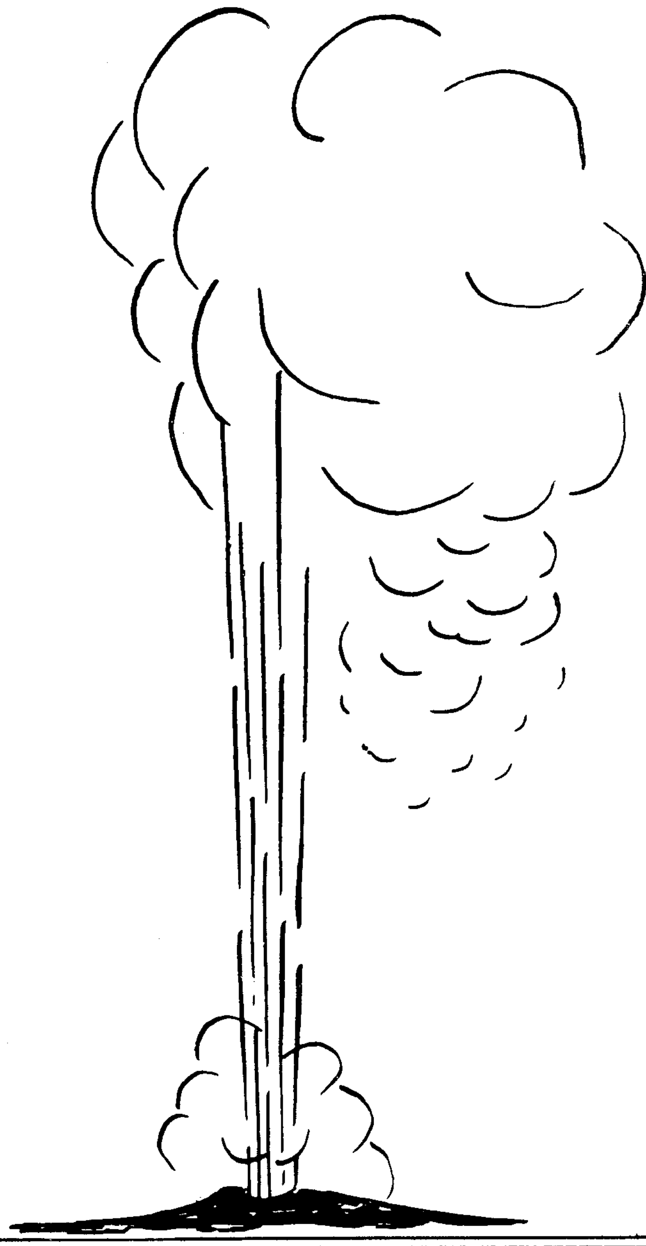
COO-4051-23



GEOTHERMAL POWER PLANTS OF NEW ZEALAND, PHILIPPINES AND INDONESIA. A TECHNICAL SURVEY OF EXISTING AND PLANNED INSTALLATIONS

Report No. CATMEC/17

By
Ronald DiPippo

June 1978

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

Division of Engineering
Brown University
Providence, Rhode Island

U. S. DEPARTMENT OF ENERGY

Geothermal Energy

Available from the National Technical Information Service, U. S. Department of Commerce, Springfield, Virginia 22161.

Price: Paper Copy $6.50
Microfiche $3.00

CATMEC/17

COO-4051-23
Distribution Category UC-66f

Geothermal Power Plants of New Zealand, Philippines and Indonesia: A Technical Survey of Existing and Planned Installations

by

Ronald DiPippo

Brown University

Providence, Rhode Island

June 1978

Performed under

Department of Energy

Division of Geothermal Energy

Contract No. EY-76-S-02-4051.A001

&B

Abstract

This report is the fourth in a series dealing with the geothermal power plants of the world ~~[DiPippo, 1978(A), 1978(B) and 1978(C)]~~. Here ~~we survey~~ the existing and planned stations in the south Pacific area including New Zealand, the Philippines and Indonesia. Details are given for the plants at Wairakei and Kawerau, and for the one proposed at Broadlands in New Zealand; for the plants proposed for Tiwi and Los Baños, and the wellhead units operating at Los Baños and Tongonan in the Philippines; and for the wellhead unit soon to be installed at Kawah Kamojang on Java in Indonesia. The geologic characteristics of the fields are described along with wellflow particulars, energy conversion systems, environmental impacts, economic factors and operating experiences, where available. The geothermal resource utilization efficiency is computed or estimated for the power plants covered. Furthermore, some discussion is devoted to the other sites which may prove exploitable for the production of electricity.

Acknowledgements

This work was performed with support from the Department of Energy, Division of Geothermal Energy, under Contract EY-76-S-02-4051.A001, Mr. C. B. McFarland, Project Manager. The author is indebted to the following people for their assistance in compiling this report:

R. S. Bolton, Ministry of Works and Development, New Zealand

P. W. Blakeley, New Zealand Electricity Department

G. A. Goodwin, Fram Corporation (New Zealand)

J. T. Kuwada, Rogers Engineering, Inc.

R. A. Lembo, Fram Corporation

N. C. McLeod, Ministry of Works and Development, New Zealand.

This report was written while the author was on sabbatic leave from Southeastern Massachusetts University, North Dartmouth.

Table of Contents

Page

List of Tables

List of Figures

Part I. New Zealand

1. Introduction

New Zealand was the pioneer country in the use of liquid-dominated hydrothermal resources for the generation of electricity.

The use of geothermal energy was first considered in the 1930's. Early investigations led to the conclusion that geothermal energy could be used to produce electrical power. A 5-year program was established in 1949 which had as its objective the winning of sufficient steam to support a 20 MW plant in an area of the Waiora Valley at Wairakei. Consulting engineers Merz and McLellan of England designed a 26 MW plant in 1953, based on the proven geothermal steam supply. Construction began in 1956, the first turbine was commissioned on November 15, 1958, and Stage One of the program was completed in March 1960. This was followed by the installation of twelve additional machines with the last of these having been brought on-line on October 7, 1963. The total installed capacity of the Wairakei geothermal power station was then 192.6 MW. [NZED, 1975].

Multi-purpose use of geothermal energy is made at Kawerau where process heating, clean steam generation and electricity production take place.

At Broadlands, the New Zealand Electricity Department (NZED) is planning to build a 150 MW plant which will employ a two-stage steam generation process, i.e., a primary separation followed by a secondary flash process.

In the following sections each of these sites will be discussed in detail.

2. Wairakei

The Wairakei geothermal field lies in an extensive thermal area on New Zealand's North Island. Wairakei is situated about 8 km (5 mi) north of the northeast corner of Lake Taupo, roughly in the middle of a thermal belt 50 km (31 mi) wide and 250 km (155 mi) long, which trends northeast-southwest across the North Island from a central group of volcanic mountains to the White Island volcano in the Bay of Plenty. Figure 1 shows the location of Wairakei (insert) and the general arrangements of the borefield and power station [Armstead, 1961].

The first bore at Wairakei delivered in 1951; the first electricity was generated in 1958. This field has been exploited for a longer period of time than any other liquid-dominated geothermal reservoir in the world. The reservoir has passed its peak of production; whereas the installed capacity is 192.6 MW, the output in 1974 was only 150 MW [Bolton, 1977]. It is expected, however, that the production will stabilize at between 125-140 MW, for an indefinite period of time.

2.1 Geology

The Wairakei thermal area is located in a region of Cenozoic subsidence and forms a part of the Taupo volcanic zone. A geological map of the thermal region is given in Fig. 2 [Grindley, 1961]. Large, active andesitic volcanoes are located at each end of the zone, and the wider central portion is dominated by acid igneous activity. These include rhyolite domes, pyroclastic pumice deposits and ignimbrites. During the late Miocene and Quaternary periods, a huge volume of lava and pyroclastic rocks (16,000 km^3 (3840 mi^3)) were erupted from the Taupo volcanic zone which led to the formation of grabens and calderas constituting the zone of subsidence.

