reservoir is a compressed liquid which partially flashes to vapor during its ascent through the well. Under high flow rates it is observed that annular flow exists in the well bore, i.e., liquid on the walls and vapor in the core [Reed, 1975].

Table 1 lists the average pressure, temperature, mass flow rate and dryness fraction for twelve wells which were supplying the power plant during January and February 1974. As pointed out in fn. (2) of the table, a more representative average wellhead pressure would be 729 kPa (106 lbf/in^2), rather than the average value of 1119 kPa (162 lbf/in^2), because of the unusually high pressures in wells M-11 and -31. The temperature of the geofluid at the separator was 165°C (329°F) and the quality averaged about 24%.

The geothermal steam contains about 1% by weight of noncondensable gases, mainly carbon dioxide and hydrogen sulfide. The average concentrations of these two constituents for eight wells (M-5, -8, -9, -11, -20, -29, -31, -34) were reported to be 7320 and 1564 ppm, respectively [Reed, 1975]. The samples were taken for an average steam flow rate of 54.5 Mg/h (120.2 klbm/h) and at an average separator pressure of 790 kPa (114.6 lbf/in^2). The impurities in the steam as it enters the turbine were quoted by Mercado as the following: CO_2...14,100 ppm, H_2S...1500 ppm, NH_4...110 ppm, Cl...0.8 ppm, Na...0.4 ppm, and SiO_2...0.2 ppm [Mercado, 1976].

The composition of the separated liquid is given in Table 2. The total dissolved solids amount to roughly 25,200 ppm or 2.5%. The main impurities are chloride, sodium and potassium, which together constitute 94% of the total. Since all of this liquid is discharged to the environment, either to the atmosphere through the silencers after flashing or to the ground and atmosphere by means of the settling/evaporation pond, attention must be given to the effects of the dissolved solids on the environment. The concentration of the principal chemical components in the pond (on July 9, 1974) were reported as follows: Cl...47,462 ppm, Na...20,412 ppm, K...4950, Ca...2169, and Li...68 ppm [Mercado, 1975 (B)].

3.4. Energy conversion system

The power plant is of the separated-steam (or "single-flash") type, with two units, each of 37.5 MW rated capacity. The units were supplied by the Tokyo Shibaura Electric Company, Ltd. (Toshiba), and are of the single-cylinder, double-flow variety with six stages of impulse-reaction blades in each flow. Unit No. 2 and a spare rotor are shown in Figs. 11 and 12, respectively.

A simplified flow diagram/heat balance schematic is shown in Fig. 13 [Akiba, 1970; Mercado, 1976]. The technical specifications are given in Table 3 [Mercado, 1976; Toshiba, 1977].

The condenser is of the barometric, direct-contact type and is located next to the power house. It is 25.35 m (83.2 ft) high, with a shell diameter of 6.7 m (22 ft), shell height of 9.6 m (31.5 ft), and tail pipe 2 m (6.6 ft) in diameter and 12 m (39.4 ft) in length. The exhaust from the turbine is conveyed to the condenser by means of a duct which is 3.6 m (11.8 ft) in diameter and about 40 m (131 ft) in length, including three right-angle bends. Noncondensable gases are removed from the top of the condenser shell through a 0.7 m (2.3 ft) diameter pipe. Figure 14 shows the condensers for units No. 1 and 2.

The gas extraction system consists of a 2-stage steam ejector with an inter- and after-condenser. There are three first-stage steam ejector nozzles operating in parallel, presumably for redundancy. Each is connected to a separate inter-condenser; there are three second-stage steam ejectors, also in parallel, and three after-condensers. The gas extraction system requires 24.2 Mg/h (53.4 klbm/h) of motive steam from the main steam line and 373 Mg/h (822 klbm/h) of cooling water.

The generator is rated at 44,200 kVA at 13.8 kV and 60 hz with a power factor of 0.85. The speed of rotation is 3600 rev/min, and both the rotor and the stator are conventionally hydrogen cooled.

The geothermal resource utilization efficiency, η_u, of the plant is 40%, based on wellhead flow conditions assuming 24% quality and a sink temperature of 26.7°C (80°F). This value is typical of geothermal plants of this type. (See, e.g., [DiPippo, 1978(B)].)

3.5. Materials of construction

Prior to the selection of materials for the various critical parts of the plant, 1000 tests were conducted on a number of candidate materials [Mercado, 1975(B)]. Samples were subjected to exposure by the geothermal steam, both aerated and nonaerated, and by condensate, for a period of 150 days. The steam was obtained from well M-8 and the condensate from steam from wells M-3 and M-5 [Tolivia, et al, 1975].

In this section we shall describe the materials used in the construction of the wells, silencers, piping, turbines, condensers, cooling towers, and electrical equipment.

3.5.1. Wells

The casings are fabricated from J-55 API standard weight pipe with buttress couplings. Extra heavy wall thickness may be required in future wells. The cement consists of API type G with silica flour, perlite and retarders as additives [Guiza, 1975].

3.5.2. Silencers

The silencers are made of concrete with wooden stacks in a twin-silo design [Mercado, 1975(B)].

3.5.3. Piping

Carbon steel is used for pipes carrying nonaerated steam. The corrosion rate follows a parabolic law and is about 0.04 mm/yr (0.0016 in/yr). The corrosion rate is 0.11 mm/yr (0.0043 in/yr) when the steam is in contact with air. Aerated-steam pipelines are, therefore, provided with an allowance of extra wall thickness. The worst case occurs in condensate lines where the corrosion rate for carbon steel is 0.66 mm/yr (0.026 in/yr). Condensate lines are provided with a corrosion allowance and coated with epoxy resin [Tolivia, et al, 1975].

3.5.4. Turbine

The turbine rotor is fabricated from a 1 Cr-1 Mo-1/4 V alloy steel forging, machined to form a solid unit composed of shafts, wheels, bearing journals and coupling flanges [Akiba, 1970]. Alloy steels containing Ni are not used because of their poor corrosion resistance. The turbine blades are machined from 12 Cr alloy steel bar stock; they are enclosed with a shroud which is hand-riveted in place using tennons on the outer edges of the blades. The blades of the last (6th) row are fitted with stellite erosion shields and fastened together with lashing wire to minimize vibrations [Akiba, 1970]. The nozzle partitions are of 12 Cr-0.2 Al alloy steel, and the labyrinth strips are of 15 Cr-1.7 Mo alloy steel. The turbine outer and inner casing are made of carbon steel according to ASTM specification ASTM-A285 [Mercado, 1976].

3.5.5. Condenser

The shell of the condenser is carbon steel with a coating of epoxy resin. The barometric pipe is made of naval brass [Mercado, 1976].

3.5.6. Cooling tower

The structural members of the cooling tower are constucted from AISI-4140 steel; the packing is redwood and fiberglass [Mercado, 1976].

3.5.7. Electrical equipment

Since electrical equipment is susceptible to corrosive attack by hydrogen sulfide, special precautions are taken for the protection of this equipment. Most switch-boards, including the main switch-board, are installed in rooms which are provided with air-conditioning systems fitted with activated carbon filters filled with activated alumina beads impregnated with potassium permanganate [Mercado, 1974]. The electrical contacts on the high-voltage side at the substation are gold-plated, although the use of platinum may have been more appropriate.

3.6. Effluent and emissions handling systems

3.6.1. Liquid discharge

Liquid which is separated from the geofluid at the wellhead separators is sent either to silencers located at each wellhead site or piped directly to the evaporation and settling pond. (See Sect. 3.3.) Eventually all waste liquid (i.e., liquid from the separators or the silencers and excess steam condensate) is discharged into the pond (see Fig. 15). It is estimated that the present pond has a capacity sufficient to support 180 MW of generation, i.e., through unit No. 5. Beyond that, another means must be found for the disposal of the waste liquid. Among the options are: (1) reinjection, (2) construction of a channel to the Laguna Salada, a dried-up lake, and (3) construction of a channel to the Sea of Cortez [Guiza, 1975; Mercado, 1975(B)].

Since the evaporation pond covers a saline clayey area that had surface thermal manifestations, it is felt that the creation of the pond caused no environmental deterioration. In fact it is suggested that the "recreational facilities" afforded by the pond to those interested in water sports and hunting amount to an ecological gain for the area [Mercado, 1975(B)].

3.6.2. Gaseous discharge

The noncondensable gases which are removed from the condenser by means of the steam ejector system are discharged to the atmosphere through 475 mm (18 in) diameter fiberglass pipes (one for each unit) which extend to a height of 40 m (131 ft) above the ground. Since the prevailing winds blow either from the northwest or the southeast, these gases should be swept away from the plant. Mercado reported the composition of the stack gases which were sampled on July 9, 1973 when unit No. 2 was generating 32 MW as follows [Mercado, 1975(B)]:

carbon dioxide, CO_2	62.5% (wt)	3440 kg/h
hydrogen sulfide, H_2S	6.5% (wt)	355 kg/h
air and other gases	6.7% (wt)	365 kg/h
water (condensate).	24.3% (wt)	1340 kg/h.

The specific discharge of H_2S is over 11,000 g/MW·h; for the sake of comparison it might be noted that the U.S. Environmental Protection Agency (EPA) is suggesting a maximum specific H_2S emission level of 200 g/MW·h for geothermal plants in the U.S. [EPA, 1978].

On windless days, the concentration of H_2S may reach dangerous levels in certain areas. An alarm system is connected to a series of H_2S detectors to protect personnel in and around the power house. Furthermore, an additional vent line was constructed from the power house at the base of the gas extraction stacks to the evaporation pond. The resin-lined, steel vent duct is 584 mm (23 in) in diameter and is 1250 m (4100 ft) in length. Since H_2S is also emitted from the cooling tower stacks, it is impossible to vent all the H_2S away from the power house. The prevailing winds, however, tend to carry the cooling tower plumes away from the power house. The cooling tower is 100 m (328 ft) from the plant and is aligned with the direction of the prevailing winds (see Fig. 5).

3.6.3. Other environmental effects

The effects of other forms of pollution from the plant, for example, thermal and acoustic, are felt to be insignificant owing to the nature of the area and the fact that it is sparsely populated. If it were deemed necessary, steps could be taken to curtail or further control the emissions from the plant; however, at this time, it is believed that the best course is to provide special materials and protective devices and procedures where needed [Mercado, 1975(B)].

3.7. Economic factors

The only economic data available to the writer were reported by C.F.E. in 1971 on the anticipated costs of units No. 1 and 2 which were then under construction. The capital investment was \$14.4 M (U.S. 1971) of which \$7.2 M was for the plant equipment, \$2.08 M was for the wells, and the remaining \$5.12 M was for labor and overhead [CFE, 1971]. This report contained an estimate of \$1.44 M for the annual operating expenses of the plant.

Furthermore, the approximate annual savings in fuel (petroleum) costs were estimated at $170,000. This was calculated before the price of oil underwent its dramatic increase in 1973, and thus vastly underestimates the savings in the 1978 market.

3.8. Operating experience

The Cerro Prieto geothermoelectric power plant has operated very reliably since it was brought on-line in April 1973. At that time unit No. 2 began generating electricity; unit No. 1 was started up in September of the same year.

The figures below give the annual electricity generation and the capacity factors for the first four years of operation [Dominguez, 1977; Mercado, 1976]:

Year	Generation/GW·h	Capacity factor
1973	205	63%
1974	445	68%
1975	518	79%
1976	570	87%

The highest monthly capacity factor was 94% in September 1975. The capacity factor of 87% in 1976 is the highest of any Mexican power plant.

Regular maintenance is performed on the units at 2-year intervals; wells are cleaned each 1-4 years. No scaling has been observed in the waste water disposal pipes when the liquid is maintained at the separator pressure (i.e., when it is not flashed down to atmospheric pressure at the wellhead silencers) and sent to the evaporation pond directly.

There has been no subsidence of the geothermal field in spite of the fact that no reinjection has taken place. It is expected that reinjection will be adopted when the field reaches full exploitation. Approximately 8×10^6 Mg/yr (2×10^{10} lbm/yr) of geofluid must be withdrawn from the field to supply each 37.5 MW unit; about 80×10^6 Mg (180×10^9 lbm) of fluid have been produced during the operating lifetime of the plant.

3.9. Plans for plant expansion

The ultimate electric generating capacity of the Cerro Prieto field is not known with certainty; 400 MW seems to be a conservative estimate.

Units No. 3 and 4, each to be rated at 37.5 MW(e) and essentially duplicates of units No. 1 and 2, are under construction at this time and are expected to come on-line in 1979. The next unit is expected to be a low-pressure unit rated at 30 MW(e) which will use steam flashed from a portion of the waste liquid produced from the first four units. Additional units will probably be 55 MW units of standardized design.

Although time schedules are difficult to predict accurately, the table below gives the plan for near-term development of Cerro Prieto:

Year	Site	Unit No.	Unit Capacity	Cum. Capacity
1979	Cerro Prieto I	3	37.5 MW	112.5 MW
1979	Cerro Prieto I	4	37.5 MW	150.0 MW
1982	Cerro Prieto I	5	30.0 MW	180.0 MW
1983	Cerro Prieto II	1	55.0 MW	235.0 MW
1984	Cerro Prieto II	2	55.0 MW	290.0 MW

4. Other areas of possible exploitation in Mexico

A large number of hydrothermal areas in Mexico are listed and described by Alonso in his paper at the Second United Nation's Symposium in San Francisco in 1975. Of the 130 sites that have been discovered, in only 9 of these have wells been drilled. Using conservative estimates, the ultimate geothermal power potential of the country has been placed at 4000 MW. In the sections below, only the most prominent sites are discussed.

4.1. Ixtlán de los Hervores

This field is located in the State of Michoacán within the area known as the Neovolcanic axis. Numerous thermal manifestations exist in the valley where five small and three large diameter wells have been drilled. A satisfactory evaluation of the site has not been accomplished owing to problems related to the completion of the large diameter wells [Alonso, 1975].

4.2. Los Negritos

The geology of this field has been studied by a variety of methods including seismic refraction, electric resistivity, gravimetric, magnetic and geochemical. The field is located in the municipality of Villamar in the State of Michoacán, also in the Neovolcanic axis. One well, drilled to a depth of 1000 m (3280 ft), produces a mixture of liquid and vapor on an intermittent basis. The rocks are believed to be basalts and andesites with numerous fractures along the east-west axis [Alonso, 1975].

4.3. Los Azufres

Another promising region in the State of Michoacán, Los Azufres has been explored by means of geophysical, geochemical, geological and electrical resistivity techniques. All indications are favorable for the existence of a hydrothermal reservoir, but no wells had been drilled as of 1975 [Alonso, 1975].

4.4. La Primavera

This volcanic caldera containing a large number of hot springs and steam vents is located west of the city of Guadalajara in the State of Jalisco. The usual exploration techniques have been applied and several small diameter wells have been drilled [Alonso, 1975].

4.5. San Marcos

Steam vents and hot springs, some with flows as large as 300 kg/s (661 lbm/s), exist in this field, located about 80 km (50 mi) southwest of Guadalajara in Jalisco. Besides the geological, resistivity and geochemical surveys which have been carried out, six small diameter wells have been sunk to depths of 50 - 300 m (164 - 984 ft) [Alonso, 1975].

Part II. Central America

5. Overview of geothermal activity in Central America

The following five countries constitute what is commonly referred to as Central America: Costa Rica, El Salvador, Guatemala, Honduras and Nicaragua. Panama and Belize (formerly British Hondures) are sometimes included. Each of these countries, with the possible exception of Belize, possesses actual or potential geothermal resources.

El Salvador has assumed a leadership role in geothermal exploitation among the Central American countries, having operated the highly successful geothermal power station at Ahuachapán for over three years. The El Salvadorenos are in the process of expanding that plant to a full 95 MW installed capacity while moving ahead with an ambitious program of exploration in the eastern portion of the country. By 1985 El Salvador will be able to meet its domestic demand for electricity by means of its indigenous hydroelectric and geothermal power plants, thus freeing the country from dependence upon imported petroleum and fossil fuels for electricity generation.

Costa Rica is exploring and developing the geothermal regions in the Guanacaste province, in particular the site at Las Hornillas de Miravalles which appears quite promising. A 40 MW geothermal plant is scheduled for this area by 1985.

Nicaragua is similarly developing a promising site at Momotombo where a power plant is expected to be built in the near future.

Guatemala, Honduras, and Panama are also investigating several potential geothermal sites. The prospects for geothermal development in these countries are known with less certainty than in those already mentioned.

A total generating capacity of 500 - 700 MW may be feasible for the Central American countries within 10 - 15 years, with El Salvador most likely having between 70 - 90% of the total.

6. El Salvador

In 1977 geothermal energy constituted 14% of El Salvador's installed electric generating capacity and supplied about one-third of the electricity produced in the country. The first 30 MW unit at Ahuachapán was put into operation in June 1975; the second, a duplicate of the first, began generating electricity a year later. Construction is underway on unit No. 3, a 35 MW separated-steam/flash ("double-flash") plant. Three other sites, Berlín, Chinameca and San Vicente, may produce 100 MW each eventually, and one at Chipilapa may support 50 MW.

A map of El Salvador is given in Fig. 16 which shows the location of the geothermal sites which are being explored, together with the existing power plants, both geothermal and conventional.

6.1. Ahuachapán

The Ahuachapán geothermal field is located in the western portion of El Salvador, 18 km (11 mi) from the Rio Paz which forms a portion of the international boundary between El Salvador and Guatemala. The power plant is sited 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 Fig. 17.

6.1.1. Geology

Information gathered since 1965 when exploration and deep drilling began at Ahuachapán 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)

young agglomerates (next 100 - 250 m)

Ahuachapán andesites (next 10 - 300 m, absent in parts)

ancient agglomerates (basement rock).

The young agglomerates serve as the reservoir cap; the Ahuachapán andesites serve as the aquifer.

The lithology of the formation is not known precisely, but Fig. 18 shows a preliminary version that is subject to modification as new data become available [Cuéllar, 1978]. The geologic cross-section shown in Fig. 18 is taken looking north at essentially a west-east elevation. It reveals three faults that cut across the field, trending north-northwest. It can be seen that the aquifer splits into two layers toward the eastern portion of the field. At the western side, the aquifer thins out to a contact surface about 500 m (1640 ft) below the surface.

6.1.2. Well programs and gathering system

A total of 28 wells have been completed at the time of this writing. The arrangement of the wells is shown in Fig. 19. The casing programs for typical production and reinjection wells are shown in Fig. 20. Since the formation is relatively hard, for about half of the wells it is not necessary to install a slotted production liner, an open hole being sufficient. For reinjection wells, the inner casing is hung from the surface (not cemented) to allow for easy removal in the event that the well may someday be used as a producer. Table 4 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 drilling program for well AH-26 is given in Fig. 21. The well was completed in 49 days to a depth of 804 m (2638 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 (1312 ft); drilling proceeded with water to the full depth of the well.

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. Figure 22 shows the layout of the production and reinjection wells as well as the location of the power house. 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 (see Fig. 23). The pipelines are shown schematically in Fig. 22 and do not depict the actual configurations which include expansion bends (see Fig. 17). The true lengths and diameters of the various steam and liquid reinjection lines are given in Table 5.

Table 6 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 is about 17% in April 1978, whereas it was nearly 19% in October 1976. The highest quality occurs at well AH-26 which delivers 35% steam. This anomalous behavior is probably caused by a relatively tight formation in the neighborhood of this well which leads to flashing in the formation. 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. Well AH-21 is also an excellent well with a 9 MW potential and 7 MW actual utilization. Figure 24 gives the overall mass balance for the wells serving units No. 1 and 2, both with and without reinjection. Figure 25 is a photograph of the wellhead equipment at well AH-20.

6.1.3. Geofluid characteristics

The amount of total 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 (5690 ppm) and potassium (950 ppm). Table 7 lists the concentration of all impurities in the liquid from nine of the ten wells which supply units No. 1 and 2. (Data on well AH-24 was not available.) Table 8 gives the average concentrations for the constituents for these nine wells.

Noncondensable gases amount to 0.05% by weight of the total well flow; 0.2% by weight of the steam flow. The composition of the noncondensable gases is given below, where the percentages shown are on a volumetric basis:

carbon dioxide, CO_2	86.8%
hydrogen sulfide, H_2S	12.1%
hydrogen, H_2	0.126%
nitrogen, N_2	0.05%
ammonia, NH_3	1%
methane, CH_4	

Prior to entering the power house, the steam passes through a final moisture separator. Table 9 gives the concentration of the various elements found in the liquid which settles in the receiver trap at the moisture separator. Also included in Table 9 is the composition of the steam condensate at the condenser hot well.

6.1.4. Energy conversion systems for units No. 1 and 2

The layout of the power house, switch yard and cooling towers is shown in Fig. 26. The cooling towers are oriented such that the prevailing wind carries the plumes away from the power house and transformers. Two steam receivers (one for each unit) are located between the cooling towers for units No. 1 and 2 at the end further from the plant. The collected steam travels by means of elevated pipelines to the final moisture separators and thence to the turbines.

A cross-sectional view of the turbine, a product of Mitsubishi Heavy Industries, Ltd., is shown in Fig. 27. It is a 5-stage, double-flow, impulse-reaction machine, housed in a single cylinder. The last stage blade height is 520 mm (20.5 in). Identical machines are used for each of the first two units.

A schematic flow diagram for each unit is given in Fig. 28. Five wells supply each unit; steam is separated by means of a simple Webre-type cyclone separator with the steam passing through a ball check valve prior to entering the steam transmission pipeline. Each turbine exhausts to a low-level, direct-contact condenser which is fitted with a slanted barometric pipe. This feature allows the condenser hot well to be located adjacent to the turbine building for ease of accessibility to circulating pumps, water treatment equipment, etc.

A 2-stage, steam ejector gas-extraction system is connected to the gas cooler section of the condenser. For each unit, there are two sets of extractors arranged in parallel, one of which serves as a stand-by system.

The cooling towers are of the cross-flow, mechanically-induced draft type. Each has five cells and uses wood packing with fiberglass for the exterior of the stacks.

The technical particulars for units No. 1 and 2 are listed in Table 10. The geothermal energy resource utilization efficiency, η_u, may be computed using the data from Table 6 for April 1978 and an output of 60 MW, relative to a sink condition at 22.0°C (71.6°F), the design wet-bulb temperature.

For these conditions, $\eta_u \approx 37\%$. The overall steam consumption for the plant is about 7.6 Mg/MW·h (16.8 lbm/kW·h).

6.1.5. Proposed energy conversion system for unit No. 3

The third unit for Ahuachapán was originally planned to be a 30 MW, low-pressure unit that would have operated on steam flashed from separated bore liquid. As the field became more developed and confidence in the steam supply grew, it was decided to install a dual-pressure unit that would be supplied with medium-pressure (MP) steam from wells together with low-pressure (LP) steam from flashed liquid. The unit was upgraded to 35 MW as well.

A highly-simplified flow diagram for unit No. 3 is given in Fig. 29. Hot water at the wellhead separator pressure is drawn from eight wells into two horizontal flash vessels. Steam thus generated leaves each vessel through a pair of ball check valves and flows to a LP-steam header. In addition, MP steam produced by separation at three wells is mixed with MP steam from the header for the existing unit No. 2 in a new MP-steam header. Provision is made for flashing a portion of the MP steam from the MP header down to the LP header, if necessary. The MP steam is admitted to the turbine entrance after being scrubbed of moisture; the LP steam is admitted to the turbine at a pass-in section. Gas extraction is carried out by a conventional 2-stage steam ejector; a single steam ejector is used to purge the turbine gland seals.

Figure 30 shows the general arrangement of unit No. 3 as envisioned by the Fuji Electric Company, Ltd.; elevation views A-A and B-B taken in Fig. 30 are shown in Fig. 31. The present power house will be extended to incorporate unit No. 3, with the new cooling tower aligned to conform with those for the first two units.

The turbine will be of the dual-pressure, double-flow type in a single cylinder with the medium-pressure section consisting of three stages (essentially impulse blading) followed by the low-pressure section of four impulse-reaction stages. Figure 32 is a sectional drawing of the turbine [Fuji, 1977]. 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 11 lists the technical specifications for the third unit, as anticipated at this time. The new unit is under construction and is expected to begin generating electricity early in 1980. According to the data that is now available, the geothermal resource utilization efficiency, η_u, will be approximately 42%. This value has been estimated on a number of assumptions and should be recalculated after the unit begins operating and the actual thermodynamic conditions are known accurately. It is interesting to note that the three units, taken together, will have an efficiency, $\eta_u \approx 43\%$, on the condition that the 13 wells which supply the plant have average conditions matching the 10 wells now serving units No. 1 and 2.