A geologic cross-section taken east-west across the thermal belt at Wairakei is shown in Fig. 3a [McNitt, 1965]. It can be seen that a magmatic intrusion at a depth of about 8 km (26,000 ft) is the source of the thermal anomaly. The Wairakei field is situated on a horst block that has been elevated some 1200 m (3940 ft) relative to the surrounding rocks. The horst is flanked by steep faults which act as feeders for the hot-water aquifer.

A detailed cross-section is given in Fig. 3b [Grindley, 1961], which shows a portion of the field at Wairakei. This view covers a width of about 1.9 km (6100 ft) to a depth of about 900 m (3000 ft) below sea level or 1300 m (4300 ft) in total depth. The major faults (e.g., Waiora, Wairakei, Kaiapo) are shown at the left; the thin vertical lines represent drilled wells. It can be seen that the reservoir consists of a pumice breccia aquifer (Waiora formation) which varies in thickness from 460 to 900 m (1500 to 3000 ft). The reservoir is capped by layers of relatively impermeable lacustrine mudstones (Huka formation) which range in thickness from 60 to 150 m (200 to 500 ft), and which lie from 180 to 300 m (600 to 1000 ft) below the surface. The surface formations comprise mainly loosely consolidated breccias (Wairakei breccia) and a top layer of recently-deposited pumice cover. These surface layers extend to a depth of about 125 m (410 ft) [Bolton, 1977].

A large proportion of the production of the field comes from the permeable Waiora aquifer. The main production zone, however, is the contact area between the Waiora formation and the underlying Wairakei ignimbrite, which by itself has a low production capacity. This producing interface lies at a depth of between 570 and 680 m (1870 and 2230 ft) over the western and central portions of the cross-section, but dips sharply to about 1100 m

(3600 ft) in the eastern region. The reservoir has not been drilled to its full depth in this area [Bolton, 1977].

2.2 Wells and gathering system

The steam wells at Wairakei produce at two pressure levels: high-pressure bores at pressures of about 1030 kPa (150 lbf/in^2) and above, and intermediate-pressure bores with pressures ranging from 620 - 860 kPa (90-125 lbf/in^2). There has been a considerable reduction in field pressure during the lifetime of the project the high-pressure wells originally produced at pressures in excess of 1400 kPa (200 lbf/in^2) [Bolton, 1977]. The dramatic decrease in field pressure may be seen in Fig. 4 which covers the period 1953-1975. The loss in pressure amounts to about 38% over the 23-year span, with nearly all of it having occurred since the date of the commissioning of the first machine. The pressure appears to be approaching a stable value, having lost only 6% during the last seven years.

It should be remarked that no reinjection of the withdrawn fluid has ever taken place at Wairakei. In addition to playing a role in the pressure loss within the reservoir, this has led to subsidence effects which will be discussed later. (See Sect. 2.4.) Furthermore, the slight reeovery in pressure which occurred during a test conducted in early 1968 was attributed to a curtailment of fluid drawoff (flow reduced to about one-third the normal value). The implication is that the reservoir is being influenced in some way by an inflow.

It has been reported recently [Hunt, 1977] that the amount of recharge of water into the geothermal field has, in fact, increased markedly over the past several years. Recharge is defined as the ratio of the mass of fluid replaced to that withdrawn, over a specified time interval. On the basis of repeat gravity measurements, Hunt indicates the following values of recharge:

1958-1961, 30%; 1961-1967, 35%; 1967-1974, 90%. These values are probably accurate to about ±15%. During the last period (1967-1974), 400 x 10^9 kg (882 x 10^9 lbm) of fluid were withdrawn and were replaced by 364 x 10^9 kg (802 x 10^9 lbm). Over the full history of the field, about 695 x 10^9 kg (1532 x 10^9 lbm) have replaced 965 x 10^9 kg (2127 x 10^9 lbm) of geofluid which have been withdrawn. If the recharge continues at 90%, it is likely that the field will not be depleted for a long time.

The practices employed for the drilling, casing, operation and maintenance of the steam wells at Wairakei have been extensively documented [Craig, 1961; Fisher, 1961; Fooks, 1961; Smith, 1961(A) and 1961(B); Stilwell, 1970; Woods, 1961]. Figure 5 shows a typical drilling rig and drilling fluid circulation layout. The cellar provides a solid base on which to mount the rig, and accommodates the wellhead equipment used during production. Early cellars were 3.0 m (10 ft) deep, but in 1966 they were redesigned for 2.1 m (7 ft), for medium-depth wells, i.e., wells of 900 m (3000 ft) nominal depth; cellars for deep wells, i.e., wells of 2300 m (7500 ft) nominal depth, are 3.4 m (11 ft) deep [Stilwell, 1970].

The drilling program for medium-depth wells is given in Table 1: the various wellhead arrangements that are used during the drilling operation are shown in Fig. 6. Table 2 and Fig. 7 contain comparable information for deep wells. A schematic cross-section of a finished well is shown in Fig. 8; the strata indicated are typical of the region in the central portion of the field, i.e., in the middle of the section shown in Fig. 3(b).

A typical drill string with blowout preventor equipment (BOPE) is shown schematically in Fig. 9. The drill string consists of the following elements: drill bit (usually tri-cone roller type), float valve (to control flow of drilling mud), drill collar (similar to drill pipe except somewhat larger and heavier), drill pipe, and the Kelly (square piece of pipe which allows torque to be transmitted from the rotary table through the square Kelly bushing).

There are, in addition, three elements which enable the well to be closed off during the drilling operation should this be necessary. There is a drill-through valve which may be used to close the well once the drill string has been removed. Next, there are the Shaffer gates, two independent horizontal gates, each of which is split in half. The inner surfaces of the semicircular sections are fitted with rubber rams capable of fitting around the drill pipe, drill collar or well casing. The gates are driven by a air-motor-actuated screw with a manual backup. Finally, the hydraulic-operated blowout preventer (BOP) is able to shut off the well completely by means of a rubber packing element that can fit around any item that may be in the well. The driller has immediate access to the controls for the Shaffer gates and the BOP in the case of an emergency [Craig, 1961].

The arrangement of the wells in the steam field is shown in Fig. 10 [after Haldane and Armstead, 1962; Bolton, 1977; Grindley, 1961]. Recent drillings have extended the drilled area beyond the borders of this plan view. There have been a total of 102 wells drilled, 68 of which have supplied steam to the turbines [Bolton, 1977].

The gathering system is a complicated one involving three pressure levels. The complexity arose because the original plans for the development of the area included a plant to produce heavy water for the U.K. Atomic Energy Authority. This proposal was made in 1953 and the steam pressures were selected to accommodate the requirements of the distillation plant. The proposal for the heavy-water plant was withdrawn in 1956, but only after the design of the steam system had been frozen and turbines were on order.

Thus, the resulting design is unnecessarily complex, and will not be repeated [Bolton, 1975].

The present gathering system is shown schematically in Fig. 11 [Bolton, 1977]. Two high-pressure wells are shown. The one on the left supplies fluid to a typical flash plant which produces steam at three pressure levels: high-pressure (H.P.), intermediate-pressure (I.P.) and intermediate-low-pressure (I.L.P.). The one at the right produces only high-pressure fluid by means of a simple cyclone separator. The figure does not show the intermediate pressure wells that also produce intermediate-pressure (I.P.) steam and additional water for the flash plant.

The wellhead separators are of two types, and are shown in Fig. 12(a) and (b) [Haldane and Armstead, 1962; Bolton, 1977]. Early wells were fitted with top-outlet cyclonic (TOC) separators (see Fig. 12(a)); recent wells use bottom-outlet cyclonic (BOC) separators (see Fig. 12(b)) [Hunt, 1961]. The former type incorporated a U-bend upstream of the admission point to the separator which removed about 80-90% of the liquid. A baffle arrangement inside the separator trapped the remaining liquid and allowed the steam to emerge with a dryness fraction of about 99%. The latter type, often called a "Webre" separator, is much simpler and has been shown to be capable of yielding steam with a dryness fraction in excess of 99.9% [Usui and Aikawa, 1970]. The hot-water pump shown in Fig. 12(b) was used on the original pilot plant which pioneered the use of the liquid fraction of the geofluid, but has since been replaced by a simple water-collection tank similar to that shown in Fig. 12(a), but without the U-bend.

The essentially dry, saturated steam is transmitted from the separators to the main steam lines by means of branch pipelines. The main transmission pipelines are 508, 762, 1067 and 1219 mm (20, 30, 42 and 48 in) in diameter (nom.); the branch lines vary from 150-300 mm (6-12 in) in diameter. The two largest steam mains are associated with the I.L.P. steam system in which the specific volume is large. Expansion loops are located every 300 m (1000 ft) roughly; each loop can absorb about 762 mm (30 in) of pipe movement. Condensate which forms during transmission is removed by means of drain pots located about 150 m (500 ft) apart. Since the drains serve to remove impurities, the steam arrives at the power house in a highly purified condition, the pipeline having acted as a very efficient scrubber.

2.3 Energy conversion system

The energy conversion system at Wairakei may be described as a multi-pressure, separated-steam, double-flash power plant. On the average, about 80% (by weight) of the high-pressure geothermal fluid at the wellhead is liquid. Steam is separated from high- and intermediate-pressure wells and sent to the power houses. Hot water which is separated from a number of H.P. wells is flashed to produce I.P. steam. An additional flash produces I.L.P. steam which is transmitted to the power plant and subsequently let down for use in the lowest pressure turbines.

The arrangement of the thirteen power turbines is shown in Fig. 13. There are two 6.5 MW and two 11.2 MW back-pressure machines which are supplied with H.P. bore steam; two 11.2 MW back-pressure turbines which receive a mixture of I.P. bore steam, I.P. flash steam, and exhaust steam from the H.P. units; four 11.2 MW condensing units which operate on L.P. steam which is obtained from the exhaust of the I.P. machines and the let-down flashed steam from the second-stage flash tanks; and three 30 MW dual-admission, condensing units which are supplied with the same steam which feeds the I.P. turbines and which receive pass-in, L.P. steam let-down from the second-stage flash vessels.

Tables 3-7 list the technical particulars of the several sets of power generating equipment. Since the plant has been undergoing modifications to compensate for the loss of pressure in the geothermal reservoir, some of the values shown in the tables are approximate or may not be current. They nevertheless represent the best information available to the writer at this time.

Figure 14 is a simplified plant flow diagram which shows the typical wellhead separator/flasher arrangements. It is expected that eventually all high-pressure wells will be adapted to a multiflash setup; there are now seven such stations. Figure 15 is a Mollier diagram (enthalpy-entropy coordinates) showing the expansion portions of the cycle; it is not drawn to scale and is intended for illustration only.

The geothermal resource utilization efficiency, η_u, has been calculated approximately. This factor is the ratio of the actual power delivered by the plant to the ideal power available in the geofluid as it flows from the wellhead, i.e., the thermodynamic availability of the geofluid:

$$\eta_u = \dot{W}/\dot{W}^o \quad . \tag{1}$$

For purposes of the calculation, $\dot{W}$ was taken equal to the installed capacity of the plant, i.e.,

$$\dot{W} = 192.6 \text{ MW} \quad . \tag{2}$$

The actual output at the present time is considerably below this value, being about 150 MW. Since the flow rates will probably also be less, there may be some compensations which may result in a relatively small effect on the resource utilization efficiency.

With reference to Fig. 14, the availability of the geofluid is composed of two contributions, one from the H.P. fluid at state a and one from the

I.P. fluid at state h:

$$\dot{W}^o = \dot{m}_a[h_a-h_o-T_o(s_a-s_o)] + \quad (3)$$
$$+ \dot{m}_h[h_h-h_o-T_o(s_h-s_o)] \quad ,$$

where $\dot{m}_a$, $\dot{m}_h$ = mass flow rate of geofluid at state a, state h;

h_a, h_h = specific enthalpy of geofluid at state a, state h;

s_a, s_h = specific entropy of geofluid at state a, state h;

h_o, s_o = specific enthalpy and entropy at the sink condition;

T_o = absolute temperature at the sink condition, T_o = 289 K (520 R).

Since mass flow rates were not available in the literature at states a and h, it was necessary to work backwards from the turbine main stop valve steam flows and employ assumptions about the average dryness fraction at the H.P. and I.P. wellheads. Fair approximations for these were obtained from Hunt [1961] and Wigley [1970], after making allowances for lower wellhead pressures. Table 8 contains a summary of the calculations.

The resource utilization efficiency of the Wairakei plant, under conditions of maximum operation (i.e., in its original design state) is about 55%. It is likely that this value is somewhat, but not much, lower than this at the present time, owing to the general deterioration of the reservoir characteristics and the corresponding mismatch between the geofluid and the energy conversion equipment. However, the conversion of more and more wells to the multiflash arrangement shown in Fig. 14 will tend to maintain the level of utilization in the face of reservoir decline. It is interesting to note that it was reported earlier [Wigley, 1970] that the plant had an "efficiency" of about 9%, based on the "heat content" of the geofluid. Such an assessment does not take into account the thermodynamic level of the thermal energy contained in the geofluid. It is becoming recognized that a more meaningful measure of system performance results from the application of the so-called "Second Law efficiency", i.e., one based on the thermodynamic available work (or availability or exergy) [Milora and Tester, 1976; Wahl, 1977; Kestin, 1978].

2.4 Materials of construction

The choice of the materials of construction is largely influenced by the composition of the geothermal fluid, including both impurities in the form of dissolved solids and noncondensable gases in the steam. The fluid produced at Wairakei is reasonably "clean" in both regards, as can be seen from the data in Table 9 [Armstead, 1961]. The total noncondensables reported at that time amounted to about 0.50% and 0.36% (by weight) of the bore steam for the H.P. and I.P. wells, respectively. Furthermore, judging from more recent investigations [Glover, 1970], it appears likely that the level of noncondensable gases is presently less than that quoted by Armstead. In fact, during the period from 1960 to 1969 the total noncondensable gas concentration decreased by 50%, although the hydrogen sulfide fraction remained essentially constant [Axtmann, 1975 (B)].

The amount of total dissolved solids in the hot liquid from the bores is of the order of 3800 ppm (by weight), but increases to about 4150 ppm and 4550 ppm following the first and second stage flash vessels, respectively [Haldane and Armstead, 1962]. Since the presence of salinity in the fluid which enters the turbine will cause stress-corrosion cracking in the blades, scrubbers are used to ensure that the total saline content of the flash steam does not exceed 10 ppm.

Mild steel is used for wellhead equipment, steam and hot water pipes, and flash vessels. There are no corrosion problems with the geothermal fluid so long as oxygen is avoided. The steam transmission lines are made of seamless steel piping, rolled and butt welded mild steel pipes, and spiral welded steel pipe for the largest sized pipes. The newer, larger pipes are insulated with 38 mm (1.5 in) of fiberglass and covered with aluminum sheathing. The older, smaller pipes have 38 mm (1.5 in) slabs of 85% magnesia which are wired on, covered by bituminous roofing felt and wire netting, and painted with bituminous aluminum [NZED, 1974].

The power houses are steel-framed buildings which are finished in aluminum and glass. Owing to the relatively low load-bearing capability of the ground, it was necessary to implant a massive raft foundation which is 4.4 m (14.5 ft) deep and which contains about 15,000 Mg (33 x 10^6 lbm) of concrete. Figures 16, 17 and 18 show, respectively, the two power houses (close up), an aerial view of the station, and an overall view of the plant including a portion of the steam field [NZED, 1974].

The condensing steam turbines are particularly susceptible to erosion in the last stages owing to condensation of the steam. Since the blades are made of soft stainless steel, as mentioned earlier, the problem of erosion will be intensified. The brazing on of erosion shields (e.g., stellite inserts) was ruled out because of the possibility of local hardening and the resulting vulnerability to stress-corrosion craking. It was decided, instead, that the blade tip speed would be kept below 274 m/s (900 ft/s), even though this limits the capacity of the individual condensing turbine units [Haldane and Armstead, 1962].