6.1.6. Auxiliary turbo-generator unit

The Ahuachapán plant is furnished with a 1.1 MW noncondensing auxiliary turbine-generator set. Since no external power source nor any cooling water is needed to operate the unit, it is used for start-up purposes from cold conditions. The unit is equipped with a single Curtis stage with an air-cooled lubricating oil system. All mechanical, electrical and control elements are mounted on a single platform. The technical particulars for the auxiliary unit may be found in Table 12 [MHI].

6.1.7. Materials of construction

The casings for the wells are J-55 API standard weight pipe. The cement used to secure the casings is straight Portland cement. The drilling mud is of the Bentonitic type, with coconut husks, coffee bean shells, mica, etc. being added to seal off loss-of-circulation zones during drilling.

The pipes which carry the geothermal steam are fabricated from ASTM A-53 Grade B seamless carbon steel pipe. The velocity of the steam is kept below 50 m/s (164 ft/s). Blocks of calcium silicate are used to insulate the steam pipes. These are wired onto the pipes, covered with composite kraft paper/aluminum sheet (which acts as a vapor barrier), and enclosed within a jacket of galvanized steel. The thickness of the insulation depends on the pipe size as follows:

Pipe diameter		Insulation thickness	
mm	in	mm	in
305	12	80	3.15
406	16	80	3.15
508	20	100	3.94

Pipes carrying waste liquid to the reinjection wells are not insulated.

Circulating water in the plant is carried by 304 stainless steel pipes; steam pipes in the plant are made of 316 stainless. Turbine blades are of 13 Cr alloy steel with stellite inserts where needed. Cooling towers contain redwood packing. Sodium hydroxide is used for pH control.

6.1.8. Effluent and emissions handling systems

Two methods are used for disposal of the waste liquid from the plant. One method is reinjection; the other is discharge to the Pacific Ocean through a covered concrete channel, 1 m^2 (11 ft^2) in cross-sectional area and 75 km (47 mi) in length.

Four wells currently serve as reinjecters (see Table 5 and Fig. 22). The total amount of liquid being reinjected (for 60 MW capacity) is

368.8 kg/s (5846 gal/min), and constitutes about 63% of the waste liquid which is discharged from the plant. The liquid to be reinjected is taken directly from the wellhead separators, at the pressure of the separator, and piped to the reinjection wells without the aid of booster pumps and without chemical treatment or exposure to the atmosphere. The temperature of the liquid is not lower than 150°C (302°F), and thus mineral deposition has been avoided in the reinjection lines and the wells [Einarsson, et al, 1975]. Over 13×10^6 Mg (29×10^9 lbm) have been returned to the formation since rejection was started in 1975.

The remainder of the liquid waste including steam condensate from the turbines is carried through a discharge channel from the plant, around, over and through the mountains, eventually to the ocean. The channel passes close to the Rio Paz on the western border of El Salvador, and for a time (until the channel was completed) a short connection between the channel and the Rio Paz allowed the waste water to be disposed of in that river. This was a temporary and not wholly satisfactory solution. During this period, it was necessary at times to curtail the output of the Ahuachapán plant in order to avoid exceeding the allowable limits on arsenic and boron in the Rio Paz which is used for irrigation and other purposes. The completed aquaduct contains sixteen siphons (made from sections of pipe) to carry the fluid over hills and through valleys across the rugged terrain that lies between the plant and the Pacific Ocean. About 90% of the length of the channel is concrete, with 10% being pipe. The route was chosen so as to minimize the average slope of the channel.

There are two labyrinth retention tanks in the borefield which provide a settling time of 50 - 60 minutes before the waste water enters the channel. One of these is located between wells AH-1 and AH-25 (see Figs. 22 and 33);

it receives all the liquid from well AH-22 and part of the liquid from AH-4. As can be seen from the photograph in Fig. 33, the tank is open rendering it considerably easier to clean than the channel which is covered with removable concrete slabs. The other settling tank is located just north of well AH-6 (see Fig. 22). The use of settling tanks has been shown to be a very effective means of controlling the deposition of silica in the effluent lines used for surface disposal of the waste liquid [Cuéllar, 1975].

There are no emissions controls on hydrogen sulfide which reaches concentrations of 1-4 ppm at the boundary of the plant site. From personal observation, the odor of H_2S is noticeable but not objectionable downwind of the power house and cooling towers. A minimum of about 100 kg/h (2200 lbm/h) of noncondensables are ejected at full output. This does not include air which enters at the turbine gland seals and in the direct-contact condenser from the cooling water. Of this amount, roughly 95 kg/h (210 lbm/h) of H_2S is emitted, or 1580 g/MW·h (3.5 lbm/MW·h), on a specific power basis.

In regard to the general environmental impact of the plant, it is the writer's opinion, again based on observation, that the designers have done an admirable job of minimizing the adverse effects possible from such a plant. Although the plant site is sparsely populated, the city of Ahuachapán is only a few kilometers away and a few families actually live on the plant property. These inhabitants make use of the hot springs for various domestic purposes and graze their cattle among the wellheads and steam pipes of the borefield. The use of a covered waste liquid channel and the careful design and arrangement of the wellhead equipment have contributed to a noticeable lack of despoilation of the countryside and a reasonable harmonization of technology and nature.

6.1.9. Economic factors

The actual capital costs for units No. 1 and 2 and the estimated capital costs for unit No. 3 are given in Table 13. The average installed capital cost per kilowatt of capacity for the first two units is about \$825/kW, including the \$10 M cost of the waste disposal channel. Table 14 contains a summary of the cost of electricity generation at Ahuachapán over the history of the plant. It must be stressed that the figures given there do not include interest payments (which are made) or taxes (which are not paid). Even so, electricity produced from geothermal energy constitutes a very inexpensive source for El Salvador, as the round figures below for alternative sources show:

Type of power plant	Cost of electricity U.S. mill/kW·h
Hydroelectric.	4
Geothermal	6
Thermal (Bunker C oil)	25
Gas turbine (Diesel)	50

Financing of the project has been through loans from the World Bank [Sheehan, 1977], C.E.L. bonds, and cash.

6.1.10. Operating experience

The operation of the Ahuachapán geothermal power plant has been highly successful. The plant is a vital link in the electricity supply system of El Salvador. The country relies on three types of power stations: hydroelectric, thermal (fossil fuel) and geothermal. As can be seen from the figures below, the Ahuachapán plant constitutes about 14% of the rated installed electric generating capacity. However, during the dry season when the actual capacity of the hydro plants falls to about 50% of their rated value, the geothermal units amount to nearly 20% of the actual capacity.

Plant Type	Unit Name	Capacity	Totals
Hydroelectric	Cerron Grande No. 1 and 2	135 MW	232 MW
	Plant of November 5th	82 MW	
	Guajoyo	15 MW	
Thermal	Acajutla	63 MW	128.2 MW
	Soyapango (gas turbine)	58.6 MW	
	Gas Turbines	6.6 MW	
Geothermal	Ahuachapán No. 1 and 2	60 MW	60 MW
	1977 Total installed capacity		420.2 MW

The electrical generation, annual capacity factors, and the percentage of total generation in El Salvador of the units No. 1 and 2 at Ahuachapán are given below. Note that unit No. 1 began in June 1975 and unit No. 2 began in June 1976.

Year	Electrical Generation	Capacity Factor	% Total Generation
1975	72,331 MW·h	47%	11.8%
1976	279,800 MW·h	67%	25.4%
1977	400,051 MW·h	76%	32.3%

The geothermal plant has been essentially free of major breakdowns. This is reflected in an availability factor of 95% based on outages caused by breakdowns alone; i.e., availability = (total hours - outage hours caused by breakdowns)/total hours. When scheduled maintenance is included along with breakdown outage, the availability factor is 84%. For the sake of comparison, the following figures are for 1977 for the hydroelectric plants, which are generically noted for high reliability:

Plant	Capacity Factor	Availability Factor
Cerron Grande	55%	96%
November 5th	43%	93%
Guajoyo	65%	93%

A complete overhaul of each unit is carried out once every two years. It takes about one month to complete each inspection. Scheduled inspections are timed to coincide with the wet season so that sufficient hydroelectric capacity is available. Wellhead equipment is given a thorough inspection and cleaning at least once per year, with each well being visited on a rotating basis. It takes about one month to cover all the wells.

The maintenance of the borefield is handled by the following teams: general maintenance by one engineer and nine mechanics; measurements by one engineer and seven persons; operations by one engineer and six persons. The geothermal plant is maintained by five engineers and 77 persons.

There have been relatively few problems with the operation of the plant. The steam filters for the No. 1 turbine failed and caused damage to the 1st and 2nd stage buckets. The shell of one of the aftercoolers in the gas extraction system split along a weld which had been exposed to the direct impingement of the flow from the 2nd-stage ejector. The power transformer for the No. 2 unit failed in June 1978. These have been the only major failures of the energy conversion equipment during the three years of operation.

In the case of the wells and gathering system, there has been some trouble with premature failure of some of the rupture disks. These 305 mm (12 in) diameter, 3 mm (1/8 in) thick aluminum disks have developed pits and failed, requiring a shut-down of the well. The failures are caused most likely by a combination of stress cracking and fatigue. Pressure relief valves will be installed on the No. 3 unit and back-fitted on units No. 1 and 2 if these prove to be an improvement.

In addition, one of the inlet elbows on a wellhead separator gave way. Finally there was a collapse and eruption of well AH-24 in November 1976 and well AH-20 in April 1978. The damage has been repaired and both wells are in production at the present time [Cuéllar, 1978].

During the 19 months from October 1976 to April 1978, there has been little change in the total geofluid mass flow rate (see Table 6). In fact, the original four (4) wells feeding unit No. 1 showed an increase of 7.8%, while the five (5) wells serving unit No. 2 dropped by 5%; overall, the total flow increased by 1.8%. In that time period a new well was brought onstream (AH-24), but the percentages quoted above have excluded the flow from this well. There has been no plugging of production or reinjection wells. Well AH-25 has not produced geofluid even though it is located within 200 m (650 ft) of four highly productive wells. Most likely there is a local zone of impermeable material surrounding this particular well. All other dry wells were at the periphery of the field and served to define the limits of the producing reservoir (see Table 4 and Fig. 19).

It has been shown by tests that the practice of fluid reinjection plays an important role in maintaining reservoir pressure. While it does not seem necessary to reinject all of the waste liquid, it is essential to control the amount being reinjected relative to the amount of fluid being withdrawn. At present about 63% of the waste liquid from the plant is reinjected; after the No. 3 unit comes into service, this percentage will fall to about 30%. Reinjection wells have been sited at the periphery of the field, downstream of the assumed northwestward recharge flow in the aquifer [Romagnoli, et al, 1975]. In some instances, the reinjected fluid finds its way upward between the reinjection well casing and the bore hole (see Fig. 20), thus flowing into the reservoir instead of into the basement as intended. Reinjection may also have contributed to the lack of trouble with subsidence, although the formation is relatively hard and should not be subject to significant subsidence in any event.

6.2. Other areas of possible exploitation in El Salvador

In order to help keep pace with the 11% growth rate in electrical demand, El Salvador is exploring four additional geothermal areas. The actual total generation from all types of power plants and the maximum demand are shown below for 1975 and projected to 1980:

	1975 (actual)	1980 (projected)
Total electrical generation	965.9 GW·h	1864.7 GW·h
Maximum demand.	183.5 MW	351 MW

To meet this expected demand, C.E.L. plans to have on-line in 1980 a total capacity of 455.2 MW with 95 MW being installed at Ahuachapán. Thus 21% of the installed electrical capacity in 1980 will be geothermal.

The sites at which future geothermal power stations may be located are briefly described in the next sections.

6.2.1. Berlín

This field is located in eastern El Salvador, about 90 km (56 mi) from San Salvador, 18 km (11 mi) east of the Rio Lempa, and 6 km (4 mi) south of the Pan American Highway. Exploration took place at Berlín simultaneously with Ahuachapán in 1965 when two deep wells were drilled. The terrain is considerably more rugged than that at Ahuachapán, and this fact influenced the decision to proceed with Ahuachapán for the first geothermal power plant, although the results of the early exploratory studies at Berlín were encouraging. The first deep well was drilled to a depth of about 1800 m (5900 ft) and encountered a temperature of 271°C (520°F). The geofluid at Berlín contains roughly 10,000 ppm (1%) of total dissolved solids. This area is expected to be the site of the next (i.e., the fourth) geothermal unit in El Salvador by 1984-1985. Exploration is continuing at the site. Its ultimate capacity is estimated to be 100 MW(e).

6.2.2. Chinameca

This field is about 20 km (12 mi) east of Berlín and 17 km (11 mi) west of the city of San Miguel. Exploration is presently underway. It is expected that a geothermal power unit will be operating there by 1985. It may eventually support 100 MW(e).

6.2.3. San Vicente

The San Vicente geothermal field is located in east-central El Salvador, 50 km (31 mi) east of San Salvador and 40 km (25 mi) west-northwest of Berlín. Extensive exploration activity is taking place. The potential of this site is estimated at 100 MW(e).

6.2.4. Chipilapa

This area is about 5 km (3 mi) east of the Ahuachapán geothermal field and was the site of the first deep well drilled in El Salvador. Chipilapa may be part of the same geothermal field as Ahuachapán and is expected to develop about 50 MW(e) in the future.

7. Costa Rica

The geothermal development program in Costa Rica is directed by the Instituto Costarricense de Electricidad (I.C.E.) and has concentrated on the Guanacaste province in the northwestern part of the country. The geothermal area extends for 30 km (19 mi) along the flank of a chain of active volcanoes [Furgerson and Afonso L., 1977]. The geology of northwestern Costa Rica consists of a coastal belt of Mesozoic marine sedimentary rocks and ophiolites, an interior lowland of Mesozoic and Lower Tertiary sedimentary rock, and an interior cordillera of Upper Tertiary and Quaternary volcanic rocks [Corrales, et al, 1977]. The cordillera is an island arc volcanic chain consisting of a series of Quaternary andesitic stratocone volcanoes that stretches from Panama to Guatemala [Blackwell, et al, 1977]. An integrated program involving heat flow, temperature gradient, geochemical, electrical and hydrological investigations is being carried out in the southwestern portion of the Cordillera de Quanacaste. Particular attention is being given to the areas of Las Hornillas de Miravalles, Las Pailas and Borinquen, where some drilling has been conducted [Blackwell, et al 1977].

A total of 35 exploratory wells have been sunk in the area; 24 of these have been to depths of 50 m (164 ft) or less and 9 of these have exceeded 90 m (295 ft). Active development is underway and a 40 MW geothermal power plant is scheduled by I.C.E. to be installed by 1984-1985 [Kuwada, 1978].

7.1. Las Hornillas de Miravalles

Geochemical studies have revealed the possibility of a deep, chlorinated aquifer with reservoir base temperatures as high as 240°C (464°F) [Gardner and Corrales, 1977]. Surface manifestations such as hot springs (of various chemical compositions) and cool (bicarbonate) springs often appear in close proximity. These may be fed from separate deep and shallow circulation systems which discharge at the surface through faults. Although there is heavy rainfall in the area near the crest of the volcanic cordillera, permeable near-surface rocks, and evidence of excess water in both the shallow and deep groundwater system, additional studies are required to confirm that sufficient recharge is present to support large fluid withdrawal rates that would accompany a geothermal power plant in the area.

Active fumaroles cover an area of 50 ha (124 acres), with indications that the entire fumarole zone extends to about 200 ha (494 acres). Temperature gradients at shallow depths exceed 1°C/m (0.5°F/ft), or about 30 times the average normal gradient, over an area of 200 ha (494 acres); the gradient measured at depths of 50 - 100 m (164 - 328 ft) exceeds 0.4°C/m (0.2°F/ft) over an area of at least 1000 ha (2471 acres). The deepest hole showed a temperature of 150°C (302°F) at a depth of 200 m (656 ft) [Blackwell, et al, 1977].

Beginning in November 1978, after the wet season comes to an end, a program of deep drilling will commence. A total depth of 4000 m (13,000 ft) has been programmed, which should allow for the completion of four wells since the aquifer is estimated to lie at a depth of between 800 - 1200 m (2625 - 3937 ft) [Kuwada, 1978].

7.2. Las Pailas

Several exploratory wells have been drilled in the Las Pailas thermal area, although only one hole exhibited a high temperature gradient. That well had a temperature of 91°C (196°F) at 50 m (164 ft); other holes were cold, indicating the presence of excessive cold water, in spite of the fact that the well was 200 m (656 ft) from a hot spring [Blackwell, et al, 1977].

7.3. Borinquen

The results have been reported on only one well in this area. A bottomhole temperature of 90°C (194°F) was observed at a depth of 100 m (328 ft). The well was located 800 m (2625 ft) from the nearest fumarole and showed a temperature gradient of greater than 0.6°C/m (0.3°F/ft) [Blackwell, et al, 1977].

8. Nicaragua

The national electric authority of Nicaragua, E.N.A.L.U.F., is predicting that 100 MW(e) of geothermal power will be installed in Nicaragua by the early 1980's, with about 150 - 220 MW(e) installed by 1985, 300 - 400 MW(e) by 2000, and as much as 800 MW(e) by the year 2020 [Meidav, et al, 1977]. The most likely candidate site for the first geothermal power plant is the Momotombo field which was investigated from 1969 to 1971 along with the San Jacinto-Tisate area. These two promising areas were explored under a program sponsored by the U.S. Agency for International Development. Work at the sites was delayed several years on account of the Managua earthquake of December 23, 1972 [Muffler, 1975].

8.1. Momotombo

The geothermal field at Momotombo is located on the lower slopes of the Momotombo Volcano, on the edge of Lake Managua. The area is about 200 ha (494 acres) in extent, being roughly rectangular, 1 × 2 km (0.6 × 1.2 mi). A total of 25 wells have been drilled in the field. Some of these wells show drastic temperature inversions, as much as -1.5°C/m (-0.8°F/ft), indicating the presence of colder fluid at depth. Some flow rates from a few of the wells have been reported [Girelli, 1977]:

Momotombo well No. 3	85 Mg/h (187 klbm/h)
Momotombo well No. 9	56 Mg/h (123 klbm/h)
Momotombo well No. 12	40 Mg/h (88 klbm/h)

It is expected that construction will begin in 1979 on a geothermal power plant at Momotombo although the size of the unit has not been decided. The site is believed capable of supporting 100 MW(e), but a smaller, 30 MW(e), unit may be installed initially until confidence in the field is thoroughly established [Girelli, 1977].

9. Guatemala

The national electric company of Guatemala, I.N.D.E., is aiming at a goal of 100 MW of installed geothermal capacity by the early 1980's [Meidav, et al, 1977]. Three areas have been under exploration with technical assistance from Japan: Moyuta, Amatitlán and Zunil.

There were high hopes for the field at Moyuta which is about 25 km (16 mi) northwest of the successful project at Ahuachapán across the border in El Salvador. Shallow wells revealed temperature gradients of about 0.25°C/m (0.14°F/ft); unfortunately two wells produced low temperatures and the site essentially has been abandoned [Dominco, 1977; Kuwada, 1978].

Attention is still being given to the other two sites; Amititlán may someday support 50 - 100 MW(e) whereas Zunil appears to be a rather small area with limited prospects.

10. Honduras

In 1977 the national electric authority of Honduras, E.N.E.E., began a program of geothermal exploration that focussed on two areas: Pavana, in the southernmost part of the country near Choluteca, and San Ignacio, which is located northwest of the capital city of Tegucigalpa [Meidav, et al, 1977]. At the present time the exploration program is temporarily in abeyance [Kuwada, 1978]. By 1982, E.N.E.E. hopes to have 50 MW of geothermal power on-line, with an additional 50 MW by 1984-1985 [Meidav, et al, 1977].

11. Panama

Panama presently has a total installed electric capacity of 237 MW with projections of 534 MW by 1984. In 1976, the consumption of electricity amounted to about 660 kW·h per capita. Although hydroelectric plants constitute a significant fraction of Panama's generating capacity, it is believed that a 75 MW plant of either conventional thermal or geothermal design will be needed by 1985. The most promising geothermal site is at Cerro Pando although it is too early to assess the quality of this potential area in the light of the minimal amount of exploratory work completed to date [Ho, 1977; Meidav, *et al*, 1977].

References

Note: The following reference is cited several times:

Proceedings of the Second United Nations Symposium on the Development and Use of Geothermal Resources, May 22-29, 1975, San Francisco, CA, Vols. 1-3; U.S. Government Printing Office, Washington, D.C., 1976. (Referred to as San Francisco-1975, hereafter).

Akiba, M., 1970, "Mechanical Features of a Geothermal Plant", Proc. U.N. Symp. on Dev. and Util. of Geot. Resources, Sept. 22 - Oct. 1, Pisa, Italy: Geothermics, Sp. Iss, 2, Vol. 2, pp. 1521-1529.

Alonso, H., 1975, "Geothermal Potential of Mexico", San Francisco-1975, Vol. 1, pp. 21-24.

Blackwell, D. D., Granados, G. E. and Koenig, J. B., 1977, "Heat Flow and Geothermal Gradient Exploration of Geothermal Areas in the Cordillera de Guanacaste of Costa Rica", Geothermal Resources Council, Transactions, Vol. 1, pp. 17-18.

CEL, 1976, "Annual Report 1976 - Comisión Ejecutiva Hidroeléctrica del Río Lempa", San Salvador, El Salvador, C.A.

CFE, 1971, "Cerro Prieto: Underground Power", Comisión Federal de Electricidad, G. V. Caravantes, Dir. Gen., Ródano 14, México 5, D.F., México.

Corrales, M. F., Koenig, J. B. and Kuwada, J. T., 1977, "Exploration of the Guanacaste, Costa Rica, Geothermal System", Geothermal Resources Council, Transactions, Vol. 1, pp. 57-58.

Cuéllar, G., 1975, "Behavior of Silica in Geothermal Waste Waters, San Francisco-1975, Vol. 2, pp. 1337-1347.

Cuéllar, G., 1978, Personal communication during conference between G. Cuéllar, M. E. Choussy, R. Caseres, C. Moreno P. of C.E.L. and C. H. Bloomster, J. T. Kuwada, R. R. Reeber and R. DiPippo, June 15-17, 1978, Comisión Ejecutiva Hidroeléctrica del Río Lempa, San Salvador, El Salvador.

Diaz Serrano, J., 1978, "Pemex Director General Reports on Mexico's Outlook", Ocean Industry, Vol. 13, No. 5, pp. 42-44.

DiPippo, R., 1978(A), "A Summary of the Technical Specifications of the Geothermal Power Plants in the World", Brown Univ. Rep. No. CATMEC/8, D.O.E. No. COO/4051-14, Providence, R.I.

DiPippo, R., 1978(B), "Geothermal Power Plants of Japan: A Technical Survey of Existing and Planned Installations", Brown Univ. Rep. No. CATMEC/9, D.O.E. No. COO/4051-16, Providence, R.I.

DiPippo, R., 1978(C), "Geothermal Power Plants of the United States - A Technical Survey of Existing and Planned Installations", Brown Univ. Rep. No. CATMEC/14, D.O.E. No. COO/4051-20, Providence, R.I.

DiPippo, R., 1978(D), "Geothermal Power Plants of New Zealand, Philippines and Indonesia: A Technical Survey of Existing and Planned Installations", Brown Univ. Rep. No. CATMEC/17, D.O.E. No. COO/4051-23, Providence, R.I.

Dominco, E., 1977, "Guatemala", Geothermal Resources: Survey of an Emerging Industry, Geothermal Resources Council Spec. Short Course No. 6, Houston, TX.

Dominguez A., B., 1977, "Cerro Prieto, Mexico", Geothermal Resources: Survey of an Emerging Industry, Geothermal Resources Council Spec. Short Course No. 6, Houston, TX.

Dominguez A., B. and Vital B., F., 1975, "Repair and Control of Geothermal Wells at Cerro Prieto, Baja California, Mexico", San Francisco-1975, Vol. 2, pp. 1483-1499.

EPA, 1978, "Pollution Control Guidance for Geothermal Energy Development", Power Tech. & Cons. Branch, Energy Sys. Envir. Cont. Div., Off. Energy, Min. & Ind., U.S. Environmental Protection Agency, Washington, D.C.

Einarsson, S. S., Vides R., A. and Cuéllar, G., "Disposal of Geothermal Waste Water by Reinjection", San Francisco-1975, Vol. 2, pp. 1349-1363.