The photograph in Fig. 19 is a view of "A" station showing the turbine hall which houses units 1-6 (foreground to background) [NZED, 1974]. The reader may refer to Haldane and Armstead [1962] for detailed plan layouts and elevation views of both power houses.

2.5 Environmental effects

When discussing the effects of the Wairakei geothermal power plant on the environment, it is important to keep in mind that the plant was designed and built at a time when environmental issues were regarded as far less important than they are today. The fact that an environmental impact report was not required for the construction of the Wairakei plant stands as evidence. Add to this the fact that Wairakei was the first liquid-dominated geothermal resource to be exploited for electrical power, and one should realize that the state of the art in geothermal technology was, in fact, in its infancy at that time (1958).

Although the plant has operated successfully for twenty years with a minimum of unpleasant impact on the human population that lives near the plant, there are nevertheless many areas of concern relative to the general environment. A very detailed report on the impact of the Wairakei plant on its environment has been published [Axtmann, 1974]; we call the reader's attention to a summary of this study which appeared in the open literature [Axtmann, 1975 (A)]. This section relies heavily on the latter reference.

The following effects will be considered here: chemical effluents in the liquids and gases which flow from the plant, physical effects including thermal discharge and subsidence, general ecological effects, and "visual pollution" or esthetics.

The waste liquid from the bore field is transported by means of open concrete trenches to the Wairakei Stream which flows into the Waikato River at a point roughly 1 km (0.6 mi) upstream of the power plant. The liquid discharge contains a number of constituents, principally sodium and chloride, but also such potentially harmful substances as arsenic, mercury, hydrogen sulfide and carbon dioxide. Table 10 lists the constituents of the discharged fluid and shows the increase they cause in the concentration of each element in the water of the Waikato River, assuming complete mixing without precipitation or absorption, at average flow conditions of the river (i.e., 127 m^3/s (2×10^6 gal/min)).

The arsenic content of the Waikato River has been studied [Reay, 1972], and it was concluded that about 75% of the arsenic in the river comes from the Wairakei plant. According to Table 10, the concentration of arsenic should be about 0.04 ppm under average conditions, which is just below the allowable concentration for drinking water in the United States (i.e., 0.050 ppm). However, samples taken at the inlet of the water supply for the Wairakei Village have shown arsenic concentrations as high as 0.07 ppm. Furthermore, in periods of drought when the flow in the river is much less than normal, the concentration of arsenic could reach values as high as 0.25 ppm [Axtmann, 1975 (A)].

The mercury found in the Waikato River is partly caused by the Wairakei plant, although several other geothermal areas in the vicinity are contributors. Mercury ores are known to be associated with hot springs, and several areas, including Broadlands, Waiotapu and Orakeikorako, discharge into the Waikato. Examination of trout taken from the Waikato about 75 km (47 mi) downstream of the power plant revealed about 4.4 times the "normal" concentration of mercury which is about 0.12 mg/kg of axial muscle tissue (wet weight basis) [Weissberg and Zobel, 1973]. These fish weighed 1.29 kg (9.4 oz.), on average, and since the accepted upper limit for mercury in fish for human consumption is 0.50 mg/kg, trout weighing more than about 1.25 kg (9.1 oz.) might be expected to be unsuitable for human consumption because the concentration of mercury is known to be proportional to the weight of the fish.

The hydrogen sulfide (H_2S) in the geothermal steam becomes divided between the condensate and the noncondensable gas stream, with about 80% of it going into solution. The rate of discharge in the liquid is about 54 kg/h (24 lbm/h).

Assuming that no oxidation to sulfur dioxide (SO_2) occurs in the direct-contact condensers, the concentration of H_2S in the river would be 0.1 ppm (average flow) or 0.9 ppm (lowest flow). Even at average flow conditions such a concentration exceeds by a factor of about 15 the safe limit for the eggs and fry of rainbow trout.

Even though the solubility of carbon dioxide (CO_2) in water is quite low at the conditions prevailing at the condenser, nevertheless, about 1 Mg/h (2200 lbm/h) of CO_2 is discharged to the Waikato River in the condenser effluent [Axtmann, 1975 (A)].

The condensed geothermal fluid which enters the Waikato contributes to the production of electricity from the system of hydrothermal power stations which are located along the river. This may be regarded as a positive or compensating environmental effect. The total rate of liquid discharged from the plant is 1.3 m^3/s (21,000 gal/min), the enhanced evaporation rate (owing to the thermal effect) is about 0.3 m^3/s (4800 gal/min), leaving a net increase of 1 m^3/s (16,200 gal/min) in the flow of water in the Waikato. This is equivalent to about 2.4 MW of electrical power from the hydroelectric plants, or the generation of 20 GW·h of electricity per year.

The important gaseous effluents consist of the following: H_2S, CO_2 and water vapor; the first of these constitutes the most serious problem owing to its hazardous nature. Hydrogen sulfide is a gas whose presence is easily detected by the human olfactory sense at extremely low concentrations (i.e., 0.002 ppm threshold). It causes eye irritation at 10 ppm, lung irritation at 20 ppm, and death in 30 minutes at 30 ppm [Miner,1969]. Roughly 14 kg/h (6.4 lbm/h) or 93 g/MW·h (0.2 lbm/MW·h) are discharged into the atmosphere from the gas ejectors through four stacks on the roof of the plant. The tops of the stacks are 30 m (98 ft) above ground level. The concentration of H_2S in the stack gas is about 5000 ppm. The odor of H_2S is not detectable in the Wairakei Village, about 2 km (1.2 mi) north of the plant, although there have been some reports of the blackening of silverware and brass [Axtmann, 1975 (A)].

The gaseous emission of CO_2 at Wairakei is less by a factor of about 60 than the emission from a conventional fossil-fuel-burning power plant, per megawatt of electricity produced.

The amount of water vapor released to the atmosphere during a total plant shutdown (i.e., all wells venting to the atmosphere) would be equivalent to the amount discharged from the wet cooling towers of a 750 MW conventional power plant (i.e., 1.9 Gg/h (4.2×10^6 lbm/h)). Under normal circumstances, however, the amount is 0.84 Mg/h (1.9×10^3 lbm/h), or about 0.04% of the maximum possible discharge. The presence of large amounts of water vapor can, of course, lead to the formation of fog which is frequently seen in the area around the power plant.

The physical effects of the Wairakei plant upon the environment are related to the drawoff of vast quantities of hot subsurface fluid and to the discharge of these fluids at the surface (i.e., without reinjection into the reservoir). As a result an area of about 6500 ha (16,000 acres) shows the effects of subsidence and horizontal land movement. The maximum total drop in elevation is in excess of 4.5 m (14.8 ft) over the 10 year period from 1964 to 1974 at a spot which is removed from the borefield but within about 500 m (1640 ft) of the steam pipelines [Stilwell, et al., 1975]. Subsidence appears to be progressing at the rate of 400 mm/y (16 in/y). The subsidence volume is likely related to the volume of fluid withdrawn from the field, but a precise correlation is not available. A study of subsidence from 1967 to 1971 by Glover showed that $V_{subsidence}/V_{drawoff} = 0.0076$, on average [Axtmann, 1975 (A)].

Figure 20 shows the area of ground subsidence relative to a bench mark, TH7, in the power house (Fig. 20a), and the subsidence which has occurred along the main steam pipelines (Fig. 20b) for the period 1964-1974 [Stilwell, et al., 1975].

Also shown in Fig. 20b is the depth of the bottom of the underlying Waiora breccia. (See Fig. 3b.) It can be seen that the most drastic subsidence corresponds to the region in which the Waiora breccia falls off along a buried fault scarp.

From about 1957 to 1965, there appeared to be a correlation between the pressure loss in the reservoir and the field subsidence. Since that time, however, the pressure has tended to level off (see Fig. 4) while the subsidence has, in fact, tended to increase.