Fuji, 1977, "Ahuachapán Unit No. 3, C.E.L., El Salvador: Technical Particulars; Steam Flow Diagram, PL 311188; General Arrangement, PL 210640 and PL 210641; Geothermal Turbine Sectional View, ST 418390", Fuji Electric Company, Ltd., Tokyo, Japan.

Furgeson, R. B. and Afonso L., P.S., 1977, "Electrical Investigations in the Guanacaste Geothermal Area (Costa Rica)", Geothermal Resources Council, Transactions, Vol. 1, pp. 99-100.

Gardner, M. C. and Corrales, R., 1977, "Geochemical and Hydrological Investigations of the Guanacaste Geothermal Project, Costa Rica", Geothermal Resources Council, Transactions, Vol. 1, pp. 101-102.

Girelli, M., 1977, "Nicaragua", Geothermal Resources: Survey of an Emerging Industry, Geothermal Resources Council Spec. Short Course No. 6, Houston, TX.

Guiza L., J., 1975, "Power Generation at Cerro Prieto Geothermal Field", San Francisco-1975, Vol. 3, pp. 1976-1978.

Ho, A., 1977, "Panama", Geothermal Resources: Survey of an Emerging Industry, Geothermal Resources Council Spec. Short Course No. 6, Houston, TX.

Kuwada, J. T., 1978, Personal communication, July 10, 1978, Rogers Engineering, Inc., San Francisco, CA.

Meidav, T., Sanyal, S. and Facca, G., 1977, "An Update of World Geothermal Energy Development", Geothermal Energy Magazine, Vol. 5, No. 5, pp. 30-34.

Mercado G., S., 1974, "The Geothermal Plant of Cerro Prieto, B.C., Mexico, and Problems Encountered During Its Development", *Geothermics*, Vol. 3, No. 3, pp. 125-126.

Mercado G., S., 1975(A), "Movement of Geothermal Fluids and Temperature Distribution in the Cerro Prieto Geothermal Field, Baja California, Mexico," *San Francisco-1975*, Vol. 1, pp. 487-494.

Mercado G., S., 1975(B), "Cerro Prieto Geothermoelectric Project: Pollution and Basic Protection", *San Francisco-1975*, Vol. 2, pp. 1385-1398.

Mercado G., S., 1976, "Cerro Prieto Geothermal Field, Mexico - Wells and Plant Operation", *Proc. Int. Cong. on Thermal Waters, Geothermal Energy and Vulcanism of the Mediterranean Area*: *Geothermal Energy*, Vol. 1, pp. 394-408, Athens, Greece.

MHI, "List of Geothermal Power Plant", Mitsubishi Heavy Industries, Ltd., Tokyo, Japan.

MHI, 1977, "Geothermal Power Plant - Ahuachapán 30,000 kW x 2 units in El Salvador, C.A.", Mitsubishi Heavy Industries, Ltd., Tokyo, Japan.

Muffler, L. J. P., 1975, "Summary of Section I: Present Status of Resources Development", *San Francisco-1975*, Vol. 1, pp. xxxiii-xliv.

Parades A., E., 1975, "Preliminary Report on the Structural Geology of the Cerro Prieto Geothermal Field", *San Francisco-1975*, Vol. 1, pp. 515-519.

Reed, M. J., 1975, "Geology and Hydrothermal Metamorphism in the Cerro Prieto Geothermal Field, Mexico", *San Francisco-1975*, Vol. 1, pp. 539-547.

Romagnoli, P., Cuéllar, G., Jimenez, M. and Ghezzi, G., 1975, "Hydrogeological Characteristics of the Geothermal Field of Ahuachapán, El Salvador", *San Francisco-1975*, Vol. 1, pp. 563-574.

Sheehan, R. H., 1977, "Economic Aspects of Geothermal Energy", in *Minutes 6th CATMEC Meeting*, Brown Univ. Rep. No. CATMEC/5, D.O.E. No. COO/4051-9, pp. 1-5 and App. A, Providence, R.I.

Tolivia,M., E., Hoashi, J. and Miyazaki, M., 1975, "Corrosion of Turbine Materials in Geothermal Steam Environment in Cerro Prieto, Mexico", *San Francisco-1975*, Vol. 3, pp. 1815-1820.

Table 1

Wellhead and separator conditions averaged over 12 wells(1) at Cerro Prieto

[after Reed, 1975]

Pressure:	wellhead	1119 ± 982 kPa(2)	(162 ± 142 lbf/in^2)
	separator	710 ± 72 kPa	(103 ± 10 lbf/in^2)
Temperature:	separator	165 ± 4°C	(329 ± 7°F)
Mass flow rate:	separated steam	47.5 ± 22.7 Mg/h	(104.7 ± 50.0 klbm/h)
	silencer liquid	130.0 ± 42.8 Mg/h	(286.6 ± 94.4 klbm/h)
	silencer steam	16.0 ± 9.2 Mg/h	(36.4 ± 20.3 klbm/h)
	total flow	194.0 ± 69.0 Mg/h	(427.7 ± 152.1 klbm/h)
Dryness fraction at separator		0.24 ± 0.06	

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(1) Samples taken from wells M-5, -8, -9, -11, -20, -25, -26, -29, -30, -31, -34, -39 during January and February 1974.

(2) Wells M-11 and M-31 showed wellhead pressures of 4170 and 1960 kPa, respectively. The average wellhead pressure for the other 10 wells was 729 kPa (106 lbf/in^2) with a standard deviation of 66 kPa (10 lbf/in^2).

Table 2

Chemical composition of separated water samples from 12 wells(1) at Cerro Prieto [after Reed, 1975]

Constituent	Concentration mg/ℓ	Standard deviation mg/ℓ
Chloride, Cl	14,370	2,220
Sodium, Na	7,760	1,060
Potassium, K	1,660	430
Silica, SiO_2	850	185
Calcium, Ca	545	110
Bicarbonate, HCO_3	50	10
Lithium, Li	18	3
Boron, B	18	4
Sulfate, SO_4	17	14
Magnesium, Mg	1.4	1.0
pH @ 25°C	8.2 ± 0.1	

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(1) Samples taken from wells M-5, -8, -9, -11, -20, -25, -26, -29, -30, -31, -34, -39 during January and February 1974.

Table 3

Country	Mexico
Unit name	Cerro Prieto, Units 1 and 2
Owner	Comisión Federal de Electricidad
Year of start-up	1973
Plant type	Separated steam ("single flash")

Turbine characteristics/unit

Manufacturer	Tokyo Shibaura Electric Company, Ltd. (Toshiba)	
Type	Single-cylinder, double-flow, 6 × 2 impulse-reaction	
Rated capacity	37.5 MW	
Maximum capacity	40.0 MW	
Speed	3600 rev/min	
Steam inlet pressure	618.1 kPa	89.6 lbf/in^2
Steam inlet temperature	160.0 °C	320.0 °F
Noncondensable gas content	∿1.0% by weight of inlet steam	
Exhaust pressure	11.9 kPa	3.5 in Hg
Turbine steam flow rate	285.45 Mg/h	0.629×10^6 lbm/h
Maximum allowable pressure	(NA) kPa	(NA) lbf/in^2
Last stage blade height	508.0 mm	20.0 in

Condenser characteristics/unit

Type	Spray jet, barometric	
Pressure	11.2 kPa	3.3 in Hg
Cooling water temperature	32.0 °C	89.6 °F
Outlet water temperature	45.3 °C	113.5 °F
Cooling water flow rate	10,710 Mg/h	23.6×10^6 lbm/h

Table 3 (cont.)

Gas extractor characteristics/unit

Type	Steam jet ejector	
Number of stages or sets	2 stages	
Suction pressure	10.7 kPa	3.1 in Hg
Capacity	∿ 32,000 m^3/h	∿ 19,000 ft^3/min
Steam consumption	24.2 Mg/h	0.053×10^6 lbm/h

Heat rejection system characteristics/unit

Type	Cross-flow, mechanical-draft cooling tower	
Number of cells	6	
Water inlet temperature	45.9 °C	114.6 °F
Water outlet temperature	32.0 °C	89.6 °F
Design wet-bulb temperature	(NA) °C	(NA) °F
Water flow rate	11.4 Gg/h	25.5×10^6 lbm/h
Water pump power	835 kW	
Draft fan type	Vertical, axial	
Air flow rate/fan	(NA) m^3/s	(NA) ft^3/min
Fan motor power	(NA) kW	

Table 4

Well information at Ahuachapán [Cuéllar, 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	Reinjecter 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; reinjecter 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; reinjecter 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	Reinjecter for AH-1.

Table 5

Lengths and diameters of steam transmission lines and liquid reinjection lines at Ahuachapán

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

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(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 6

Characteristics of well production for units No. 1 and 2

Well No.	October 1976				April 1978			
	P(1) kPa	$\dot{m}_\ell$ kg/s	$\dot{m}_v$ kg/s	$\dot{m}_t$ kg/s	P(1) kPa	$\dot{m}_\ell$ kg/s	$\dot{m}_v$ kg/s	$\dot{m}_t$ kg/s
Unit No. 1								
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

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(1) Pressure at wellhead separator

Table 7

Chemical analysis of liquid from wells at Ahuachapán

Substance	AH-1	AH-4	AH-5	AH-6	AH-7	AH-20	AH-21	AH-22	AH-26
	Well number								
Cl	10600	9050	9110	10900	12500	10900	11500	9217	10130
Na	5800	5000	5000	6000	6600	6000	6100	5080	5600
K	1000	740	680	1050	1280	1040	1140	710	900
SiO_2	577	534	470	500	610	556	535	552	500
Ca	425	400	440	439	486	450	480	437	430
B	147	144	138	156	178	155	169	127	142
Br	46.0	35.7	38.1	43.0	50.4	45.9	48.4	39.8	47.7
HCO_3	34.4	32.5	28.1	46.5	26.6	31.6	40.3	31.5	36.3
SO_4	30.8	34.2	40.8	29.7	23.3	30.2	40.5	32.7	44.2
Li	18.5	15.7	14.8	18.8	20.0	18.5	19.1	15.0	17.5
As	10.8	10.0	9.9	11.6	14.0	12.0	11.8	10.2	11.0
I	8.2	6.5	7.0	8.5	9.2	8.5	10.1	6.9	8.5
Rb	7.9	5.6	5.1	8.3	8.5	7,9	8.3	5.2	7.3
Cs	5.8	4.6	4.1	6.3	6.6	6.0	6.3	4.5	5.8
Sr	4.5	4.6	5.7	4.5	4.8	4.5	4.7	4.7	4.5
Sb	2.3	1.9	1.8	2.1	2.5	-	-	-	-
F	1.5	1.3	1.2	1.8	1.8	1.6	1.7	1.3	1.4
Mg	0.09	0.13	0.24	0.09	0.08	0.07	0.01	0.16	0.30

Note: All values in ppm.

Table 8

Average chemical composition of liquid from wells at Ahuachapán(1)

Substance	Concentration/ppm
Chloride, Cl	10430
Sodium, Na	5690
Potassium, K	950
Silica, SiO_2	537
Calcium, Ca	443
Boron, B	151
Bromide, Br	43.9
Bicarbonate, HCO_3	34.2
Sulfate, SO_4	34.0
Lithium, Li	17.5
Arsenic, As	11.3
Iodide, I	8.1
Rubidium, Rb	7.1
Cesium, Cs	5.5
Strontium, Sr	4.7
Antimony, Sb	2.1
Fluoride, F	1.5
Magnesium, Mg	0.13

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(1) Samples taken from wells AH-1, -4, -5, -6, -7, -20, -21, -22 and -26.

Table 9

Composition of steam condensate at receiver and hot well

Liquid at receiver trap		Condensate in hot well	
Constituent	Concentration	Constituent	Concentration
Cl	13.6	Cl	59.3
Na	7.15	Na	130
K	1.25	K	0.35
SO_4	0.6	SO_4	181.5
SiO_2	1.61	SiO_2	0.86
Ca	0.80	NH_4	0.36
HCO_3	2.90	Fe	0.10
B	0.75	$CaCO_3$	6.49
		S	0.15
pH	5.28	pH	7.22

Concentrations are in ppm.

Table 10

Country	El Salvador
Unit name	Ahuachapán, Units 1 and 2
Owner	Comision Ejecutiva Hidroelectrica del Rio Lempa (CEL)
Year of start-up	1975 (Unit 1), 1976 (Unit 2)
Plant type	Separated steam ("single flash")

Turbine characteristics/unit

Manufacturer	Mitsubishi Heavy Industries, Ltd.	
Type	Single-cylinder, double-flow, 5 × 2 impulse	
Rated capacity	30.0 MW	
Maximum capacity	35.0 MW	
Speed	3600 rev/min	
Steam inlet pressure	558.9 kPa	81.1 lbf/in^2
Steam inlet temperature	156.1 °C	313.0 °F
Noncondensable gas content	0.2 % by weight of inlet steam	
Exhaust pressure	8.33 kPa	2.46 in Hg
Turbine steam flow rate	230.0 Mg/h	0.507×10^6 lbm/h
Maximum allowable pressure	984.0 kPa	142.7 lbf/in^2
Last stage blade height	520.0 mm	20.5 in

Condenser characteristics/unit

Type	Spray jet, barometric	
Pressure	8.33 kPa	2.46 in Hg
Cooling water temperature	27.0 °C	80.6 °F
Outlet water temperature	40.3 °C	104.5 °F
Cooling water flow rate	8,650 Mg/h	19.1×10^6 lbm/h

Table 10 (cont.)

Gas extractor characteristics/unit

Type	Steam jet ejector	
Number of stages or sets	2	
Suction pressure	7.84 kPa	2.32 in Hg
Capacity	11,700 m^3/h	6,886 ft^3/min
Steam consumption	4.1 Mg/h	9.04×10^3 lbm/h

Heat rejection system characteristics/unit

Type	Cross-flow, mechanical draft cooling tower	
Number of cells	5	
Water inlet temperature	40.3 °C	104.5 °F
Water outlet temperature	27.0 °C	80.6 °F
Design wet-bulb temperature	22.0 °C	71.6 °F
Water flow rate	9.02 Gg/h	19.9×10^6 lbm/h
Water pump power	(NA) kW	
Draft fan type	Vertical, axial	
Air flow rate/fan	443.3 m^3/s	0.939×10^6 ft^3/min
Fan motor power	80.0 kW	

Table 11

Country	El Salvador
Unit name	Ahuachapán, Unit 3
Owner	Comision Ejecutiva Hidroelectrica del Rio Lempa (CEL)
Year of start-up	1980
Plant type	Separated steam/flash ("double flash")

Turbine characteristics

Manufacturer	Fuji Electric Company, Ltd.	
Type	Single-cylinder, double-flow, 7 x 2, pass-in	
Rated capacity	35.0 MW	
Maximum capacity	40.0 MW	
Speed	3600 rev/min	
Main steam inlet pressure	548.1 kPa	79.5 lbf/in^2
Main steam inlet temperature	155.3 °C	311.6 °F
Secondary steam pressure	150.0 kPa	21.8 lbf/in^2
Secondary steam temperature	111.4 °C	232.6 °F
Noncondensable gas content	0.2 % by weight of main steam	
Exhaust pressure	8.33 kPa	2.46 in Hg
Main steam flow rate	171.0 Mg/h	0.377×10^6 lbm/h
Secondary steam flow rate	145.0 Mg/h	0.320×10^6 lbm/h
Maximum allowable pressure	(NA) kPa	(NA) lbf/in^2
Last stage blade height	565.0 mm	22.2 in

Condenser characteristics

Type	Spray jet, low-level barometric	
Pressure	8.33 kPa	2.46 in Hg
Cooling water temperature	27.0 °C	80.6 °F
Outlet water temperature	40.3 °C	104.5 °F
Cooling water flow rate	12,260 Mg/h	27.0×10^5 lbm/h

Table 11 (cont.)

Gas extractor characteristics

Type	Steam jet ejector	
Number of stages or sets	2	
Suction pressure	(NA) kPa	(NA) in Hg
Capacity	(NA) m^3/h	(NA) ft^3/min
Steam consumption	(NA)	

Heat rejection system characteristics

Type	Cross-flow, mechanical-draft cooling tower	
Number of cells	5	
Water inlet temperature	40.3 °C	104.5 °F
Water outlet temperature	27.0 °C	80.6 °F
Design wet-bulb temperature	22.0 °C	71.6 °F
Water flow rate	12.26 x Gg/h	27.0×10^6 lbm/h
Water pump power	(NA) kW	
Draft fan type	Vertical, axial	
Air flow rate/fan	(NA) m^3/s	(NA) ft^3/min
Fan motor power	(NA) kW	

Table 12

Country	El Salvador
Unit name	Ahuachapán Auxiliary Turbo-Generator
Owner	Comisión Ejecutiva Hidroelectrica del Rio Lempa (CEL)
Year of start-up	1975
Plant type	Separated steam ("single-flash")

Turbine characteristics

Manufacturer	Mitsubishi Heavy Industries, Ltd.	
Type	Single-cylinder, Curtis stage, geared, noncondensing	
Rated capacity	1.1 MW	
Maximum capacity	1.3 MW	
Speed, turbine/generator	7129/1800 rev/min	
Steam inlet pressure	552.9 kPa	80.2 lbf/in^2
Steam inlet temperature	156 °C	313 °F
Noncondensable gas content	0.2 % by weight of inlet steam	
Exhaust pressure	96.2 kPa	28.4 in Hg
Turbine steam flow rate	21.0 Mg/h	0.0463x 10^6 lbm/h
Maximum allowable pressure	974.5 kPa	141.3 lbf/in^2
Last stage blade height	(NA) mm	(NA) in

Condenser characteristics

Type	(None)	
Pressure	- kPa	- in Hg
Cooling water temperature	- °C	- °F
Outlet water temperature	- °C	- °F
Cooling water flow rate	- Mg/h	- lbm/h

Table 13

Capital costs for geothermal power units at Ahuachapán

Item	Unit No. 1	Unit No. 2	Unit No. 3
	U.S. $ (1975)	U.S. $ (1976)	U.S. $ (est.)(2)
Turbogenerator, condenser, cooling water system, wellhead equipment, turbine controls	3,423,740.48	5,205,803.80	8,000,000
Steam piping, including supports, insulation and drains	536,526.00	991,679.20	1,950,000
Electrical equipment	790,272.18	613,576.60	700,000
Auxiliary equipment	225,484.06	68,313.00	110,000
Well drilling and piping	3,200,000.00	3,200,000.00	1,000,000
Other civil engineering, installation of equipment, studies, engineering, administration, etc.	23,389.967.55(1)	7,952,309.00(1)	8,240,000
Totals	$31,565,990.27	$18,031,681.60	$20,000,000

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(1) Cost of waste water disposal channel ($10,000,000) has been allocated between units No. 1 and 2; later it will be allocated among the three units upon completion of unit No. 3.

(2) Estimates were made in 1975; latest estimates for unit No. 3 total about $35,000,000.

Table 14

Cost of electricity generation at Ahuachapán (exclusive of interest)

Expenses	1975(1)	1976(2)	1977(3)	1978 (est.)
Production/$	82,191	398,363	584,340	613,600
Depreciation/$	235,619	591,222	1,350,731	2,040,000
General/$	24,313	114,580	187,650	192,000
Total	$342,123	$1,104,165	$2,122,721	$2,845,600
Generation(4)/MW·h	72,330.6	279,800	400,051	418,400
Specific cost(5)/(mill/kW·h)	4.73	3.95	5.31	6.80
Specific cost(6)/(mill/kW·h)	5.14	4.29	5.77	7.39

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(1) Unit No. 1 for 7 months of the year.

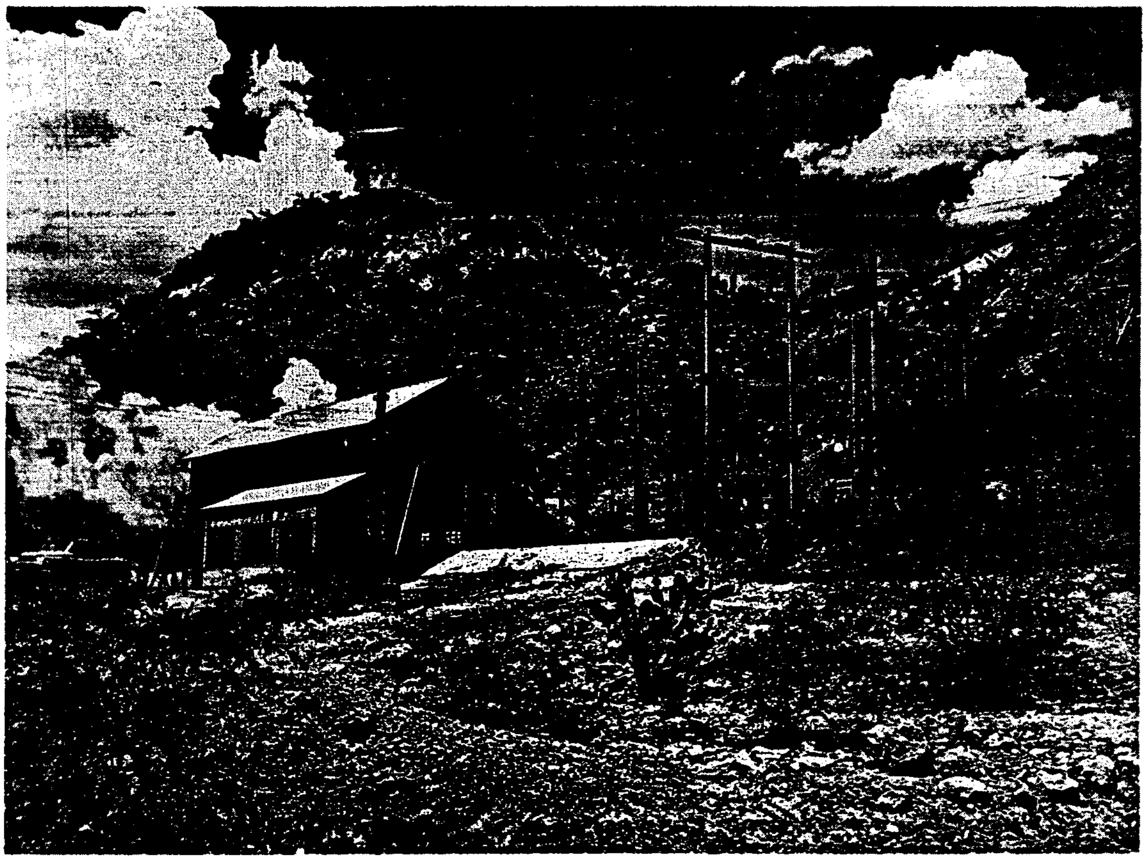
(2) Unit No. 1 for full year; unit No. 2 for 5 months.

(3) Both units for full year.

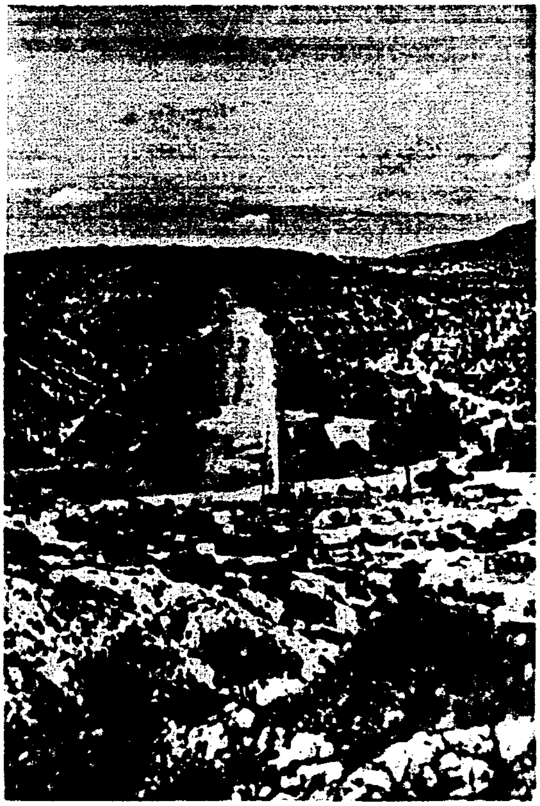
(4) Gross generation; net generation is 8% less.

(5) Based on gross generation.

(6) Based on net generation.



(a)



(b)

Fig. 1. (a) Power house and substation for Pathé geothermal unit, and (b) well No. 2 discharging at Pathé geothermal field [CFE, 1971].