Horizontal ground movement has been traced since 1966, and Fig. 21 shows a vector diagram of the movement of a number of ground stations in the field. All movements tend to be toward the region of maximum vertical displacement, with GS6, for example, showing a displacement of nearly 500 m (20 in) in a westerly direction over the 8-year period from 1966 to 1974.

In the light of the amount of both vertical and horizontal ground movement in the Wairakei field, it is indeed fortunate that the power house was sited along the Waikato River instead of near the middle of the borefield.

The so-called "waste heat" which is rejected from the plant through residual liquid geofluid from the wells and condensate from the power house influences the temperature of the Waikato River. Liquid flows from the borefield at about 60°C (140°F) and 1.3 m^3/s (21,000 gal/min) whereas condensate flows at roughly 33°C (91°F) and 10 m^3/s (159,000 gal/min). The maximum increase in the temperature of the Waikato would be 1.3°C (0.7°F) when the river is flowing at its mean value of 127 m^3/s (2×10^6 gal/min) [Axtmann, 1975 (A)]. This temperature change is far less than natural temperature swings during the year. However, during periods of extreme drought when the flow rate in the river is abnormally low (e.g., 28 m^3/s (444,000 gal/min) as during the spring of 1974), it is possible for the power plant to produce significant temperature elevations, in excess of what is permitted under New Zealand's water standards.

Baseline (i.e., pre-plant) ecological data does not exist at Wairakei since it was not required to complete an environmental impact statement at the time of the construction of the plant. Axtmann suggests, however, that the portion of the Waikato River which lies between the Wairakei stream and the Aratiatia Dam constitutes a severely stressed ecosystem [Axtmann, 1975 (A)]. Several reasons are listed in support of this conclusion, among which is the observation that a lack of diversity exists among the various species of plankton in this part of the river.

The judgment of the esthetics of a power plant is, to some degree, subjective. In the view of Axtmann, the Wairakei plant lies on a scale somewhere between a typical fossil-fuel plant ("visual abomination") and a typical nuclear plant (somewhat resembling a planetarium when imaginatively designed). His description of the general scene at Wairakei is worthy of full quotation: [Axtmann, 1975 (A)].

> *"... the Wairakei borefield ranks high in New Zealand's superb hierachy of visual delights. If a tramper of Highway 1 were to pause at dusk 8 km north of Taupo on a moist day with a stiff breeze, he would see an eerie scene of haunting beauty. Scores of fleecy plumes arc skyward only to be seized and devoured by green demons that haunt the boughs of imperial conifers; bundles of silvery bullwhips, cracked by an invisible giant who lurks behind the western hill, are caught in stop-action as they rise and fall in unison. It is an odd amalgam of technology and nature, of the Tin Woodsman of Oz and the Sorcerer's Apprentice, gently underscored by the whispering, slightly syncopated 'whuff-whuff... whuff... whuff' of the wellhead silencers."*

2.6 Economic factors

The total capital investment at the Wairakei geothermal power plant, as of March 31, 1969, was NZ $43,367,000. This includes NZ $1,300,000 for exploration, NZ $17,176,000 for exploitation, and NZ $24,891,000 for utilization. Based on an installed capacity of 192.6 MW, the capital cost works out to about NZ $225/kW [Smith and McKenzie, 1970]. Table 11 lists a detailed breakdown of the capital expenditures.

The average annual operating costs over the 4-year period from 1965 to 1969 amounted to NZ $5,778,000. This is about 4.8 NZ mill/kW·h of electricity generation, on the average. Table 12 gives the average operating costs for the project, including those for the borefield and for the power station. In addition to the working expenses shown in Table 12, there are charges for the use of capital and administrative costs which contribute to the total O & M expenses:

Total working expenses	NZ $1,210,200
Capital charges	4,239,200
Administrative charges	328,500
Total operating and maintenance charges	NZ $5,777,900

2.7 Operating experiences

The Wairakei plant has an outstanding record of reliability; forced outages have been essentially negligible. During 1973/74, the station was in service 85% of the time (availability factor) with a capacity factor of 80%. This performance is unmatched by any other power station, hydro or thermal, and is significantly superior to any thermal power plant in New Zealand. In fact, the Wairakei geothermal power station has maintained this excellent record since it was fully commissioned in 1964 [Ravenholt, 1977 (B)].

On the average there are about 150-160 people involved in the various phases of operation of the station, including administration (8), operation of the power house (43), operation of the borefield (8), maintenance of the power house (50), maintenance of the borefield (40), and operations related to the Permanent Village and services (12) [Smith and McKenzie, 1970].

The generating history of the Wairakei plant is given in Table 13. Since it has never been possible to generate sufficient geothermal steam to supply fully the installed electrical capacity of 192.6 MW, the capacity factors listed in the fourth column of the table have been adjusted accordingly. The so-called "field-limited" capacity factor is based upon the maximum load during any given year, as shown in the third column.

The generation of 1207 GW·h in 1969 constituted 9.9% of the entire electricity generation in New Zealand for that year. The latest figures available (1974) show that the plant is producing about 10% of the electricity requirements of North Island, although this pereentage is expected to fall as the electrical generating capacity of the country as a whole increases [Bolton, 1977].

The most serious accident associated with the operation of the plant occurred in January 1960 when Bore 26 exploded, creating a violently steaming crater and several smaller steam jets and boiling mud pools. The blowing well was eventually brought under control through the drilling of another well, Bore 26A, spudded 61 m (200 ft) away from Bore 26. The new well was sunk with a deviated bore and passed within 1.2 m (4 ft) of Bore 26 at a depth of 453 m (1486 ft). Figure 22 shows the deviated bore in its programmed and actual form. The operation was supervised by an American drilling team. In order to secure the foundation of the new well, it was necessary to grout an area of 0.186 ha (0.46 acres) by means of 250 holes of 30 m (100 ft) depth, into which was poured 1500 Mg (3.3 x 10^6 lbm) of cement. After Bore 26 had been intersected in the open hole below the production casing (November 1960), large amounts of 1762 kg/m^3 (110 lbm/ft^3) cement slurry were pumped down Bore 26A, to no avail. Finally about 7.6 m^3(10 yd^3) of pea gravel were poured in, followed by another large batch of cement, and the violent thermal activity came to an abrupt halt. Restoration of the landscape was completed, and two highly productive wells, Born 26A (extended) and Bore 26B, now occupy the area (NZED, 1974; Craig, 1961].

There are at present no plans to expand the installed capacity at Wairakei [McLeod, 1977], although exploration is continuing at the nearby geothermal field of Te Mihi [Smith and McKenzie, 1970], and at other promising sites in the thermal belt. Additional geothermal power in New Zealand will likely come from new plants at such sites as Kawerau and Broadlands, which are discussed in the following sections.

3. Kawerau

Multiple use is being made of the geothermal resource at Kawerau, 97 km (60 mi) northeast of Wairakei. The Tasman Pulp and Paper Company, in fact, relocated their mills in the early 1950's specifically to take advantage of the geothermal energy available at Kawerau. Steam and hot water from a number of wells are used for the production of electricity, for the generation of clean steam by means of heat exchangers, and for a number of process applications including timber drying, recovery boiler shatter sprays, liquor heaters and log handling equipment. In this section we will concern ourselves with the geology of the site, the drilling of wells and the production of geofluid, the transmission of the fluid to the mill, its use in the generation of electric power, some of the environmental aspects, and the potential of the site for expanded utilization.

3.1 Geology

The geothermal steam field layout including the pulp and paper mill is shown in Fig. 23. The most active surface manifestations of geothermal energy lie to the west of the Tarawera River (cross-hatched areas), although highly productive wells have been drilled on the east bank in close proximity to the mill.

The region possesses a top layer of recent alluvium (which probably conceals a number of faults) with the following formations at depth: a shallow layer of breccia to about 75 m (250 ft), a thick layer of rhyolite to about 400 m (1300 ft), an aquifer of pumice breccia imbedded with sandstones to about 730 m (2400 ft), another layer of rhyolite, another aquifer of extensively fissured andesite to about 820 m (2700 ft), and a basement of dense ignimbrite. Several wells have been drilled to depths in excess of 915 m (3000 ft) and have penetrated the basement ignimbrite. The deeper layer of rhyolite serves as a cap for the lower aquifer and may act as an insulator between the lower, hotter aquifer and the upper one which appears to be influenced by an influx of cooler circulating water [Smith, 1970].

3.2 Wells and gathering system

From 1952 to 1955 three small diameter exploratory wells were drilled: KA1, KA4, and KA5. The latter was a nonproducing well owing to the low temperature encountered, 85°C (185°F) bottom-hole temperature. Table 14 lists the geofluid production from the other two wells during this period. Both of these wells were fitted with 102 mm (4 in) production casings; KA1 ran to 449 m (1473 ft) and KA4 to 499 m (1636 ft).

During 1956-1957 seven additional wells were sunk: KA7A to 605 m (1985 ft), KA8 to 585 m (1918 ft), KA10 to 634 m (2080 ft), KA11 to 624 m (2046 ft), KA12 to 622 m (2042 ft), KA13 to 603 m (1979 ft), and KA14 to 615 m (2018 ft). All of these had a 311 mm (12.25 in) diameter drilled hole and a 219 mm (8.625 in) diameter production casing. All were good producers, with the exception of KA13.

From 1958 to 1960, these wells deteriorated considerably. Several (KA11, 12 and 14) developed calcite deposits and required reaming, after which the flow rates were still poor. Significant declines in temperature were observed, ranging from 6-20°C (11-36°F), which were caused by an invasion of cooler water in the production zones. Another problem was caused by probable clogging of the slots in the production casing from calciting, together with the fact that the slotted liners were installed as a single string cemented to the surface above the slots, thus making it impossible to remove for cleaning.

During the period 1961-1969, several wells were deepened, increasing their depths by 221-374 m (726-1227 ft), and three new wells were sunk: KA3 to 1092 m (3584 ft), KA16 to 972 m (3189 ft), and KA17 to 1033 m (3388 ft). Each of these consists of a 219 mm (8.625 in) production casing, a 194 mm (7.625 in) diameter open hole, and a 168 mm (6.625 in) diameter slotted liner. Each slotted liner has 52 slots/m (16/ft), with each slot being 19 x 51 mm (0.75 x 2 in). A few of the wells have become nonproductive either from calciting or low aquifer permeability. As of late 1969, the following four wells were producing steam at a pressure of 791 kPa (114.7 lbf/in^2): KA7A... 13.6 Mg/h (30 klbm/h), KA14... 10.9 Mg/h (24 klbm/h), KA16... 56.7 Mg/h (125 klbm/h), and KA17... 13.6 Mg/h (30 klbm/h). Well KA8 delivered 59.0 Mg/h (130 klbm/h) of steam at a pressure of 1480 kPa (214.7 lbf/in^2); an additional 13.6 Mg/h (30 klbm/h) of steam was flashed from the liquid of KA8 at a pressure of 791 kPa (114.7 lbf/in^2).

With the abrupt escalation of world petroleum prices in 1973-1974, there was a renewed interest in the development of the Kawerau field and two more wells were drilled, KA21 and 22.

Noncondensable gases constitute about 2.5% (by weight) of the geothermal steam; about 91% is carbon dioxide, with the rest being mainly hydrogen sulfide.

The gathering system includes branch pipes from the individual wellheads to the main steam lines; these branch lines are 203, 305 and 406 mm (8, 12 and 16 in) in diameter. The low-pressure wells feed the plant through a 610 mm (24 in) diameter steam main which is capable to handling 145 Mg/h (320 klbm/h) of steam at 791 kPa (114.7 lbf/in^2). The high-pressure well (KA8) delivers through a 305 mm (12 in) supply line, at a maximum flow rate of 36 Mg/h (80 klbm/h) and a pressure of 1480 kPa (214.7 lbf/in^2). New steam lines are insulated with 51 mm (2 in) of resin-bonded fiberglass; older pipes have 51 mm (2 in) of asbestos and 85% magnesia. All are protected with a covering of aluminum sheet [Smith, 1970].

3.3 Energy conversion system

Details about the non-electrical use of the goethermal fluid may be found elsewhere [Bolton, 1975; Bolton, 1977; Lindal, 1973; Smith, 1970; Stilwell, *et al.*, 1975]. It is sufficient to note that geothermal energy contributes about

21% of the energy required for process applications, the rest being supplied by the burning of waste products and fuel oil.

The plant purchases 80% of its electricity from the NZED grid and produces the other 20% in-house. A bank of turbo-alternators operate in parallel, being fed by boiler steam and geothermal steam. The latter supplies one 10 MW, non-condensing unit. Table 15 gives the technical specifications for this unit. Since the steam which supplies this unit is excess geothermal steam, beyond the process needs of the plant, this unit is part-loaded most of the time. Nevertheless, it is capable of operating at full load in the event of a failure of the other turbo-alternator units. At full output, the unit has a specific steam consumption of about 14.5 kg/kW·h (32 lbm/kW·h). This corresponds to a geofluid utilization efficiency for electrical production of about 24%, assuming a wellhead quality of 30% and taking the available sink temperature as 27°C (80°F).

3.4 Environmental effects

No detailed environmental study exists for this plant. A level network to keep track of subsidence was established in 1970, and checks made in 1972 revealed a subsidence rate of 15 mm/y (0.6 in/y) in the area of maximum fluid draw-off. However, since the mill is located near the center of the field, the effects of subsidence will, unfortunately, be largest at the mill. The rate of subsidence there is 28 mm/y (1.1 in/y). Thus, differential settling throughout the plant may lead to trouble with the operating equipment, and necessarily limit the ultimate exploitation of the field by restricting the rate of fluid withdrawal [Stilwell, et al., 1975].

Reinjection of waste fluid has not been reported; excess liquid is presumed to be dumped into the adjacent Tarawera River which empties into the Bay of Plenty about 20 km (12 mi) northeast of the plant.

3.5 Possible expansion of geothermal utilization

Although the main thrust of the plan for geothermal energy utilization at Kawerau has been aimed at process heating and other industrial applications, it is likely that serious consideration will be paid to the expansion of the facility for the generation of electricity. Encouragement comes from the fact that one of the newest wells, KA21 (see Fig. 23), by itself, appears capable of supporting a 20-30 MW generator. This is 4-6 times larger than the potential of an average geothermal well. Thus, it is expected that a separate generating station, one able to supply all of the electrical needs of the mill, will be constructed at the site as soon as present investigations justify the additional investment [Ravenholt, 1977 (B)].

4. Broadlands

The New Zealand Electricity Department is proposing to construct a 150 MW(e) geothermal power plant near Broadlands, about 28 km (17 mi) northeast of Taupo and Wairakei. The plant will be situated adjacent to the Waikato River and will be supplied with geothermal steam from the liquid-dominated reservoirs at Ohaki and Broadlands. It is expected that the plant will be built in three phases, with each phase culminating in the installation of a 55 MW (gross), 50 MW(e) turbo-alternator unit. The first of these is planned to be in operation in October 1983, while the second and third units are expected to be commissioned in April 1984 and October 1984, respectively.

In the following sections, we shall discuss the geology of the Ohaki-Broadlands thermal area, the drilling program and the productivity of the wells, the proposed energy conversion scheme, and some of the anticipated environmental problems and suggested solutions.

4.1 Geology

The Broadlands geothermal field has been intensively studied and several reports on the geology of the site are available [Browne, 1970; Grindley, 1970; Grindley and Browne, 1975; Hochstein and Hunt, 1970; Macdonald, 1975]. The drilling of exploration wells began in 1965 with well BR1 and has continued since that time.