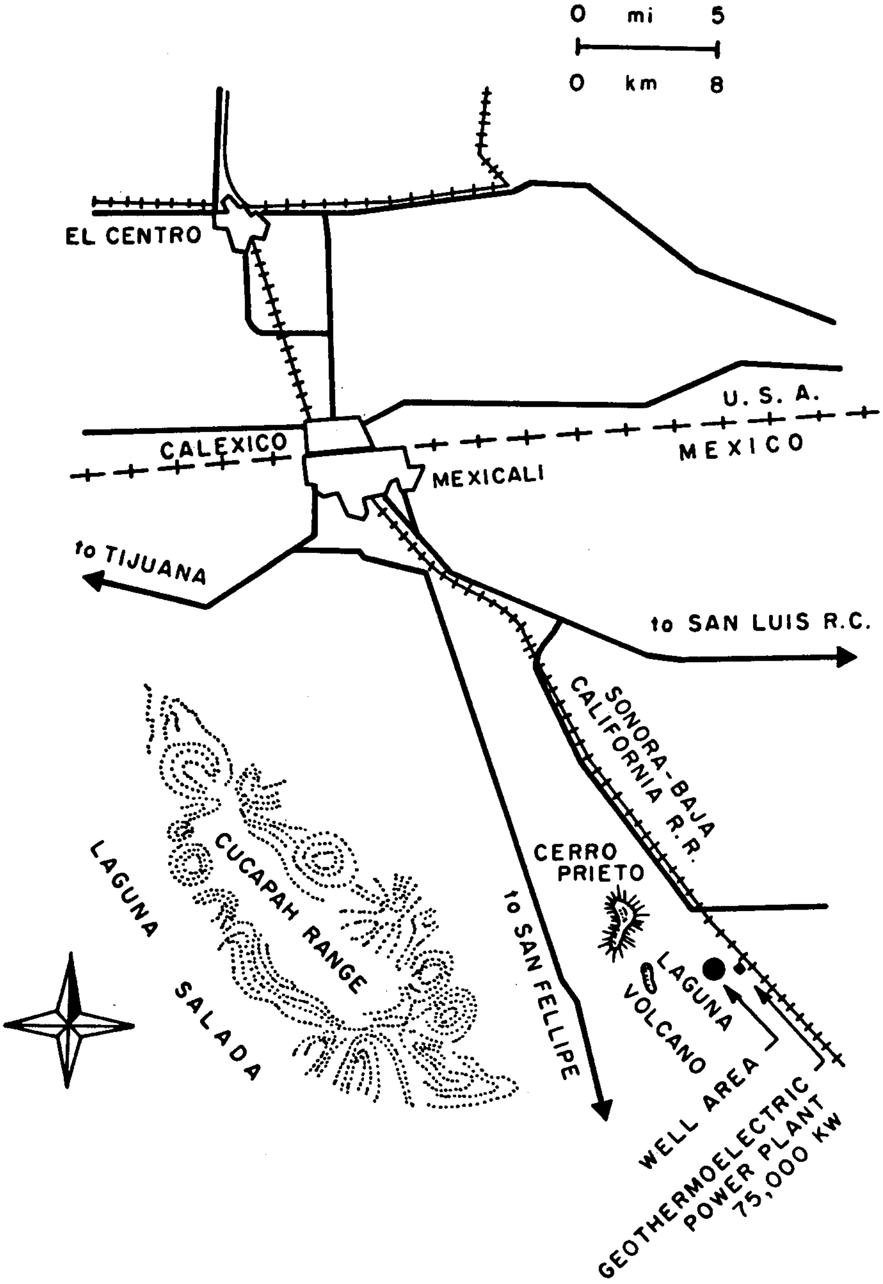


Fig. 2. Geographical location of Cerro Prieto geothermal field [CFE, 1971].

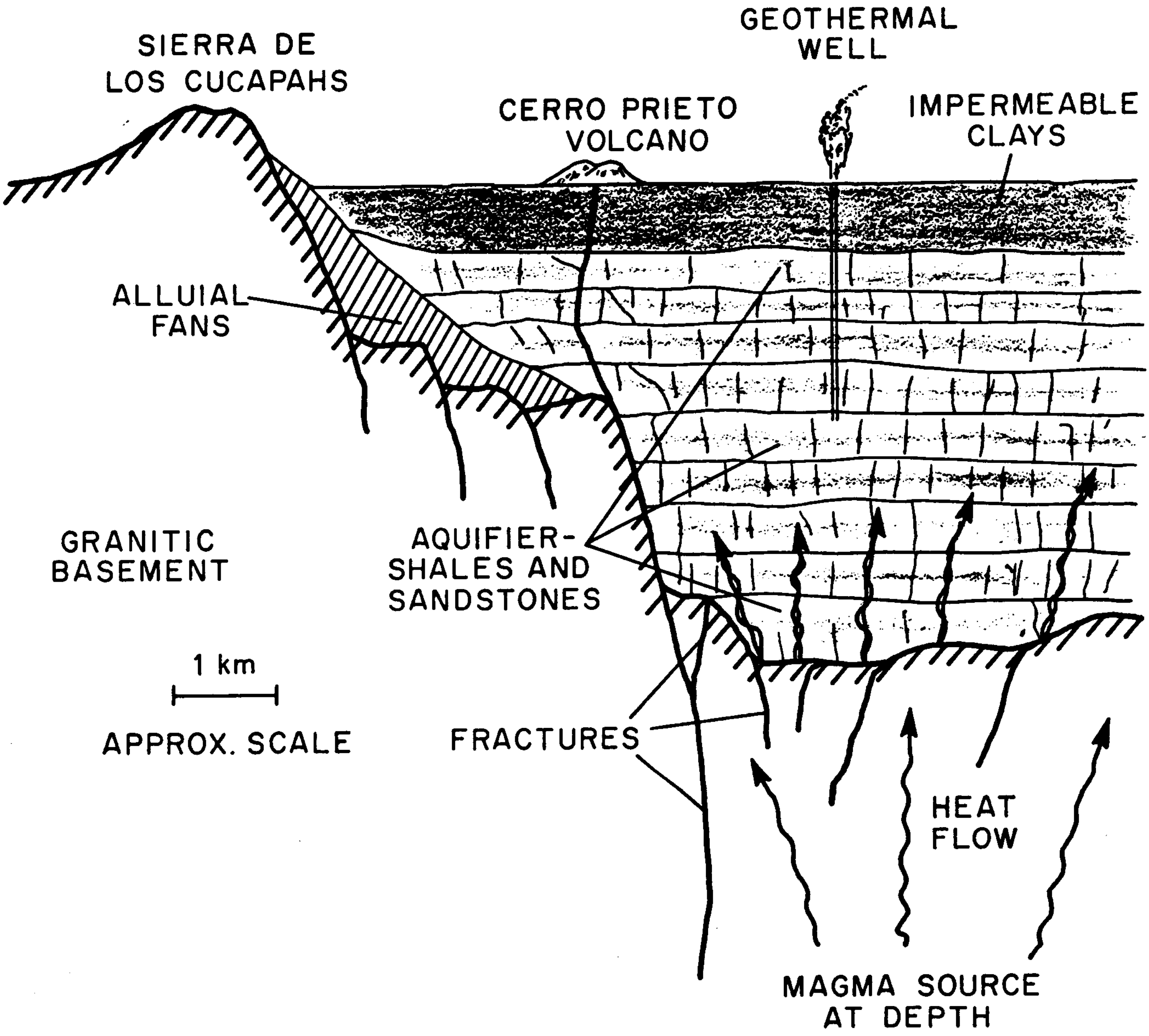


Fig. 3. Schematic cross-section of Cerro Prieto geothermal field [after CFE, 1971].

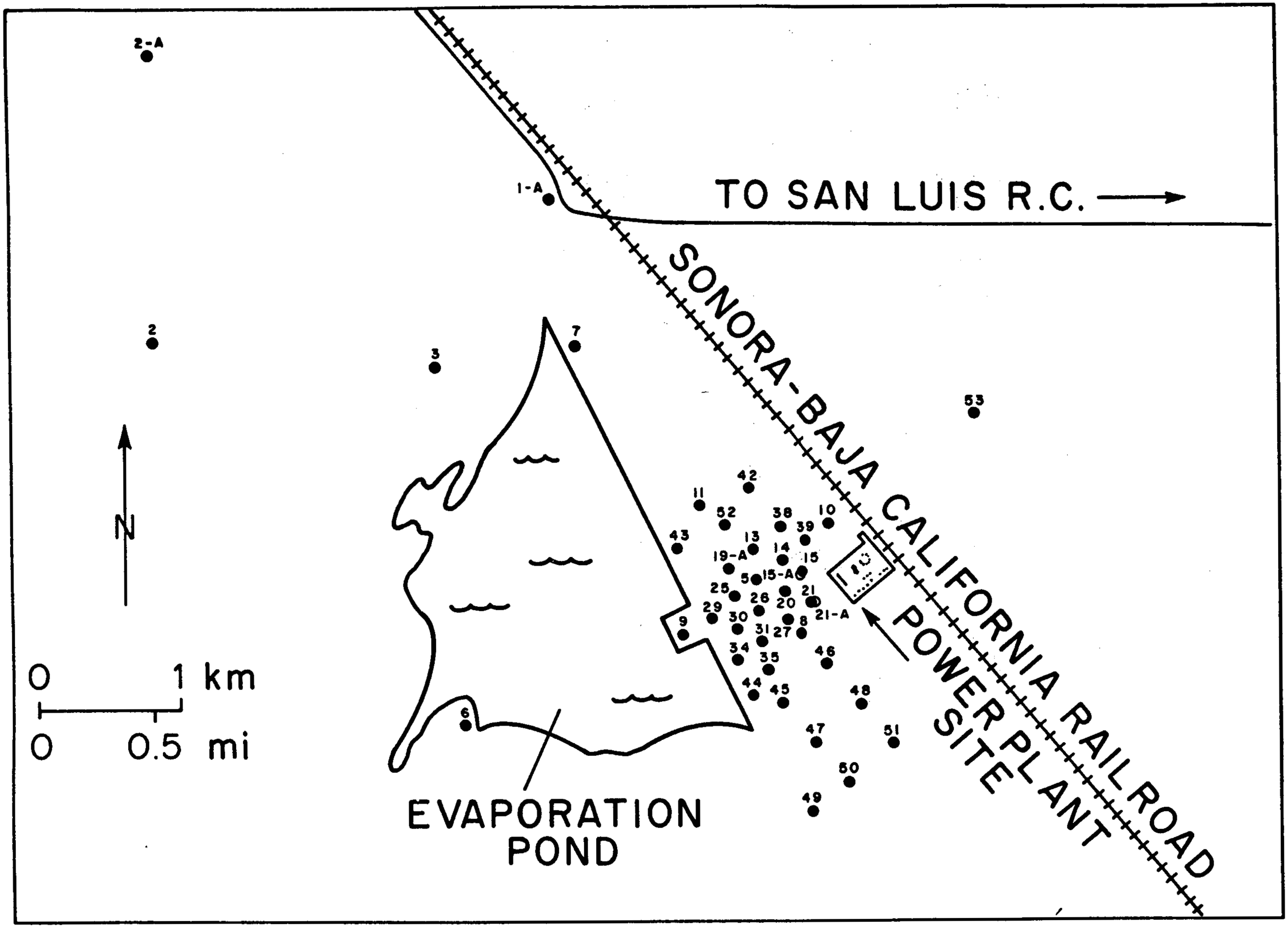


Fig. 4. Well locations at Cerro Prieto [after Dominguez and Vital, 1975; Mercado, 1976].

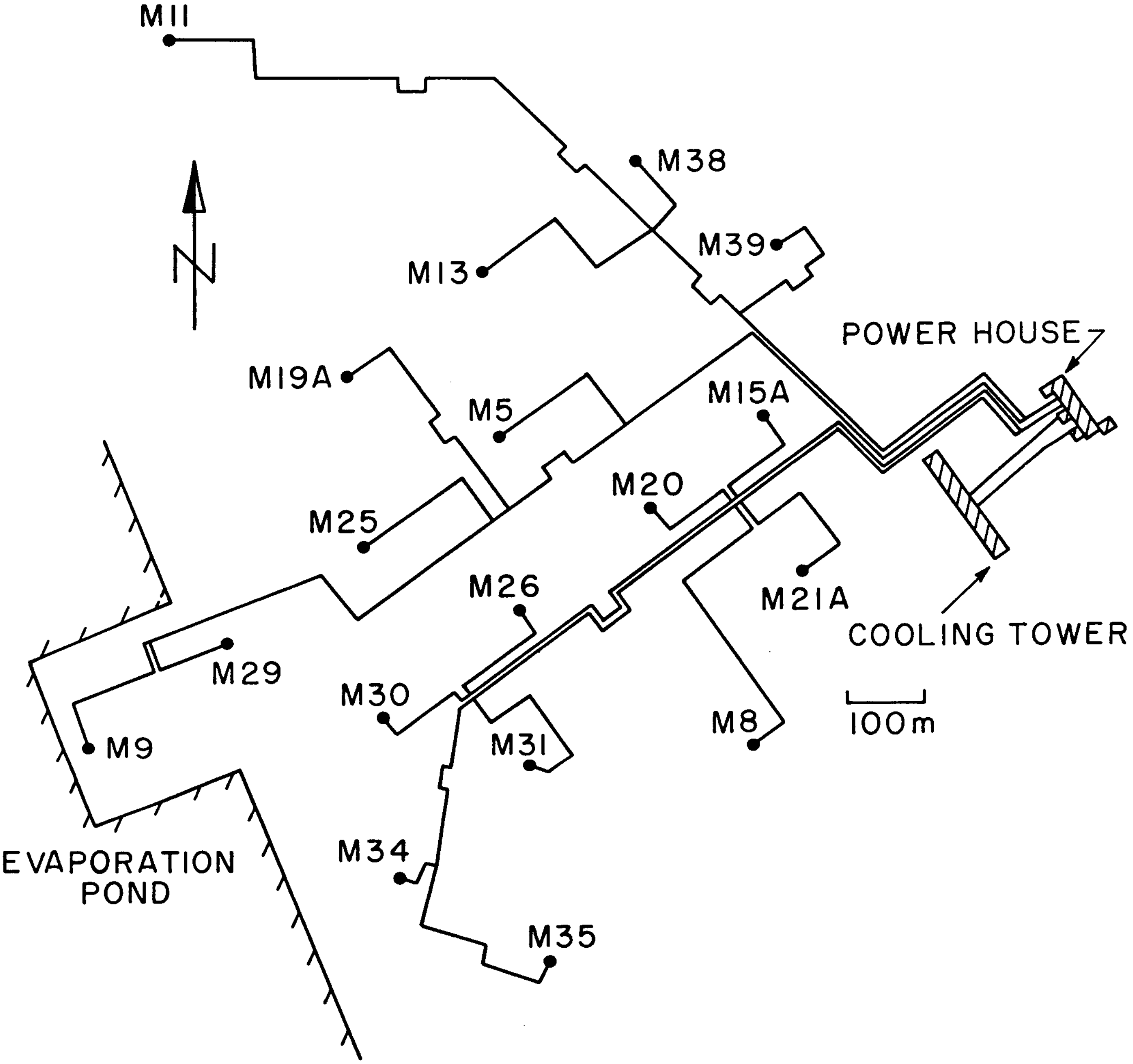


Fig. 5. Steam pipeline gathering system for units No. 1 and 2 at Cerro Prieto [after CFE, 1971; Mercado, 1975(B)].

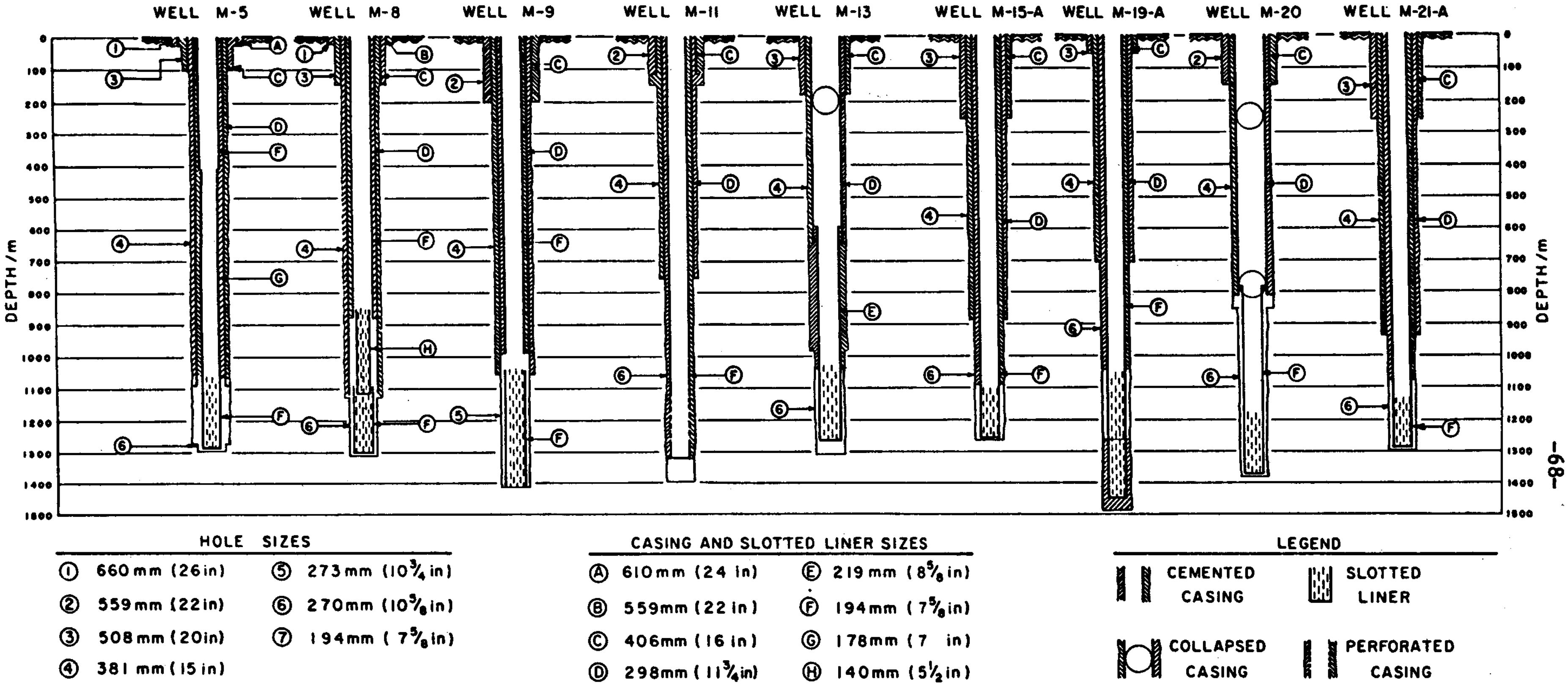


Fig. 6. Well profiles for wells M-5, -8, -9, -11, -13, -15A, -19A, -20, and -21A at Cerro Prieto [after Dominguez and Vital, 1975].

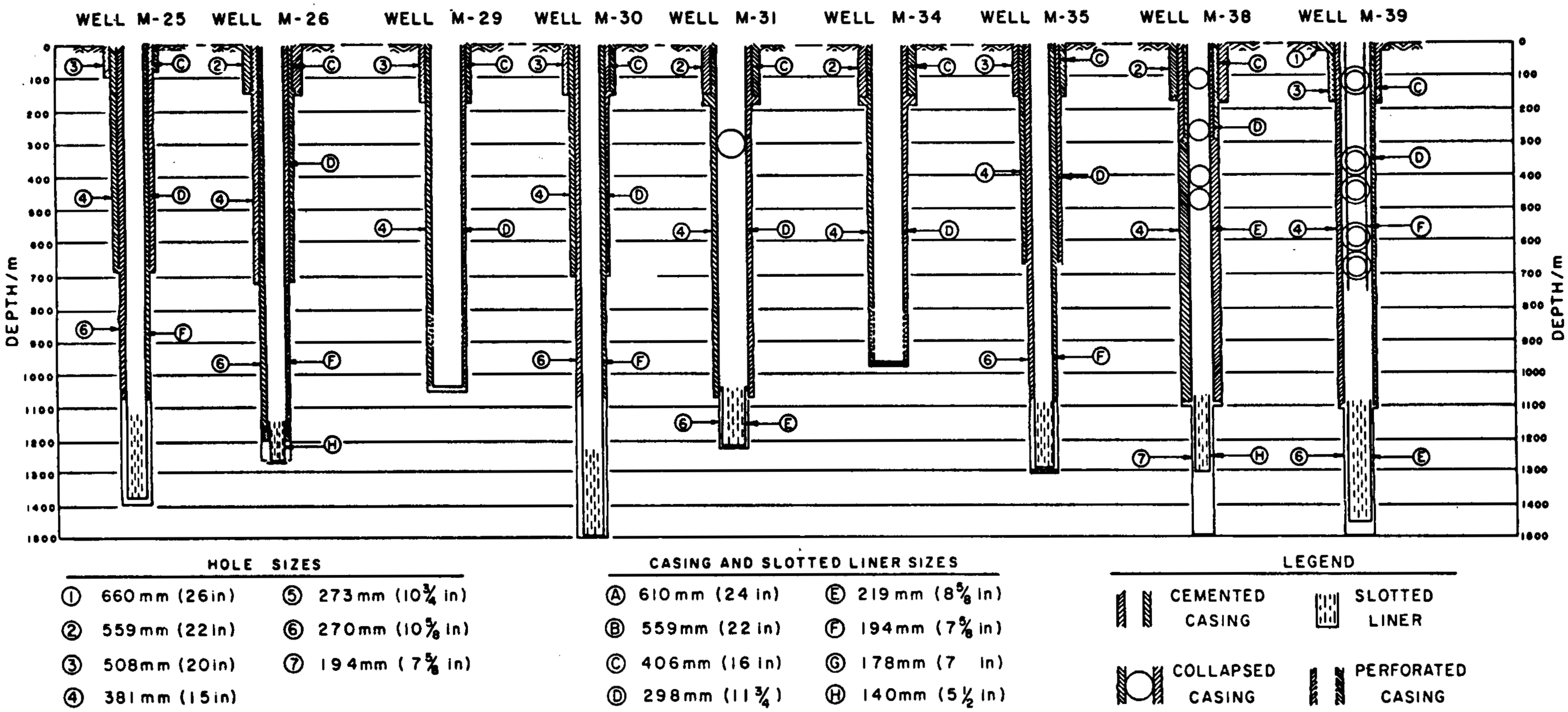


Fig. 7. Well profiles for wells M-25, -26, -29, -30, -31, -34, -35, -38, and -39 at Cerro Prieto [after Dominguez and Vital, 1975].

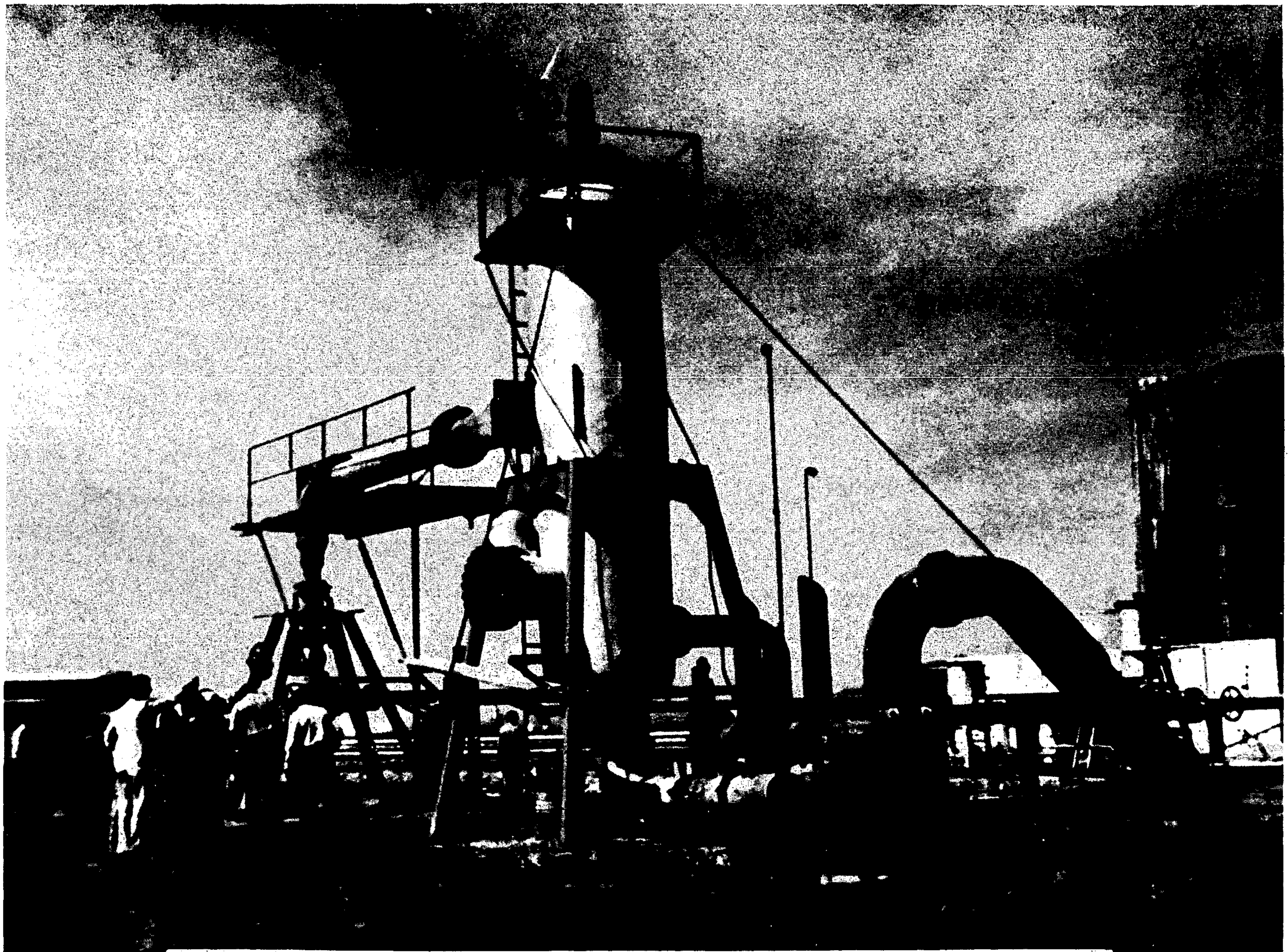


Fig. 8. Well M-8 at Cerro Prieto showing wellhead, separator, ball check valve and twin silencer [photo courtesy of D. J. Ryley].

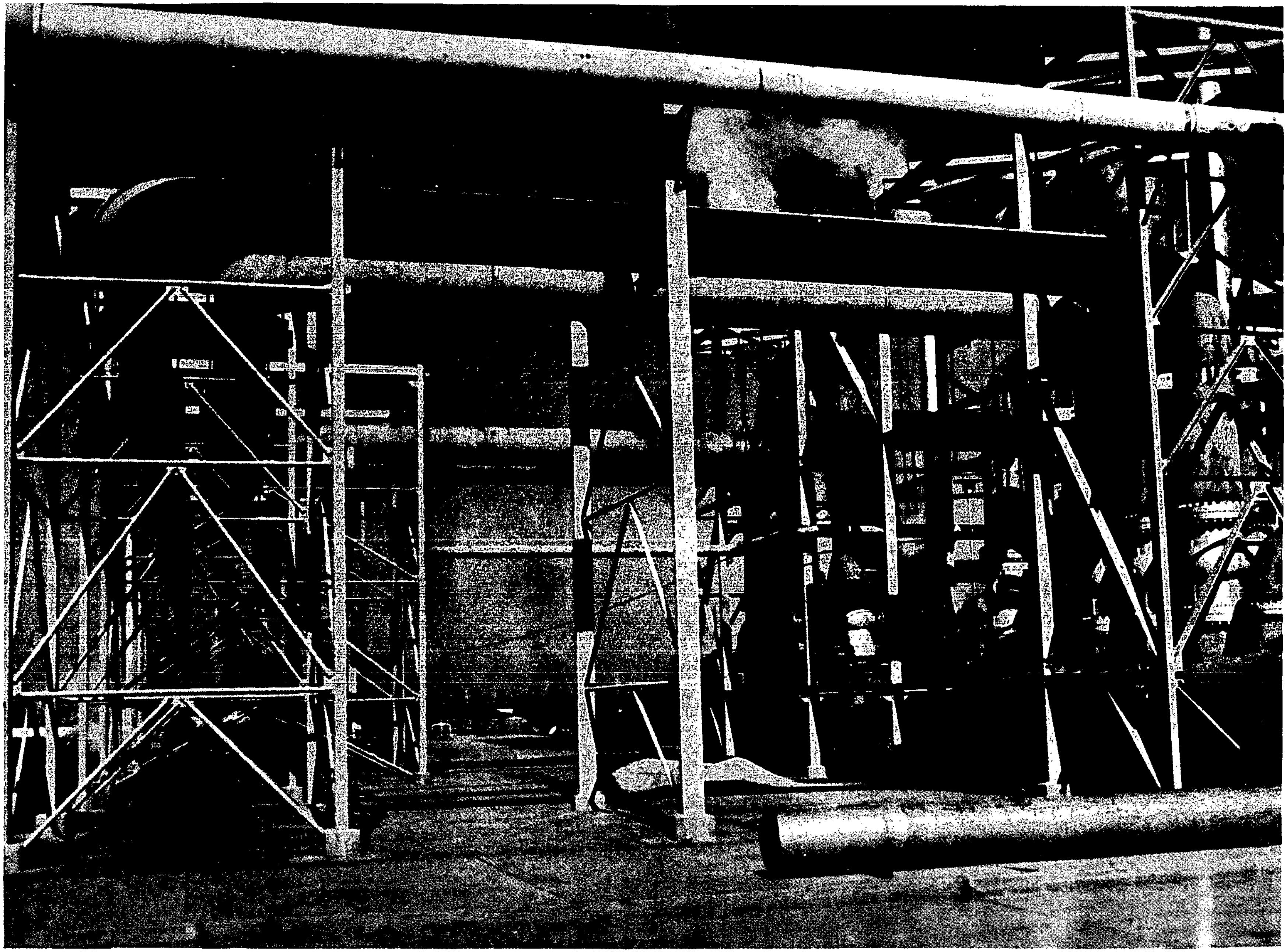


Fig. 9. Steam receivers at Cerro Prieto [photo by R. DiPippo].

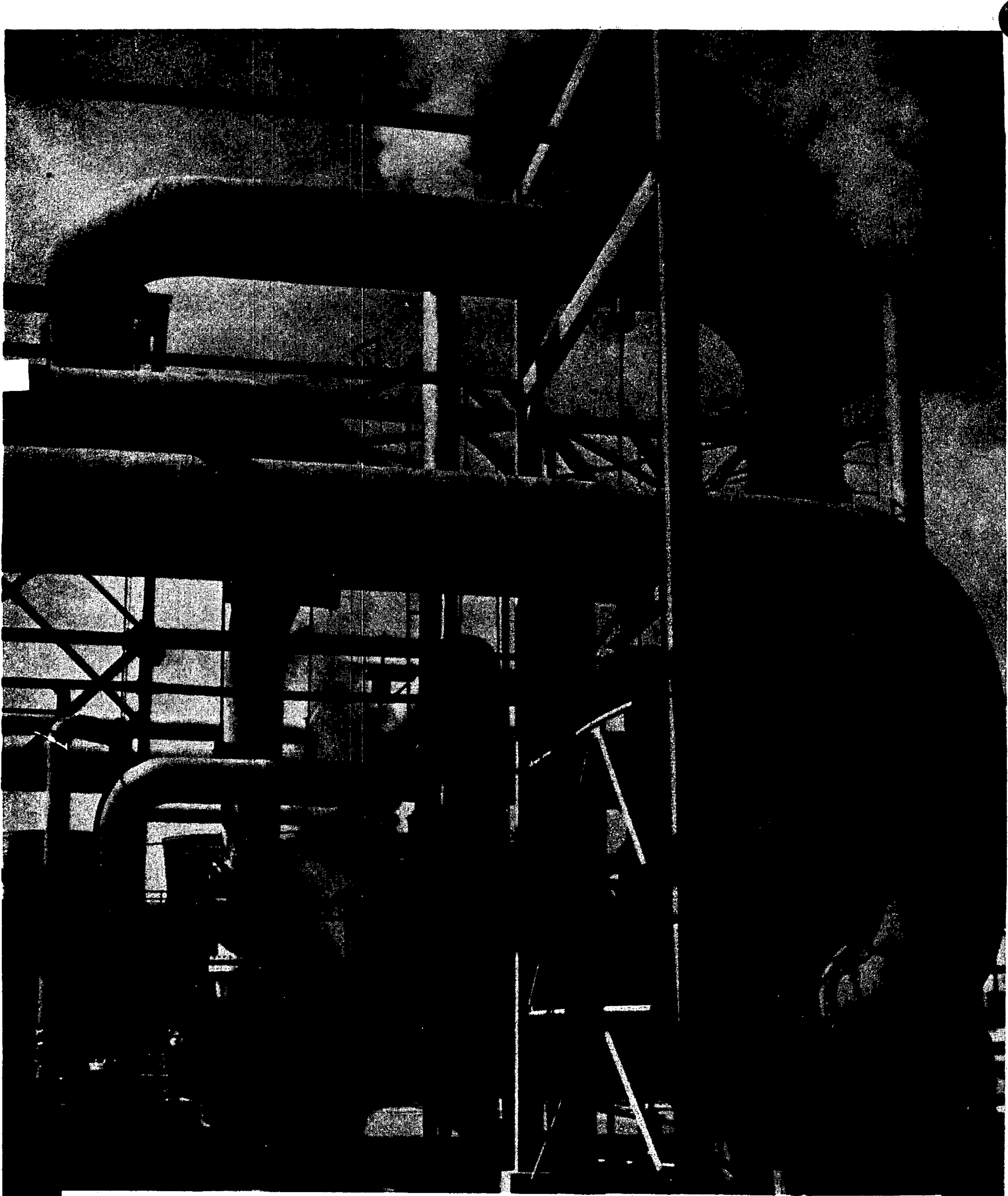


Fig. 10. Final moisture separator at Cerro Prieto [photo by R. DiPippo].

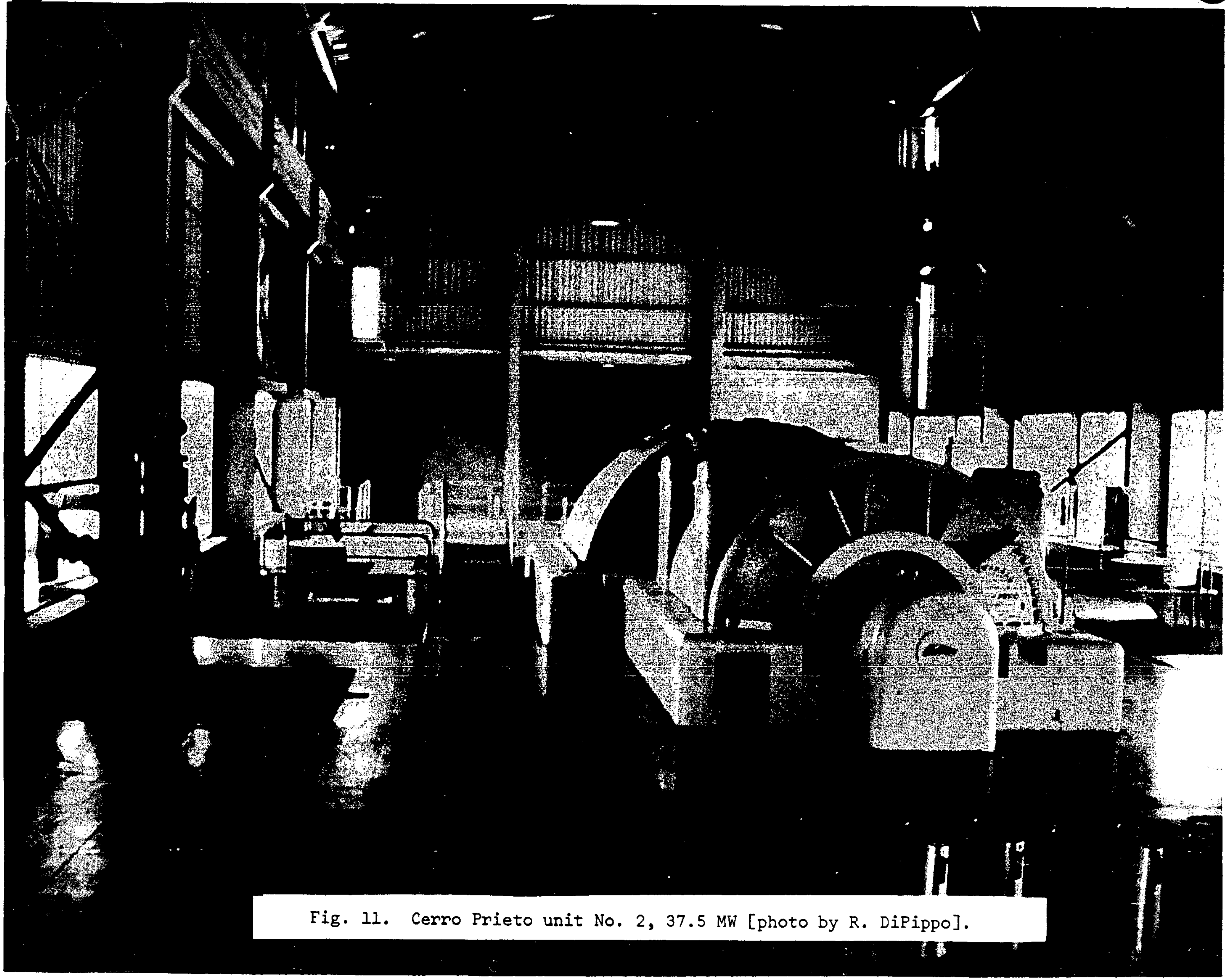


Fig. 11. Cerro Prieto unit No. 2, 37.5 MW [photo by R. DiPippo].

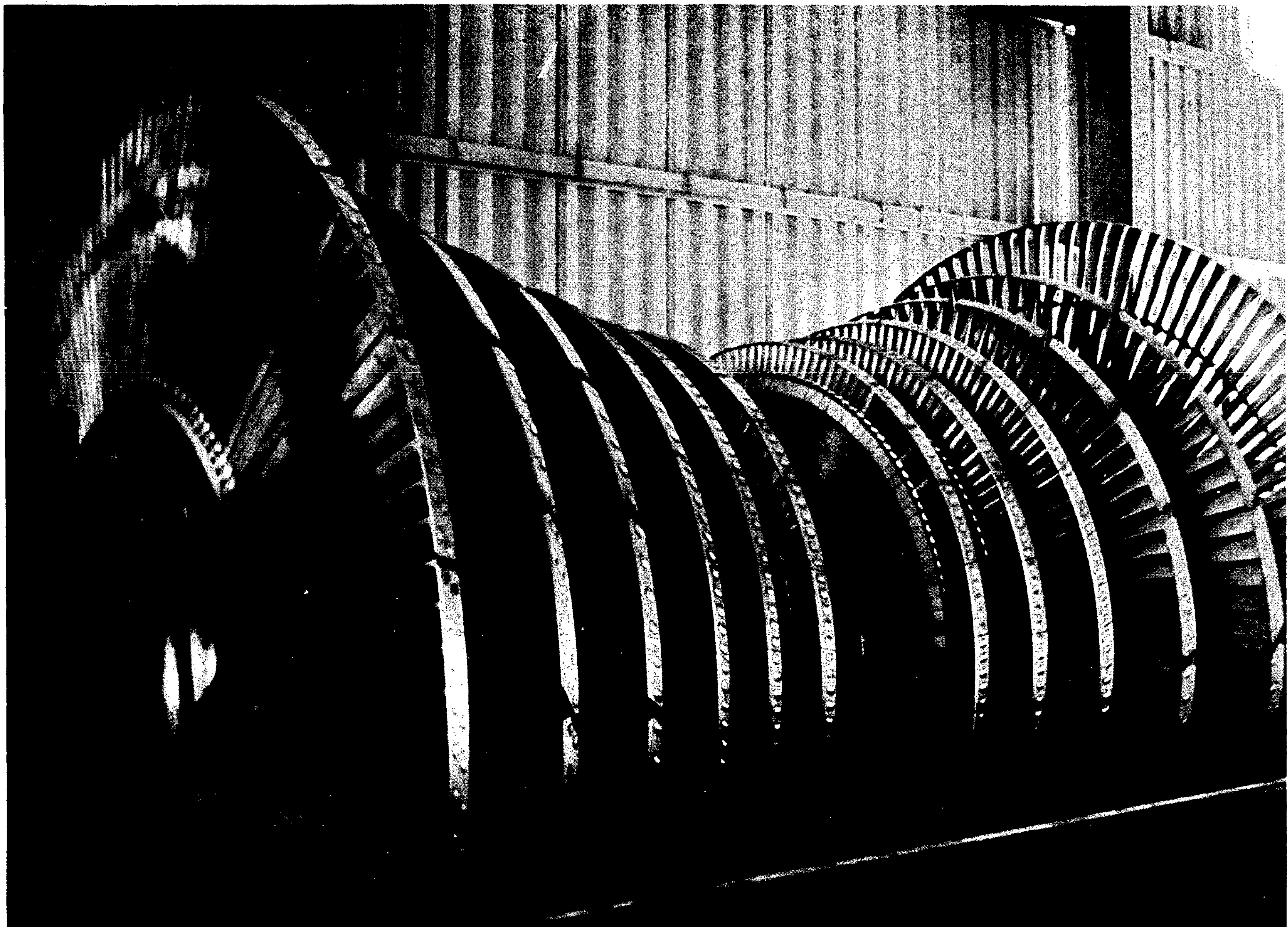


Fig. 12. Spare 6 x 2 impulse-reaction turbine spool, Cerro Prieto [photo by R. DiPippo].

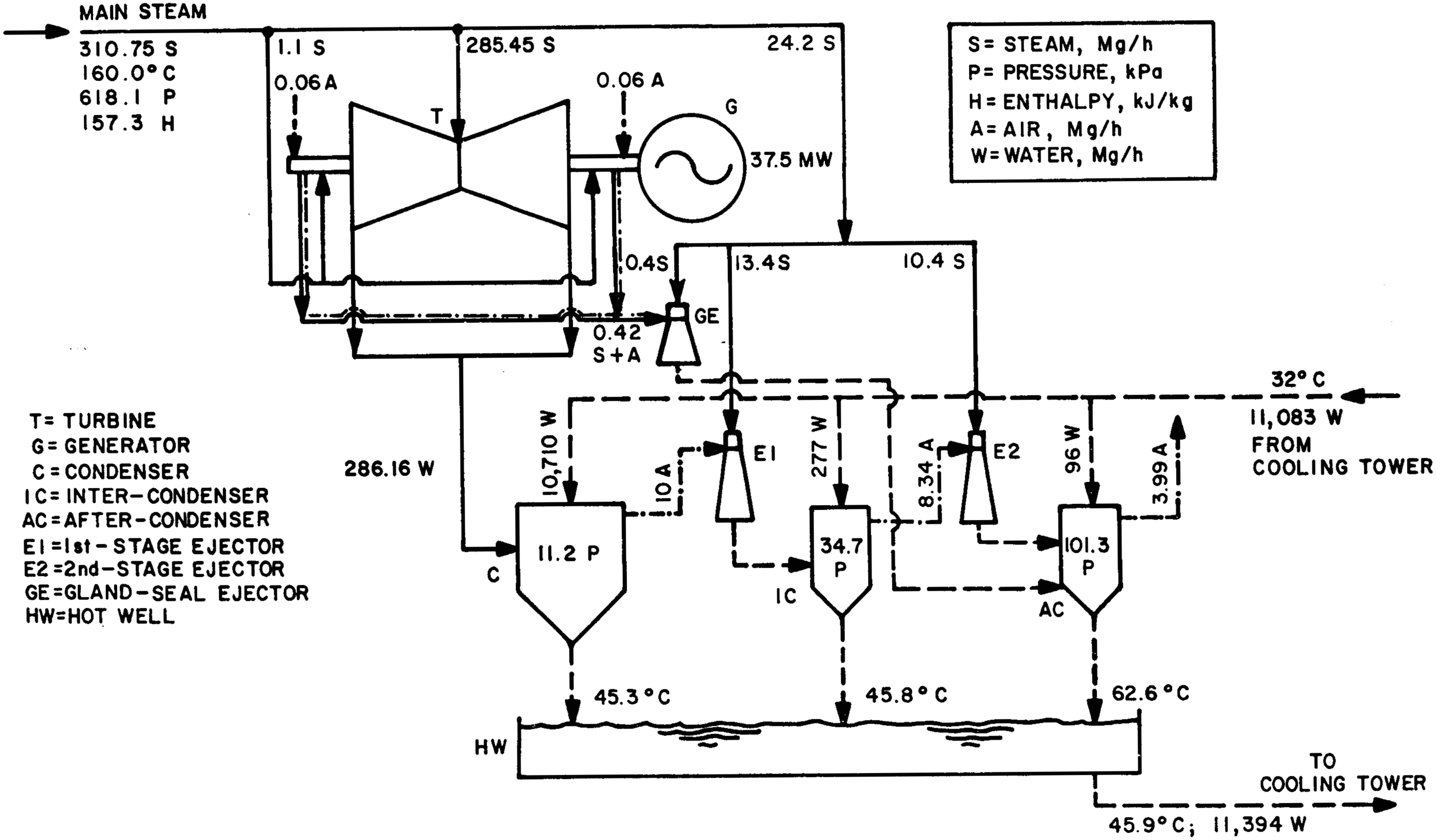


Fig. 13. Simplified flow diagram for energy conversion system for each unit at Cerro Prieto [after Akiba, 1970; Mercado, 1976].

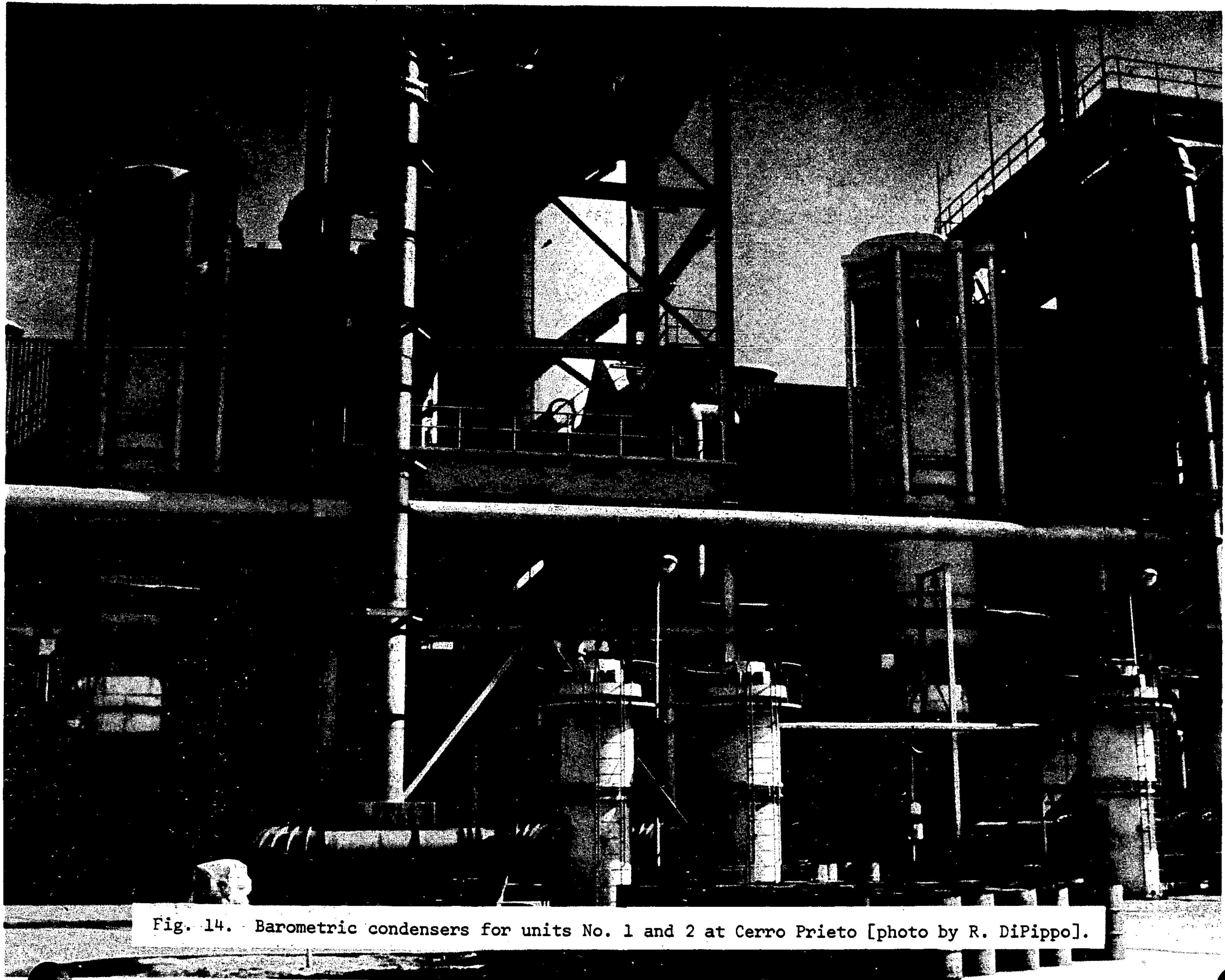


Fig. 14. Barometric condensers for units No. 1 and 2 at Cerro Prieto [photo by R. DiPippo].