Figure 24 [after Bauer, *et al.*, 1977] shows the general layout of the field including the existing wells, both productive and nonproductive, the proposed steam pipe lines and a possible position for the power house and the cooling towers. The cross-section line, A-B-C, is also indicated on Fig. 24. The geologic cross-section through the field along this line is drawn in Fig. 25, in which some of the wells are also shown [Grindley, 1970].

There are three surface areas in which the ground temperature is at least 5°C (9°F) above the ambient at a depth of 1 m (3.3 ft). These are: (1) an area of roughly 365 m (1200 ft) radius centered on well BR7 (i.e., the so-called Broadlands thermal anomaly); (2) an area of roughly 550 m (1800 ft) radius centered on well BR9 (i.e., the so-called Ohaki thermal anomaly); and (3) an elongated area lying between wells BR6 and BR13 and extending about 1220 m (4000 ft) in a north-south direction [Smith, 1970]. The first two thermal areas may be seen to coincide with the Broadlands and Ohaki faults, respectively (see Fig. 25). Of the two, the Ohaki area is by far the more productive.

The complex geologic formations shown in Fig. 25 may be described as follows, with main emphasis being placed on the hydrological functions of the several layers. The surface layers consist basically of recent pumice alluvium. The Huka Falls is made up of lacustrine sediments, tuffs and grits, and serves as a cap rock for the reservoir. The Ohaki rhyolite consists of pumiceous and spherulitic rhyolite with an underlying mudstone layer. This forms a partial cap. The Waiora formation is an aquifer of pumiceous tuff-breccia. It is the shallowest useful aquifer in the Broadlands geothermal region. The thickness of the permeable layer is about 60-200 m (200-660 ft), much thinner than the corresponding area at Wairakei. It should be noted also (see Fig. 25) that this layer becomes vanishingly thin toward the southeast section of the field, i.e., at the Broadlands thermal anomaly.

The Broadlands rhyolite forms the main cap rock in the Broadlands thermal area, ranging in thickness up to 460 m (1500 ft). The Rautawiri formation of vitric-crystal-lithic tuff and tuff-breccia constitutes the next aquifer. It spans the entire thermal field. The thickness of this zone ranges from 180-335 m (600-1100 ft). The lower layer of Broadlands rhyolite, at one time, was thought to be a source of essentially dry steam for well BR7; however, this well is no longer a producer and the value of this formation has diminished. The Rangitaiki ignimbrite forms a dense cap layer. The Waikora formation appears fairly impermeable, as does the Ohakuri group. The latter is a potential aquifer consisting of pumiceous pyroclastics. The greywacke basement is essentially impermeable except possibly along the dipping fault line between wells BR14 and BR10 (see Fig. 25). Mainly, however, all joints and fractures in the greywacke are sealed with calcite and quartz.

4.2 Wells and production

As of 1977, there had been 32 wells drilled; however, only 16 of these are considered sufficiently productive to be suitable for power production. It will take 20 producing wells to supply the required steam flow for a 150 MW(e) power plant. The wells currently believed suitable for power plant use are: BR2, 3, 8, 9, 11, 13, 17-23, 25, 27 and 28.

The geological logs from the first 16 wells drilled [Smith, 1970] are shown in Fig. 26. Technical information on these wells is given in Table 16. Figure 27 shows a log of well operations for the period 1966-1969. Table 17 gives the productivity of selected wells as a function of wellhead pressure. Note that the average quality is a fairly high 42% at a pressure of 0.79 MPa (114.6 lbf/in^2)which will be required at the primary separators for the power station.

The Ohaki area behaves as a connected reservoir, whereas the Broadlands area, with considerably lower permeability, contains essentially isolated individual wells. Pressure effects induced by well production communicate, however, across the Ohaki reservoir in about one year, thus effectively isolating even the Ohaki wells on a time scale of, say, a few months. This behavior should be contrasted with that of the Wairakei field in which all wells appear to behave in unison [Grant, 1977].

Furthermore, in Wairakei the hydrothermal reservoir is probably a single-phase fluid (i.e., a pressurized liquid) with boiling occuring during drawdown. In the case of the Broadlands field, two-phase (i.e., liquid and vapor) conditions exist down to depths of about 2 km (6600 ft) owing to the pressure of a large amount of noncondensable gas (i.e., 6% CO_2 in the deep reservoir at 300°C (572°F)). In the production zone, the Waiora formation, the temperature is 260°C (500°F), the gas content is 0.6% (by weight) in the liquid phase and 23% (by weight) in the vapor phase, the pure steam saturation pressure is 4.7 MPa (681.5 lbf/in^2), and the CO_2 partial pressure is 1.5 MPa (217.5 lbf/in^2) [Grant, 1977].

The amounts of carbon dioxide (CO_2), hydrogen sulfide (H_2S) and ammonia (NH_3) in the geothermal bore steam are shown in Table 18 for several wells tested in 1976. These nine wells produced 1490 Mg/h (3.28×10^6 lbm/h) of total mass flow; the total flow of CO_2 was 12.4 Mg/h (27×10^3) lbm/h) or 0.83% (by weight) and that of H_2S was 0.159 Mg/h (351 lbm/h) or 0.011% (by weight). This amounts to about 2.4% (wt.) of CO_2 and 0.031% (wt.) of H_2S of the steam flow (based on an assumed quality of 35%) [Bauer, et al., 1977].

The composition of the separated liquid from the wellbore (at atmospheric pressure) is given in Table 19. The principal impurities in the water are: chloride, sodium, silica, bicarbonate and potassium. Boron and arsenic, both potentially dangerous elements, are also present in non-negligible amounts. We shall return to a discussion of these impurities in Sect. 4.4.

Pressure recovery and recharge studies have been conducted during the three-year period from 1971-1974, during which time the wells were essentially closed in. The pressure recovery rate averaged about 170 kPa/y (25 $lbf/in^2 \cdot y$) in the main producing area. This amounted to a recovery of about 50% of the pressure loss sustained during flow tests up to 1971.

The mass recharge was estimated to be 360 Mg/h (790 klbm/h), or the equivalent of one good producing well [Hitchcock and Bixley, 1975]. However, it is not known whether the recharge will increase or decrease when the field is being exploited. A gravity survey [Hunt and Hicks, 1975], on the other hand, showed no net mass loss from the field by 1974.

4.3 Energy conversion system

Present plans call for the construction of a 150 MW(e) geothermal power station, in three phases of 50 MW(e) each. The energy conversion system will be a separated steam/hot-water flash system (or so-called "double flash").

Certain details about the plant design are undecided at the time of writing. Nevertheless the basic plant layout will follow the generalized schematic shown in Fig. 28 (shown, however, with a direct-contact condenser). It remains to be determined whether the primary separators will be located at each wellhead or at the power house (with two-phase geofluid transmission from wellheads to power house). Furthermore, the condensers may be either direct-contact (as shown in Fig. 28) or shell-and-tube type, depending on the type of control that will be used for the emissions of H_2S.

Table 20 contains the technical specifications for the plant as proposed at this time. On the basis of these figures, the plant would have a geothermal energy resource utilization efficiency of about 43%, relative to the thermodynamic available work of the geofluid at the wellhead (with a calculated quality of 25%, assuming an isenthalpic process between the wellhead and the primary separator) and a sink at a temperature of 27°C (80°F). This efficiency is somewhat low for a double-flash plant and corresponds more nearly to that for a single-flash (or separated steam) plant [DiPippo, 1978 (B)]. For example, a comparison may be drawn between the proposed Broadlands plant and the plant at Hatchobaru, Japan, which is of similar design. The resource at Hatchobaru is of slightly better quality although the temperatures are essentially the same. The significant difference appears to be in the choice of flash temperature (or equivalently, pressure). At Hatchobaru, the flash point has been chosen more nearly to agree with the accepted rule for optimum performance (i.e., equal temperature differences between geofluid, flash vessel and condenser), whereas at Broadlands, the flash point seems to be on the high side, perhaps to avoid the possible problems associated with a flash pressure near atmospheric. As a result, the Broadlands plant will have utilization efficiency of 43% while the value for Hatchobaru is 52%.