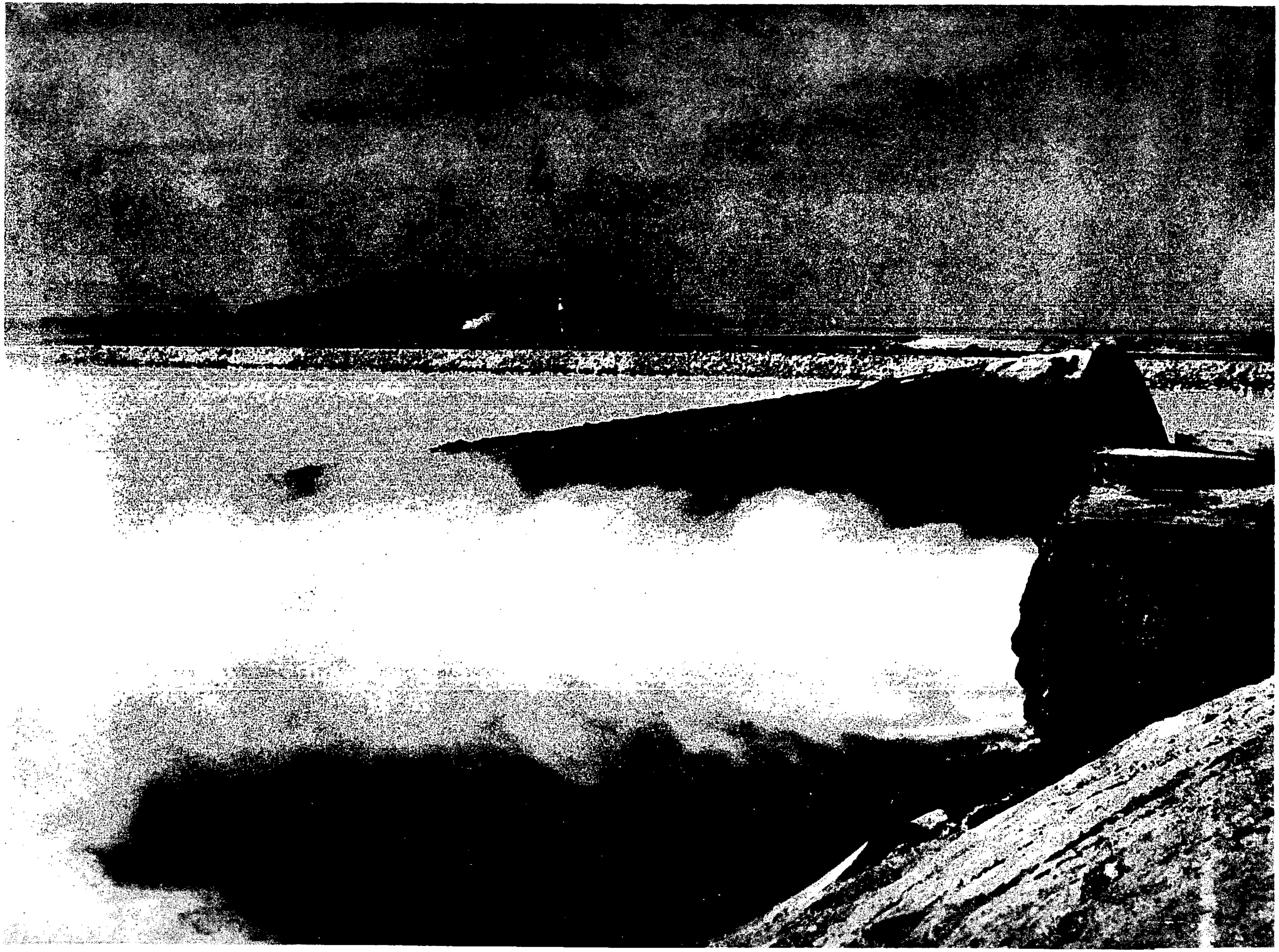


Fig. 15. Discharge of waste liquid into evaporation pond, with wellhead M-9 in background and volcano Cerro Prieto on the horizon [photo by R. DiPippo].

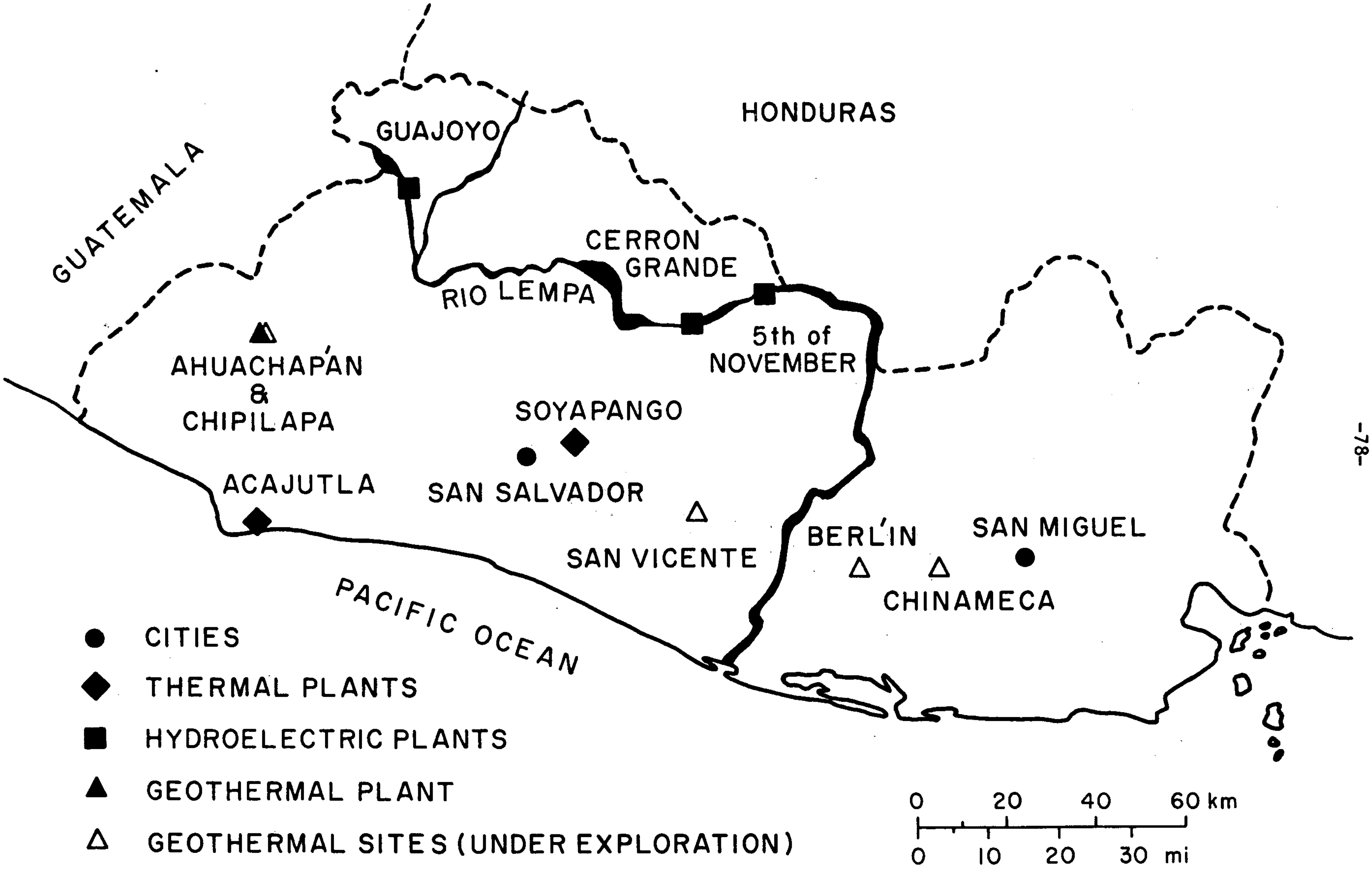


Fig. 16. Map of El Salvador showing geothermal sites and existing power plants [after CEL, 1976].

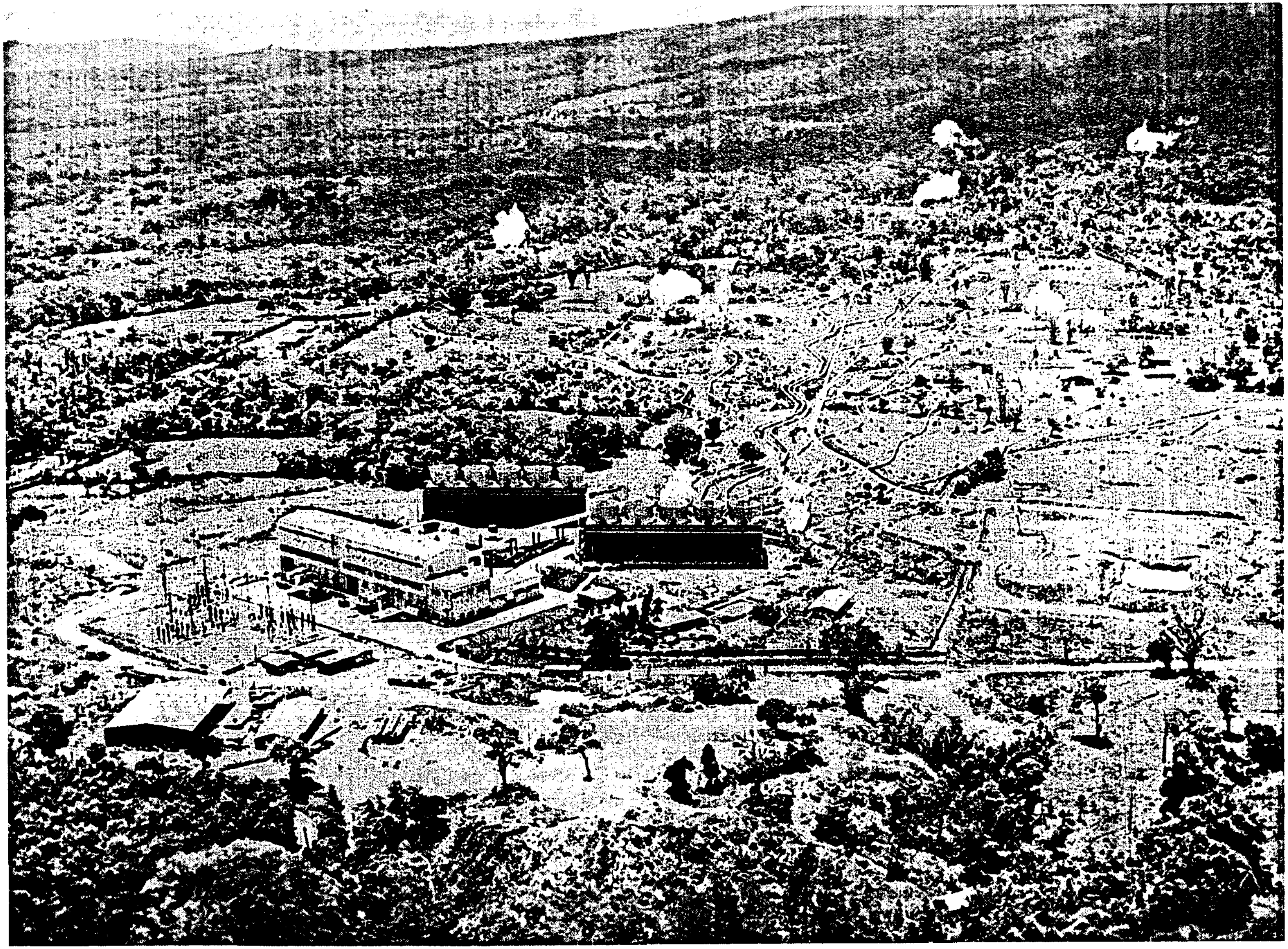


Fig. 17. The Ahuachapán 60 MW geothermal power plant and borefield [CEL, 1976].

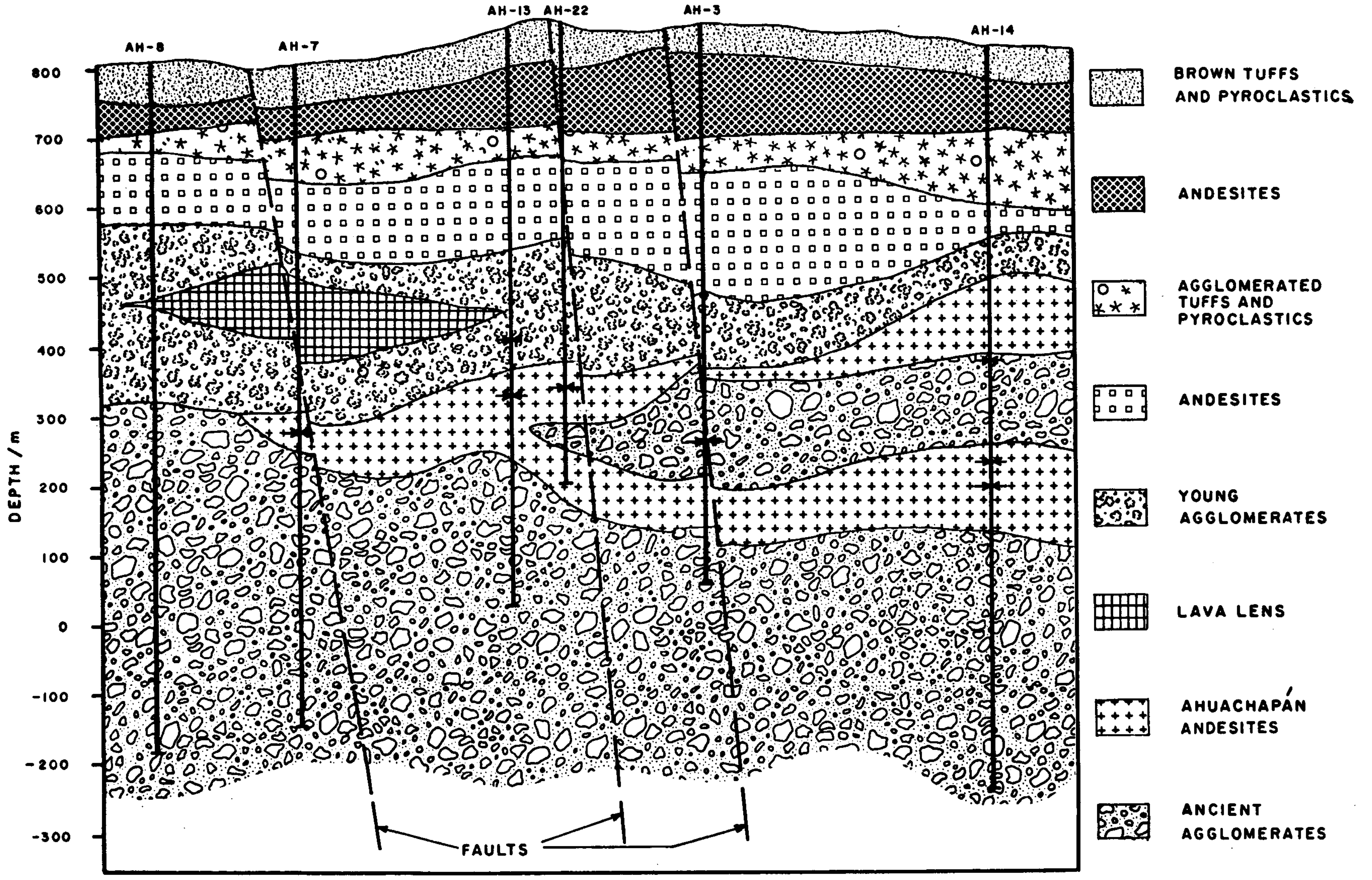


Fig. 18. Geologic cross-section through Ahuachapán: west-east elevation, looking north [Cuéllar, 1978].

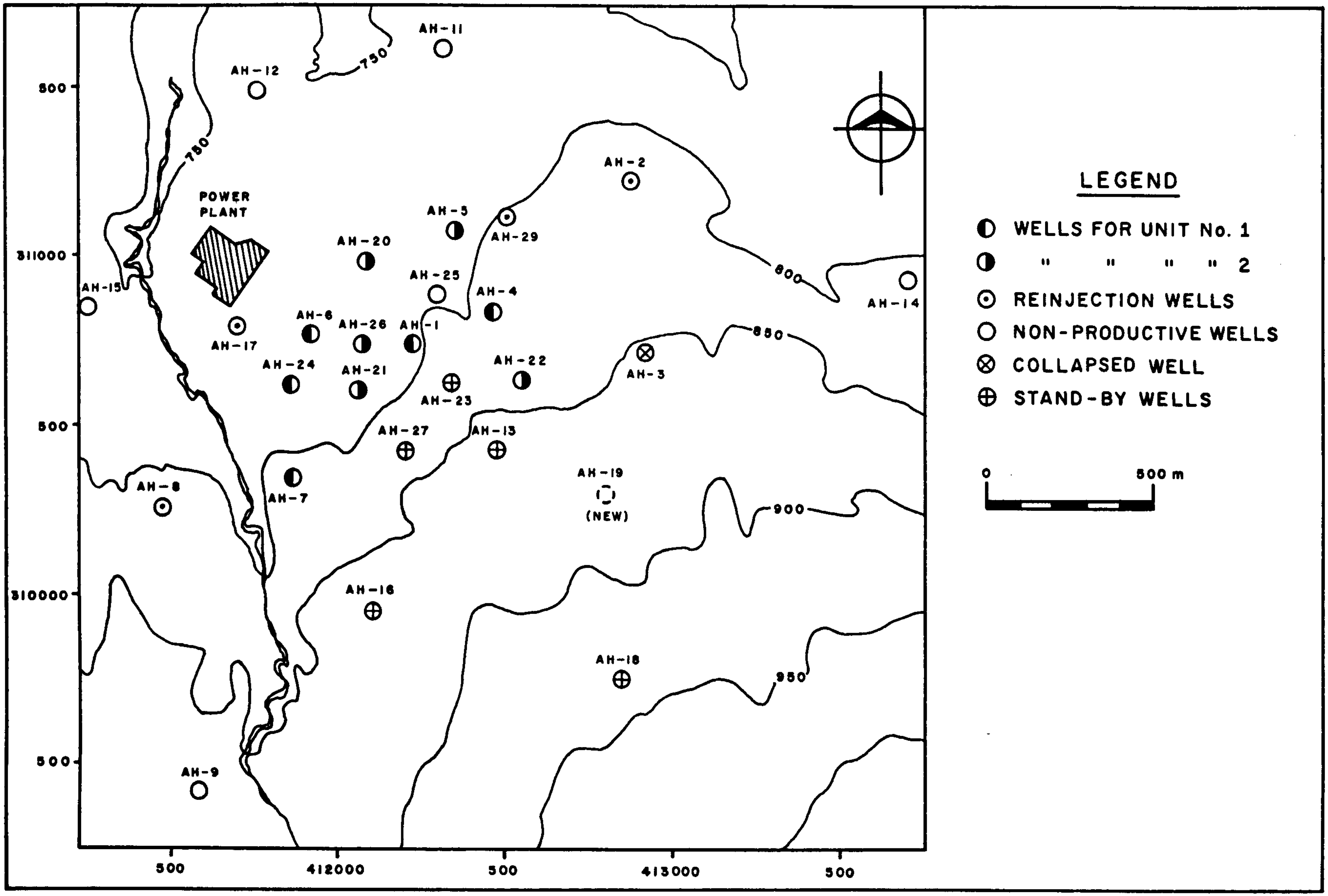


Fig. 19. Well arrangement at Ahuachapán geothermal field [Cuéllar, 1978].

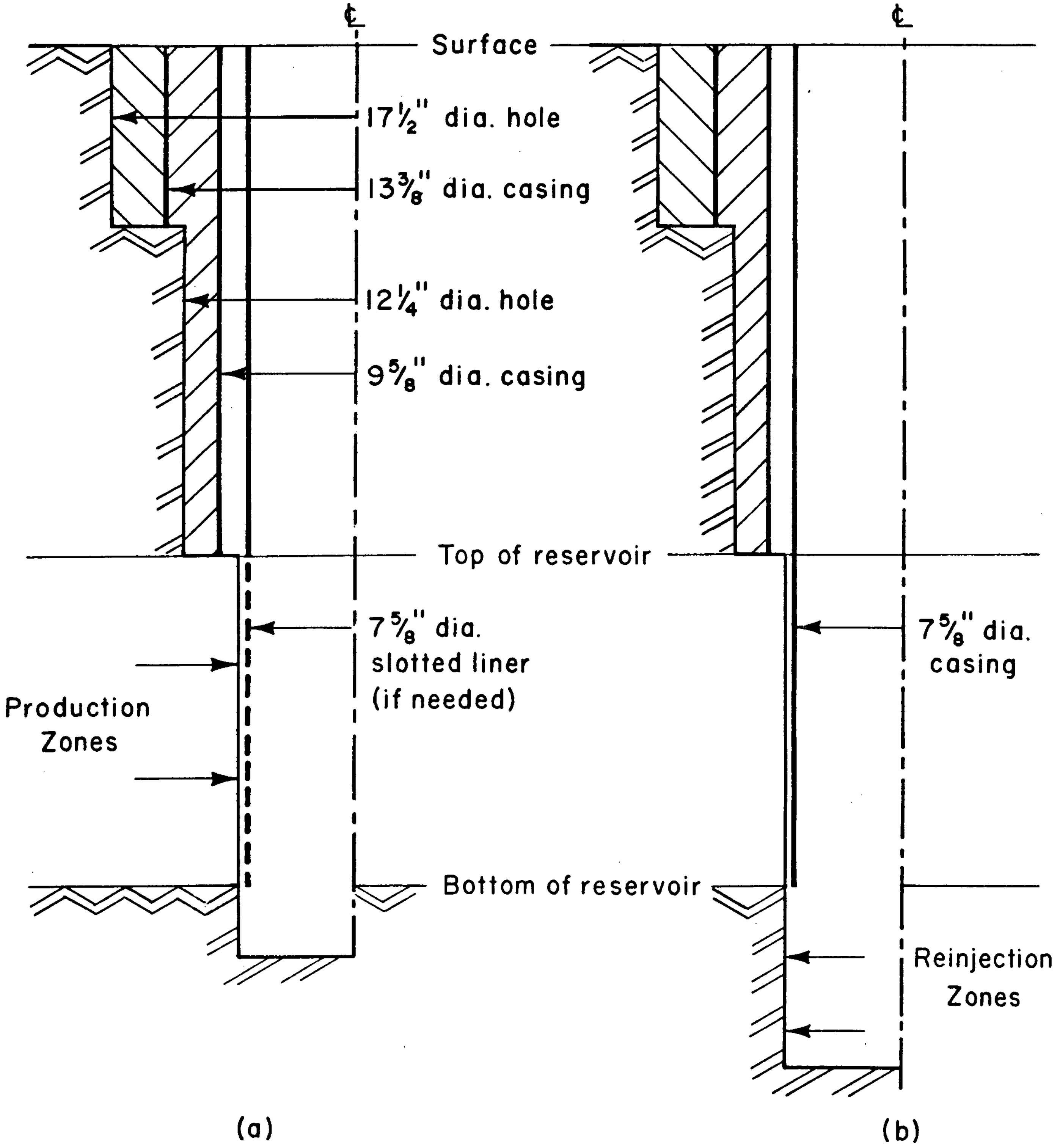


Fig. 20. Typical well casing programs for (a) production and (b) reinjection wells at Ahuachapán.

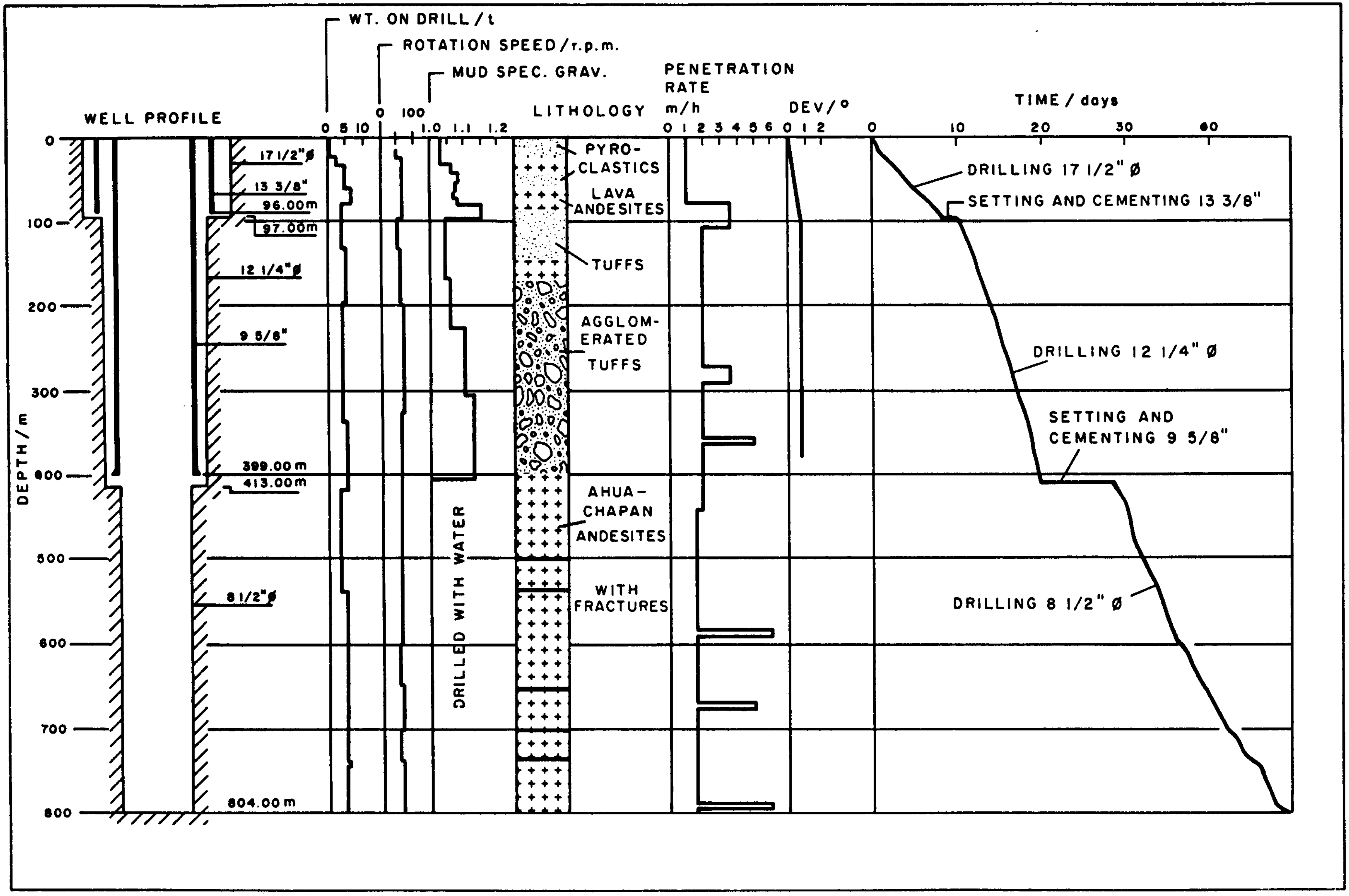


Fig. 21. Drilling program for well AH-26 at Ahuachapán [Cuéllar, 1978].

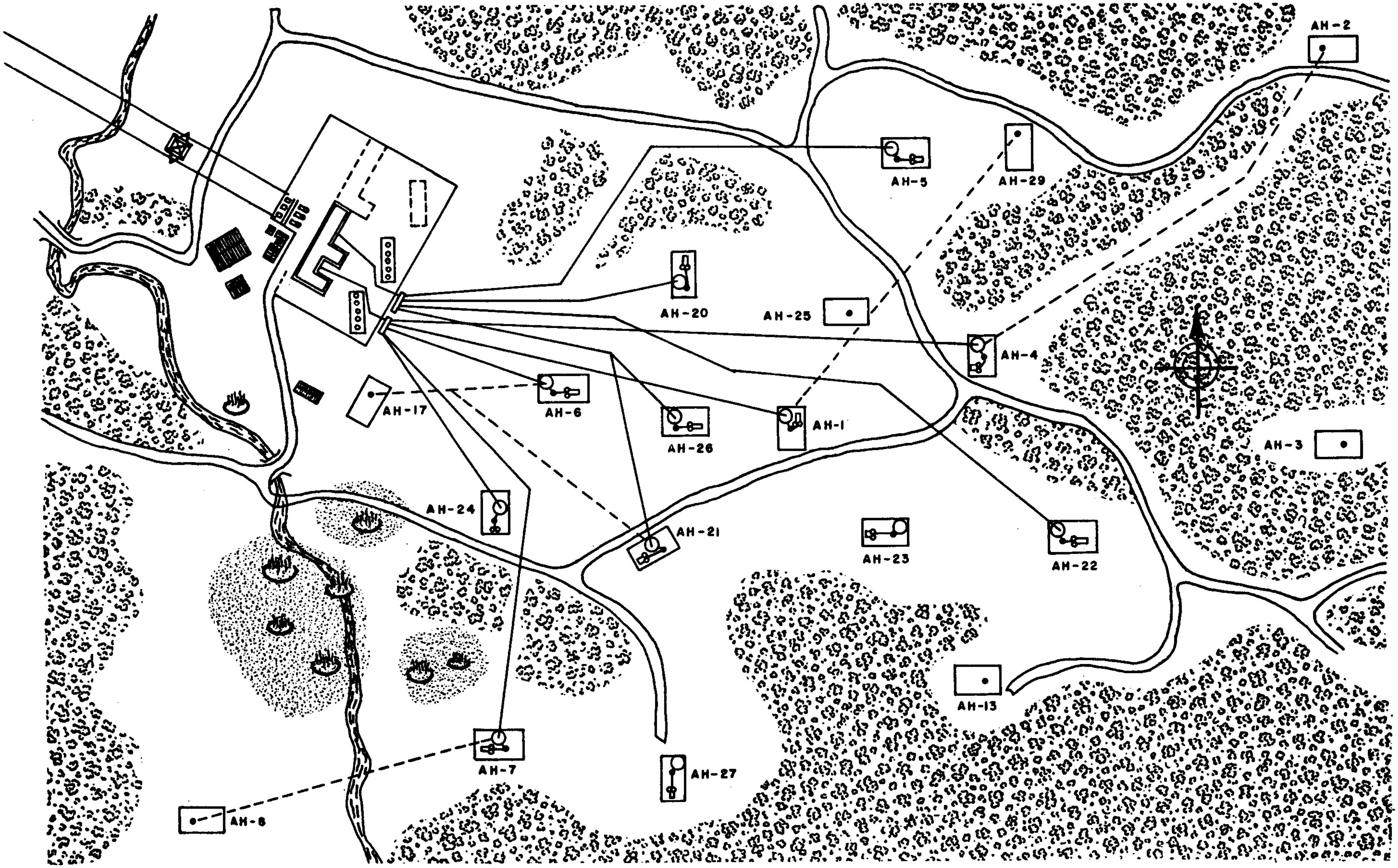


Fig. 22. Layout of production and reinjection wells for units No. 1 and 2 at Ahuachapán [Cuéllar, 1978].

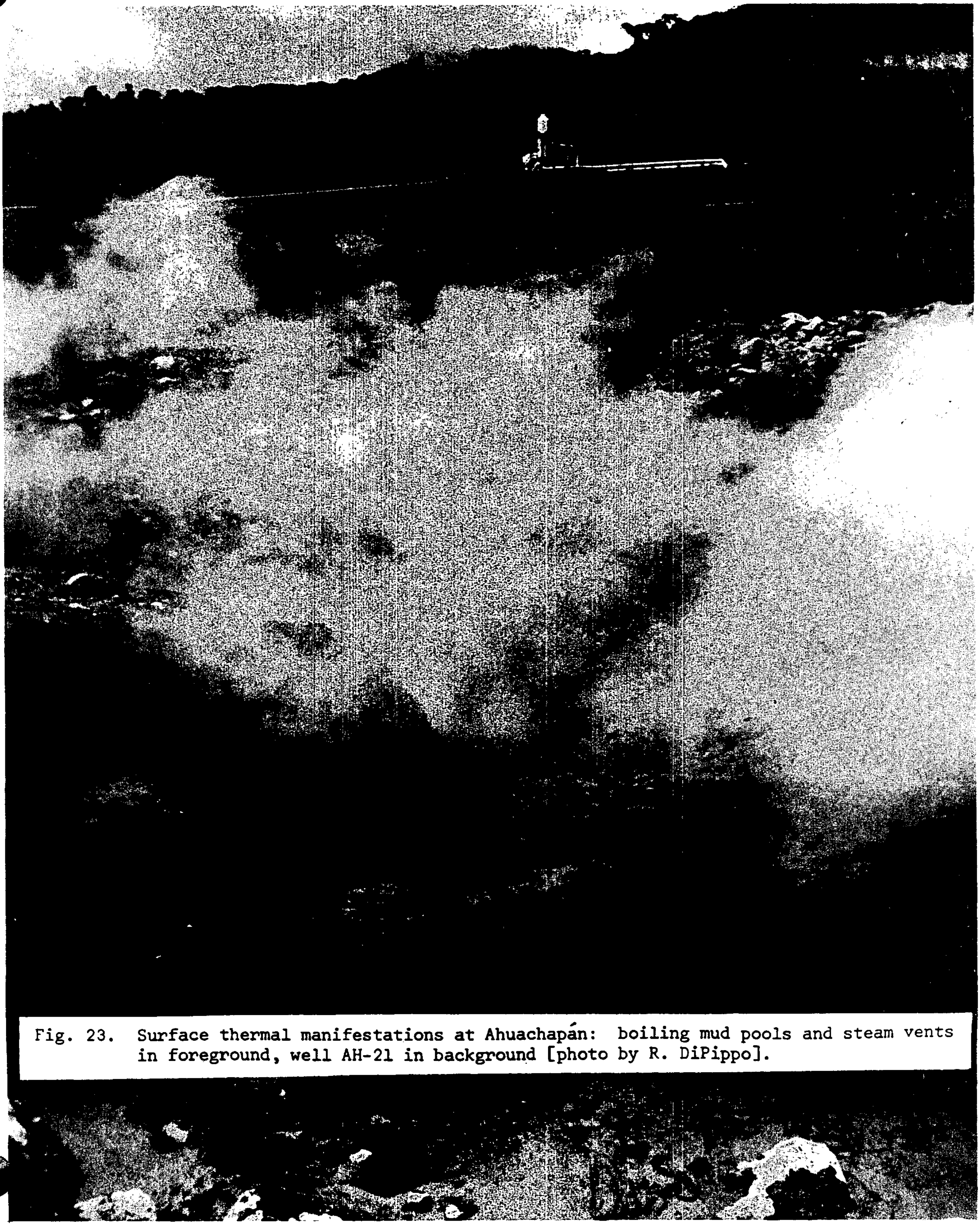
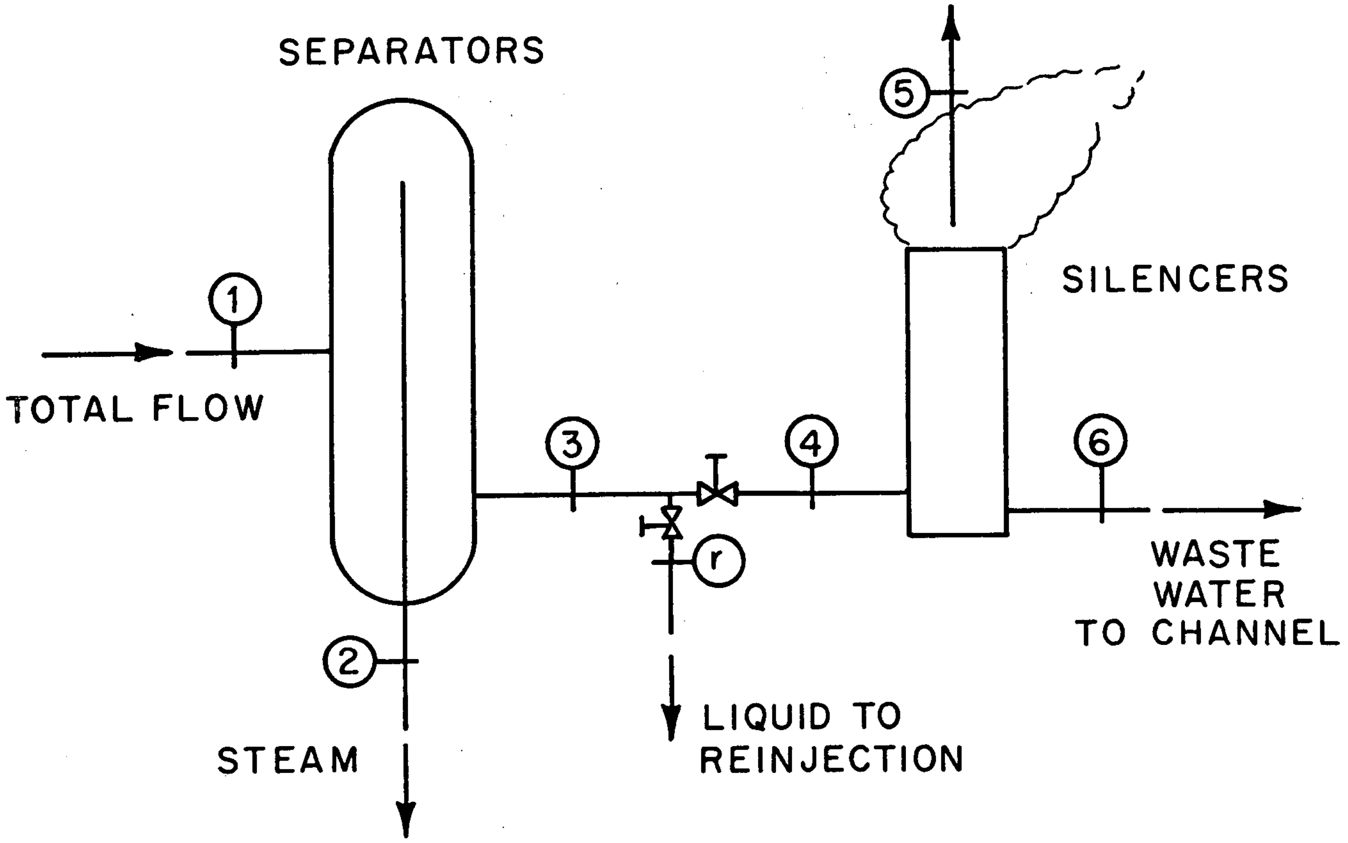


Fig. 23. Surface thermal manifestations at Ahuachapán: boiling mud pools and steam vents in foreground, well AH-21 in background [photo by R. DiPippo].



WHEN REINJECTION TAKES PLACE	
①	726.33 kg/s
②	126.77
③	599.56
ⓡ	368.8
④	230.76
⑤	23.08
⑥	217.68

WHEN NO REINJECTION TAKES PLACE	
①	726.33 kg/s
②	126.77
③	599.56
ⓡ	0.00
④	599.56
⑤	46.56
⑥	553.00

Fig. 24. Overall mass balance for ten wells serving units No. 1 and 2 at Ahuachapán.

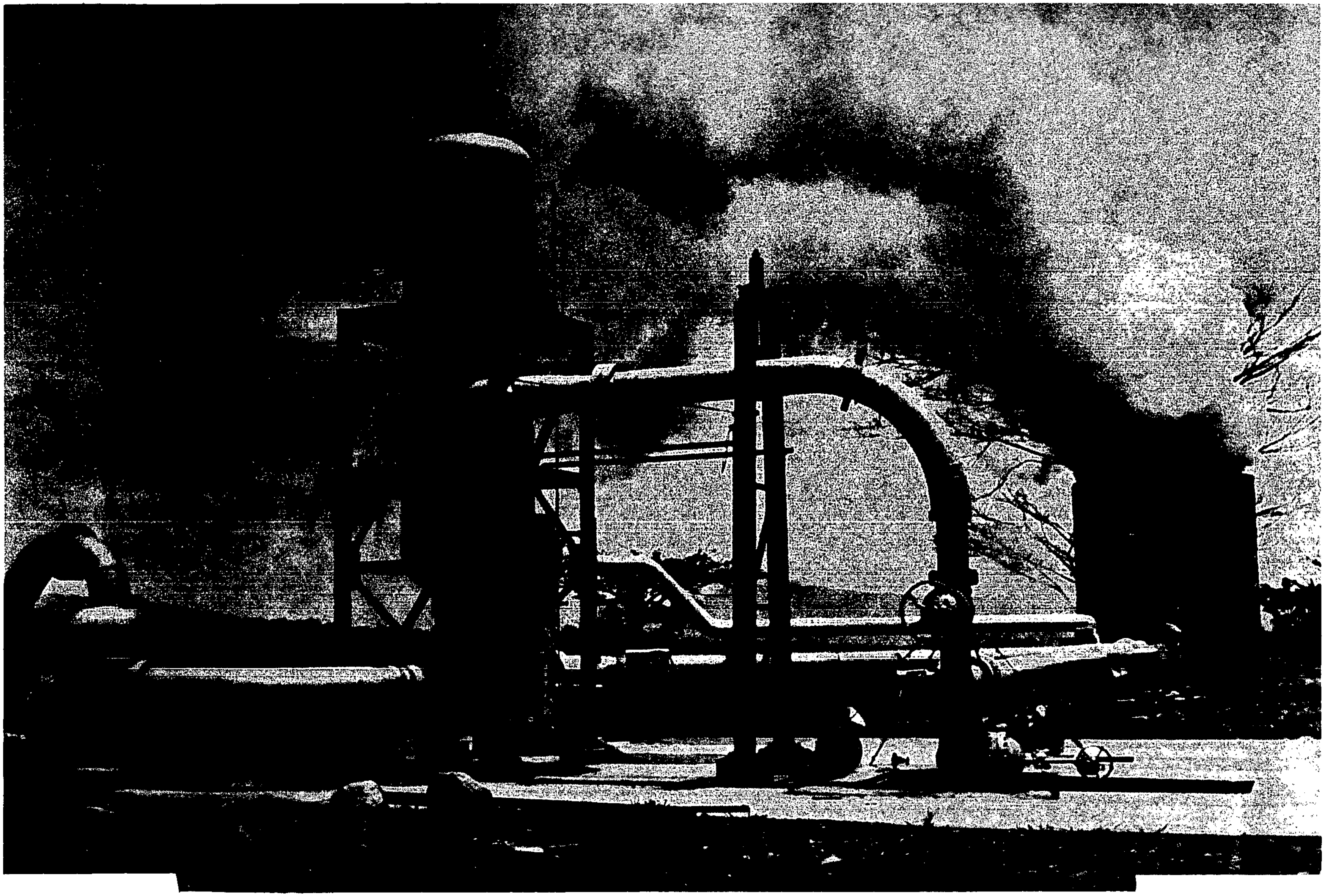


Fig. 25. Wellhead equipment for well AH-20 at Ahuachapán [photo by R. DiPippo].

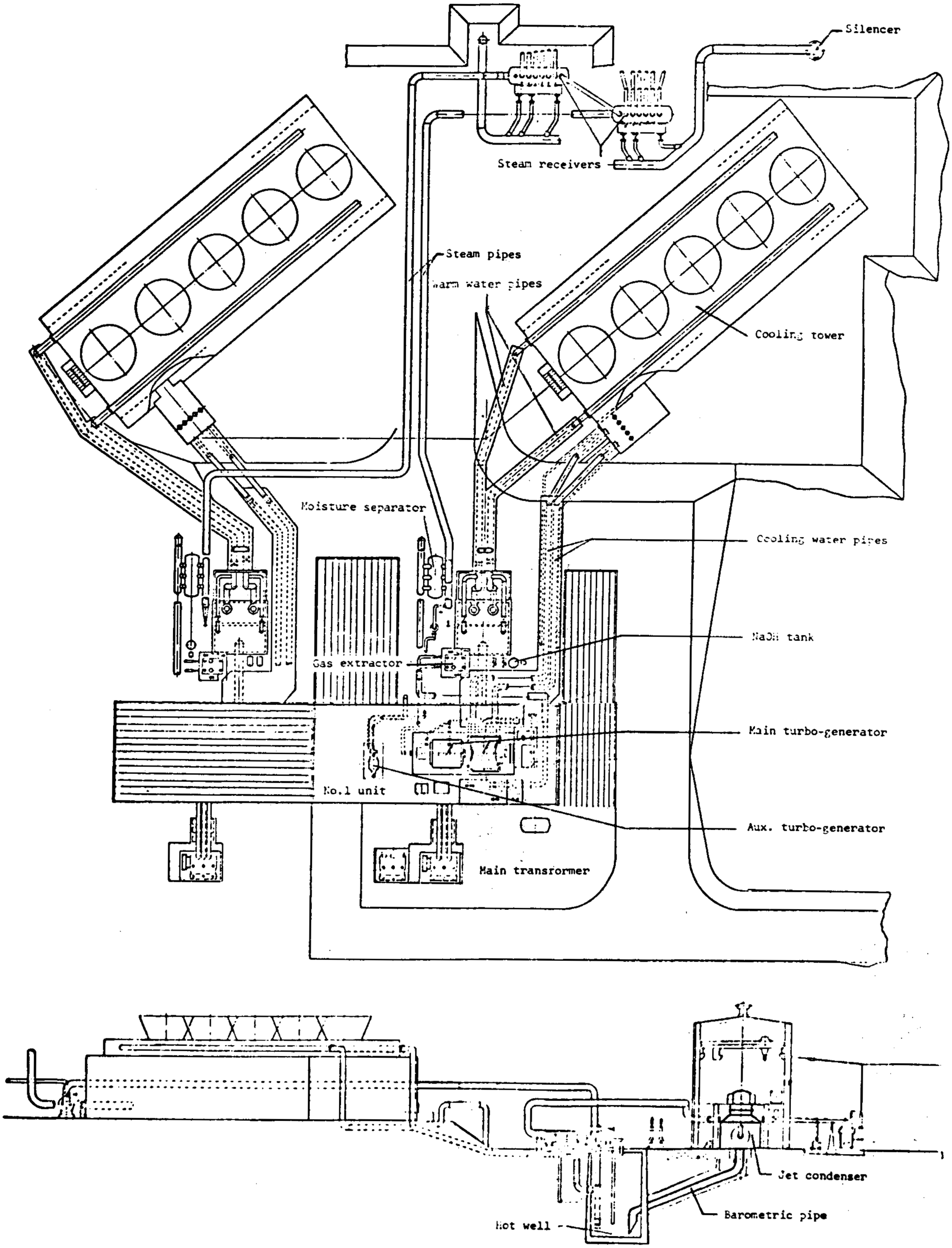


Fig. 26. Power plant site arrangement: Ahuachapán units No. 1 and 2 [MHI, 1977].

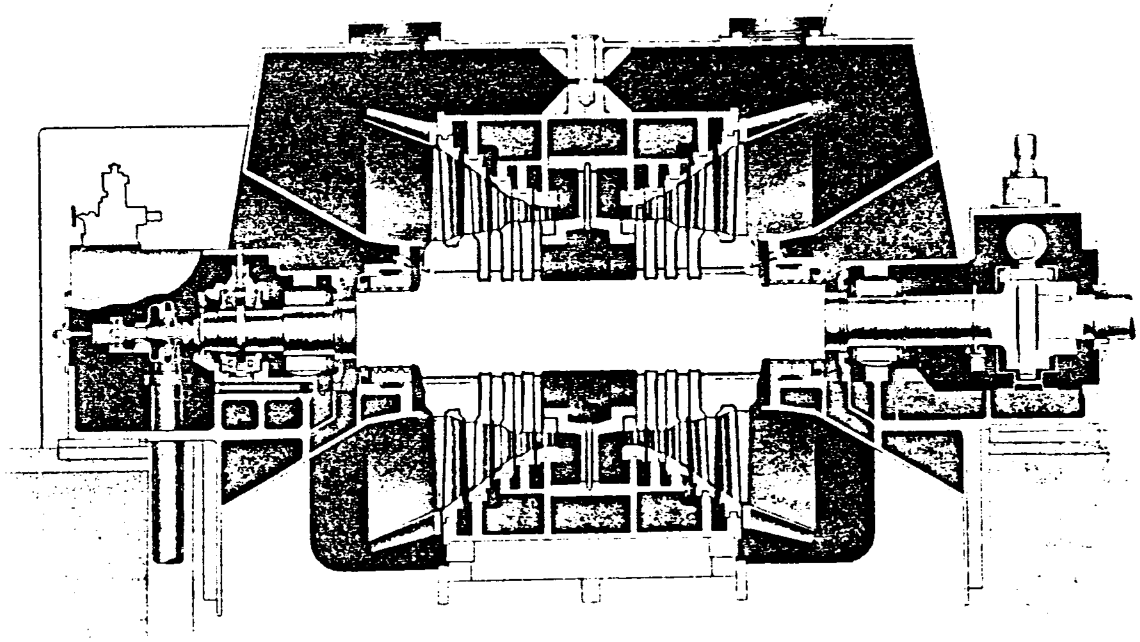


Fig. 27. Cross-section of turbine for units No. 1 and 2 at Ahuachapán [MHI, 1977].

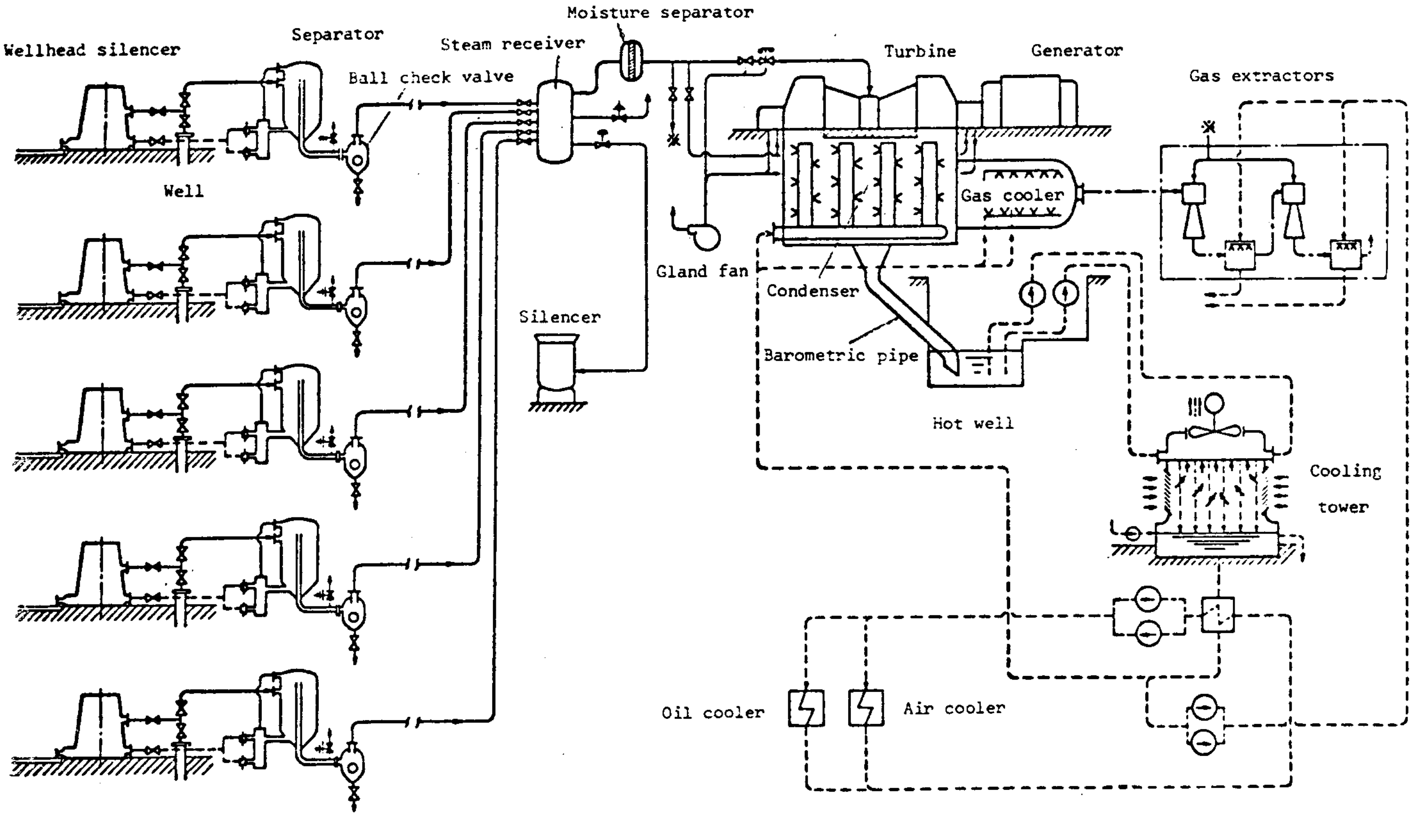


Fig. 28. Flow diagram for units No. 1 and 2 at Ahuachapán [after MHI, 1977].

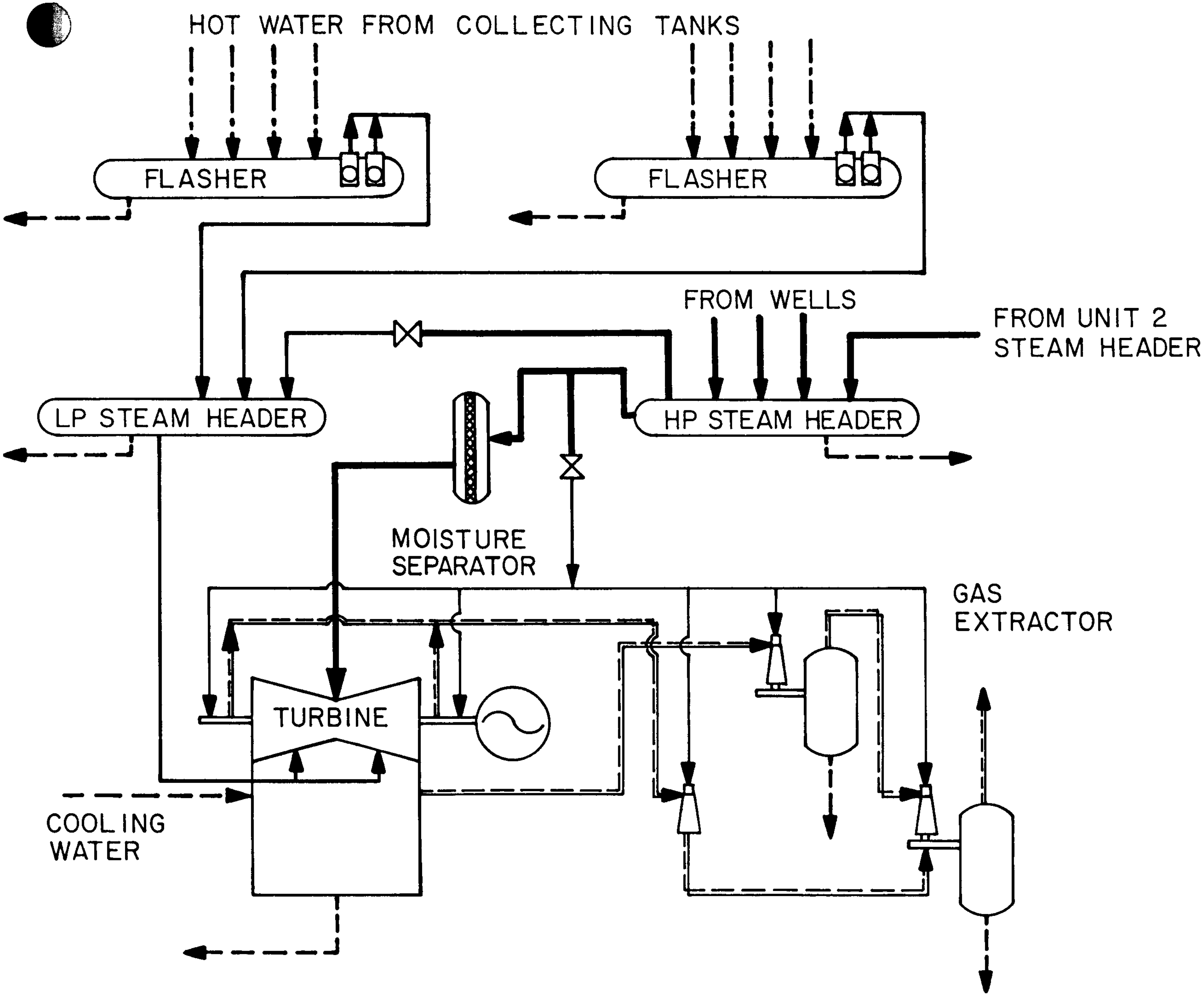


Fig. 29. Simplified flow diagram for unit No. 3 at Ahuachapán [after Fuji, 1977 (PL 311188)].

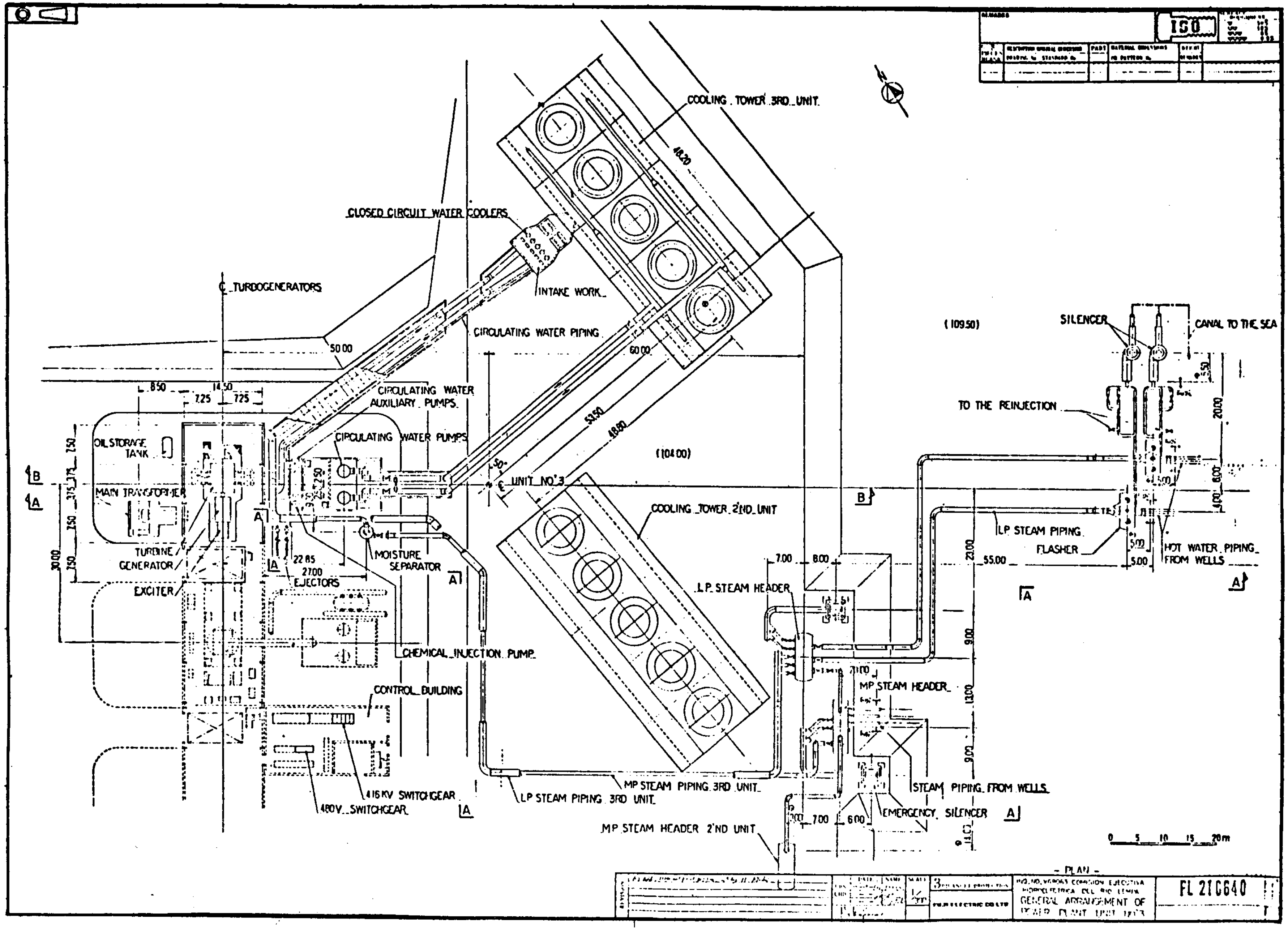


Fig. 30. General arrangement for unit No. 3 at Ahuachapán [Fuji, 1977 (PL 210640)].

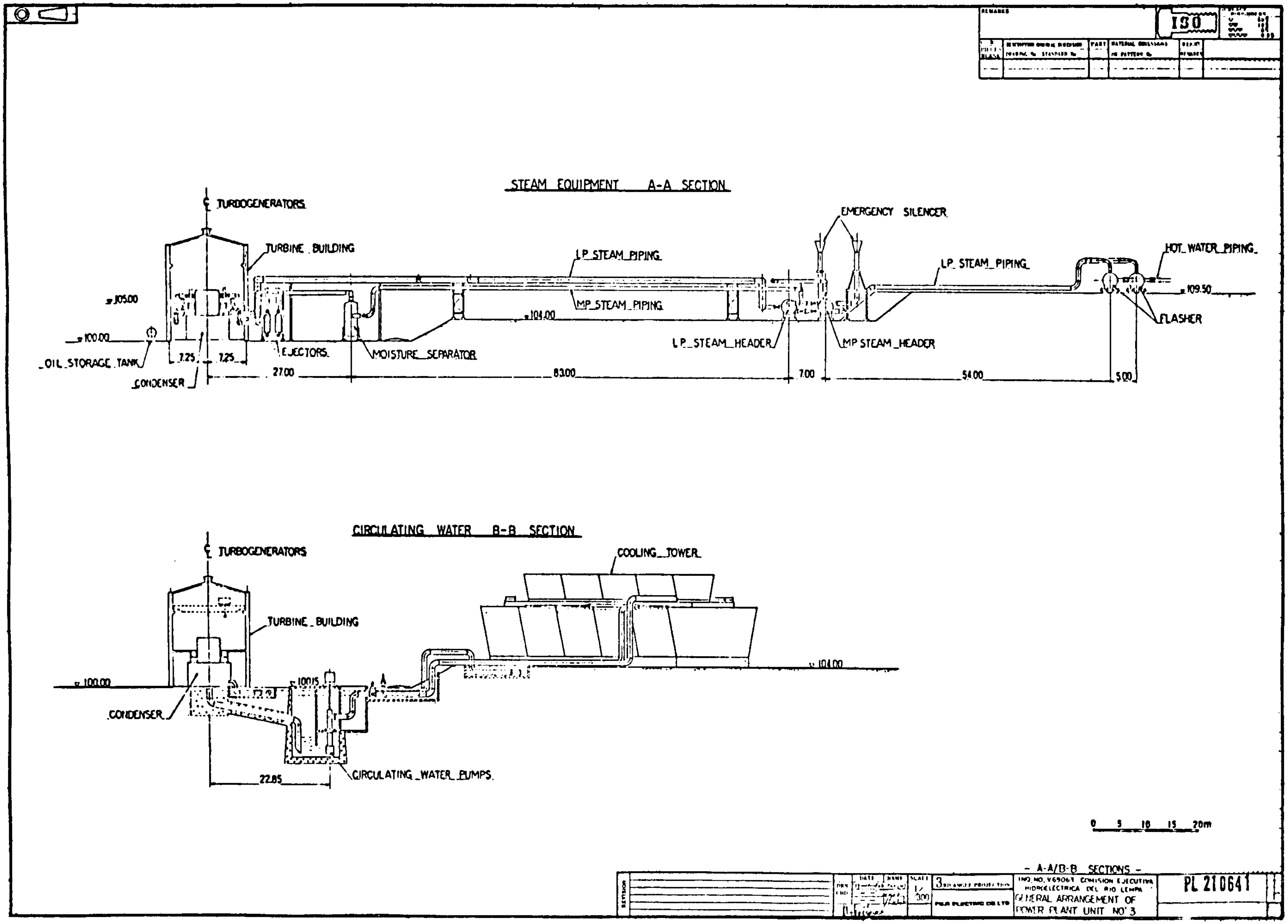


Fig. 31. Elevation views of unit No. 3 at Ahuachapán [Fuji, 1977 (PL 210641)].

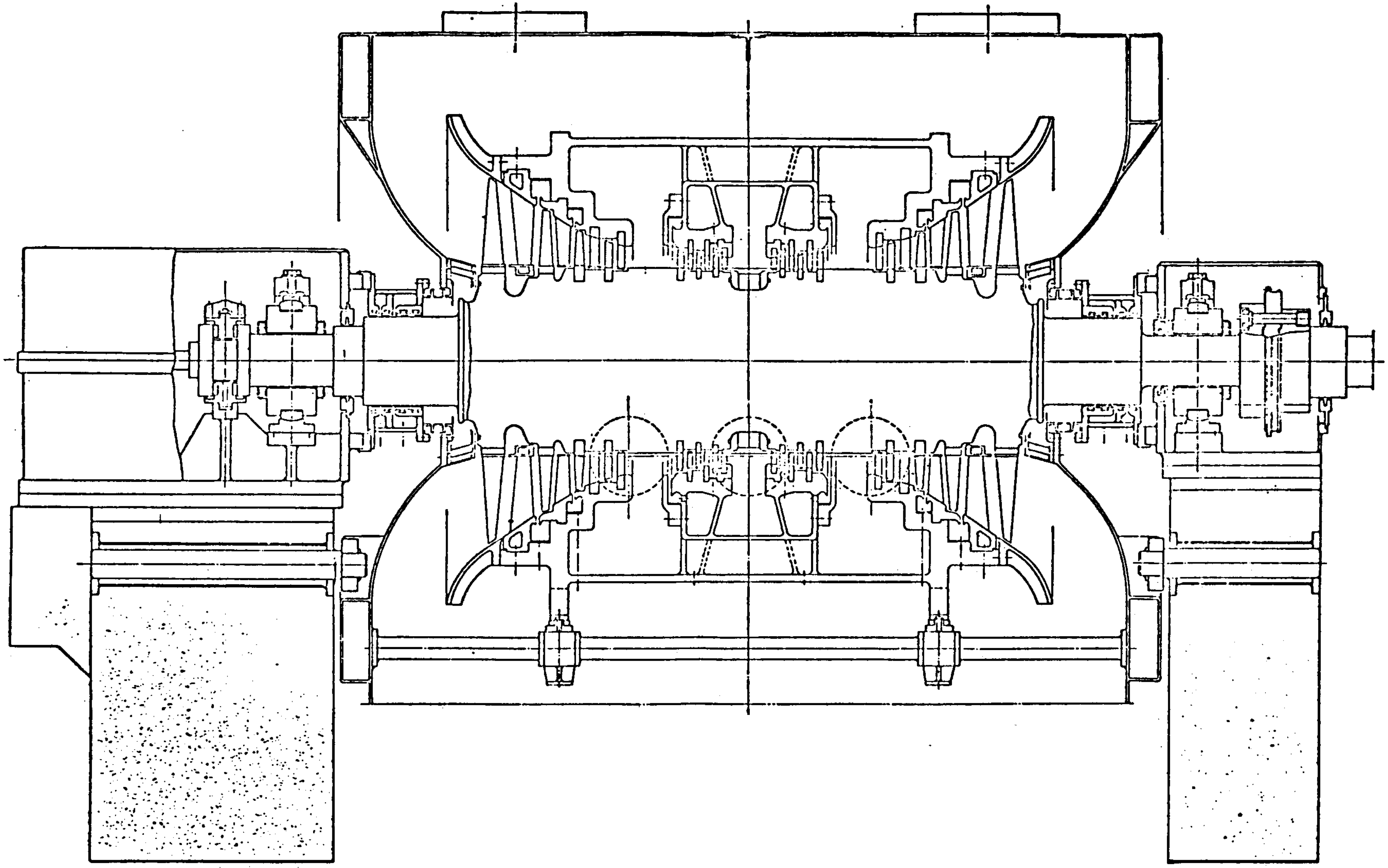


Fig. 32. Cross-section of dual-pressure turbine for unit No. 3 at Ahuachapán [Fuji, 1977 (ST 418390)].

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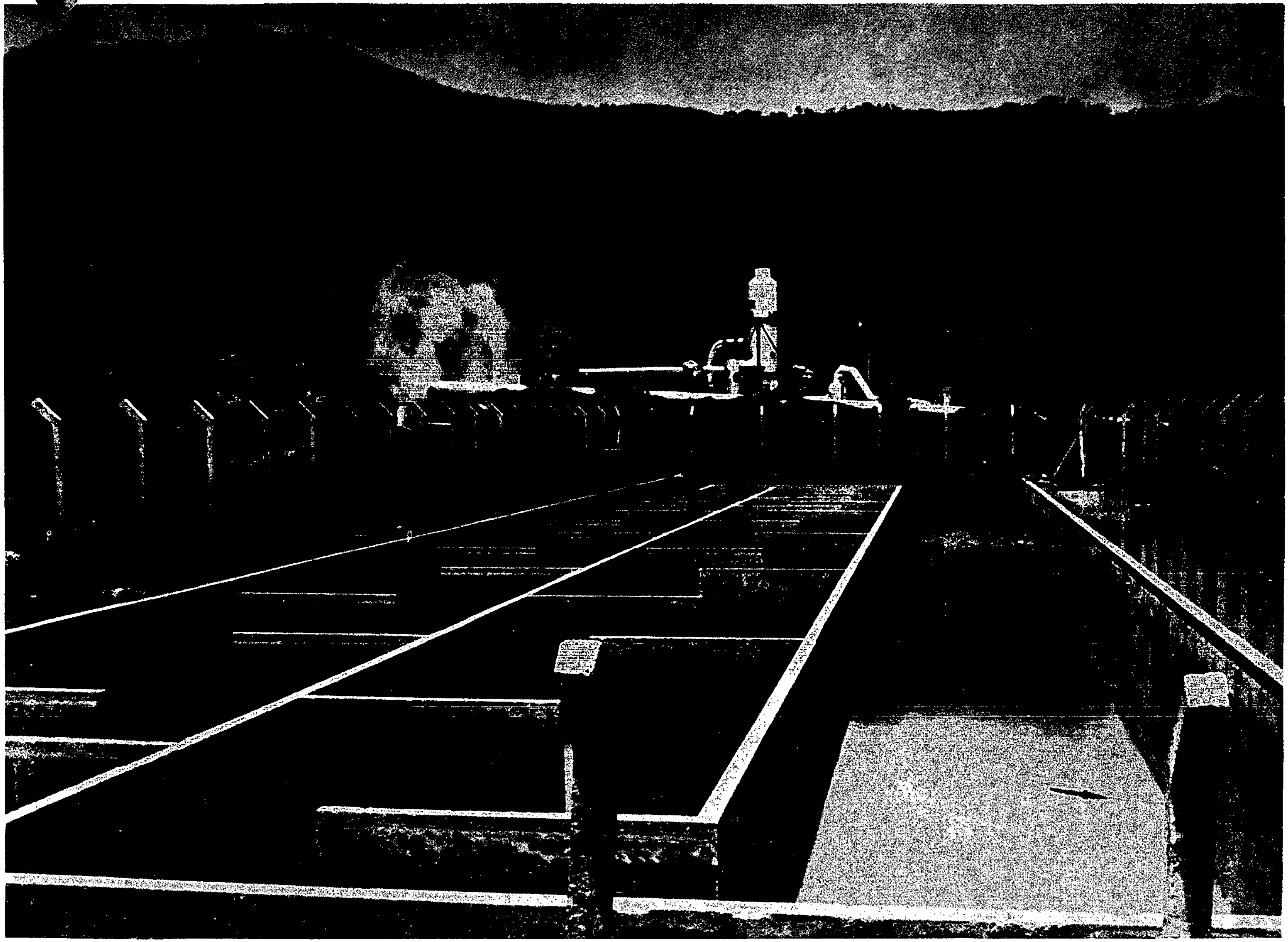

Fig. 33. Labyrinth hold-up settling tank (one of two) at Ahuachapán, with well AH-1 in background [photo by R. DiPippo].