4.4 Anticipated environmental effects

The potential damages to the environment from the Broadlands geothermal power development project have been documented in detail in the NZED Environmental Impact Report [Bauer, et al., 1977]. The material in this section is based mainly on that report. We shall concentrate our attention on the following topics: land usage, liquid and gaseous effluents, thermal discharge and subsidence.

The total area encompassed by the Ohaki and Broadlands thermal region amounts to about 1380 ha (3410 acres), with roughly 565 ha (1396 acres) lying to the west of the Waikato River where the main geothermal field is located and where the power plant will be built. Most of this land is owned by the Maori. Land on which wells are drilled has been leased from the Maori owners, and it has been made clear that geothermal development will not encroach upon sacred lands or artifacts of special tribal importance.

The power house is expected to be of the following size: 80 m in length, 35 m in width and 30 m in height (263 x 115 x 98 ft). About 4 ha (10 acres) will be reserved for the switch yard, allowing for future growth.

Although four options were given consideration for the disposal of waste bore liquid, it has been recommended that reinjection be adopted. Nevertheless, a standby cooling pond is being included in the plant design because long-term operational characteristics of reinjection remain uncertain. Should it become necessary to dump 100% of waste water into the 40 ha (100 acre) pond, at full output, it would take 31 days to reach maximum pond level. Even so, the fluid discharge would be at a temperature only 5°C (9°F) above the ambient river temperature, causing a mere 0.1°C (0.18°F) rise in the river temperature upon complete mixing. Figure 29 shows the proposed location of the cooling pond, two power house site options, and the steam/hot water mains.

The most serious chemical elements carried by the geothermal liquid (in terms of their effects on the ecology of the Waikato River) are: ammonia, NH_3; arsenic, As; boron, B; lithium, Li; and mercury, Hg (listed in order of decreasing effect). Should it become necessary to discharge the full amount of geothermal liquid into the Waikato (say, in the event of a total failure of the reinjection system), then the increment of the composition of these elements in the river water would be in the following ranges:

NH_3	0.066 - 0.360 ppm
As	0.016 - 0.080 ppm
B	0.210 - 1.000 ppm
Li	0.052 - 0.260 ppm
Hg	$(22.3 - 101.0) \times 10^{-6}$ ppm.

The range of values corresponds to average and low river flows, respectively. The NH_3 values include the amount which would enter the cooling water from the vapor phase of the geofluid. This would enter the cooling water either in the condenser (if it is of the direct-contact type) or in the wet cooling tower. About 2% of the amount shown is carried in the separated liquid stream. The same general situation exists in the case of Hg, where about 99% of this impurity is carried in the steam and only about 1% in the separated bore liquid.

There are three gaseous effluents of primary concern as regards the impact on the environment: carbon dioxide, CO_2; hydrogen sulfide, H_2S; and radon, Rn-222.

Under conditions of full power output, i.e., 150 MW(e), the following amounts of these would be released to the atmosphere, with no emissions controls on the plant:

CO_2 . . . . 35 Mg/h (55,000 lbm/h)

H_2S . . . . 0.45 Mg/h (992 lbm/h)

Rn-222 . . . . 11 nCi/h (7.5 x 10^{-17} kg/h or 1.7 x 10^{-16} lbm/h)

This quantity of CO_2 is believed to be insignificant, certainly much less than is emitted by a typical thermal power station. For H_2S, this level of emission would mean a specific emission rate of 3000 g/MW·h (6.6 lbm/MW·h), and may be compared with the proposed standard of 200 g/MW·h (0.44 lbm/MW·h) for geothermal power plants in the United States [EPA, 1978]. Furthermore, Broadlands would vent about 13 times as much H_2S into the atmosphere as does the plant at Wairakei. The concentration of Rn-222 in the exhaust stack gas would be about 0.3 pCi/ℓ, which is below the legal limit of 1 pCi/ℓ, even without dilution in the atmosphere.

Table 21 gives the concentrations of the main gaseous elements in the gas exhauster stack, assuming no emissions controls upstream of the power plant and that the condenser is of the shell-and-tube type, thus concentrating all noncondensables into the exhauster stack.

Hydrogen sulfide appears to be the only gaseous effluent which will require abatement equipment. There are several possible techniques to handle this problem:

1) iron catalyst added to cooling water,

2) incineration of H_2S to form SO_2 which is then scrubbed,

3) Stretford sulfur recovery process,

4) modified Claus process,

5) Takahax process (similar to Stretfcrd process),

6) Giammarco-Vetrocoke process.

In any case, it appears feasible to reduce the H_2S emissions from 0.45 Mg/h to about 0.07 Mg/h, or less, by means of treatment of the exhaust stack gas alone. By adding shell-and-tube condensers and preventing the H_2S from dissolving in the cooling water, this could be reduced a full order of magnitude to 0.007 Mg/h (15 lbm/h) or 47 g/MW·h (0.10 lbm/MW·h).

Land subsidence at Broadlands could result in a serious problem of inundation by the waters of the Waikato River if subsidence trends during exploration continue. Figure 30 shows subsidence contours during the period May 1968 - March 1974. Maximum subsidence was about 190 mm (7.5 in) for a total mass draw-off of about 35×10^9 (77×10^9 lbm). This is very nearly the required annual draw-off to supply the 150 MW(e) plant. The center of the subsidence area is within about 500 m (1640 ft) of the west bank of the Waikato River. It is likely that some type of retaining wall may be necessary to prevent inundation of the field after, say, 20 years of operation. Furthermore, as the wells on the east side of the river begin producing in larger quantities, the center of the subsidence may, in fact, shift even closer to the river, thereby causing a more immediate problem. The power house will be located west of the area affected by subsidence and presumably will not be subjected to problems of differential ground movement. (Cf. Figs. 24 and 30.)

5. Other geothermal areas in New Zealand

The thermal belt across North Island from Lake Taupo to White Island in the Bay of Plenty abounds with thermal areas, some of which may prove useful for the generation of electricity, district or process heating, or other commerical or industrial applications.

Some of the areas that have been investigated include:

Ngawha ... bottom-hole temperature ≈ 236°C (457°F), but low reservoir permeability.

Orakeikorako ... few producing wells, low quality steam, infiltration of cold water.

Reporoa ... unimpressive temperature and low reservoir permeability.

Rotokawa ... bottom-hole temperatures ≈ 306°C (583°F), high steam quality, but high noncondensables and only moderate reservoir permeability.

Tauhara ... adjacent to Wairakei, very similar temperatures with higher pressures, some weak linkage between Wairakei and Tauhara but not enough to influence production at either site.

Te Kopia ... field aligned with fault scrap, steam output is moderate but of low quality, highest temperatures occur in upper formation, become indifferent at depth.

Te Mihi ... extension of Wairakei field, at least one well has been connected to Wairakei system.

Waiotapu ... area of considerable thermal potential, shallow wells rapidly develop calcite deposits, deep wells are more promising.

There are other areas that hold promise, and the interested reader may consult several references for further details [Dench, 1961; Smith, 1970; Smith and McKenzie, 1970; Bolton, 1977]. Presently, however, there are no plans to install electric generating stations at any of these geothermal areas.

Part II. The Philippines

6. Introduction

Geothermal energy presently accounts for 3 MW of electricity in the Philippines. According to optimistic projections this will rise to 1320 MW by 1985. By that time, geothermal energy would supply nearly one-quarter of the total electric generating capacity of the country.

In this report we shall cover the main geothermal areas in some detail and briefly discuss the ambitious geothermal development program of the Philippines.

7. Tiwi

Tiwi is the site of one of the principal geothermal fields in the Philippines. It has been one of the most popular hot springs on the island of Luzon in Albay Province. It is located at the far southeastern tip of Luzon, about 300 km (185 mi) from Manila [Muffler, 1975].

7.1 Exploration

The Tiwi field has been investigated using a number of techniques including Wenner and dipole-dipole resistivity surveys, geological, heat flow and geochemical methods. The exploratory work began in 1964 through the Philippine Commission on Volcanology, supported with financial assistance from the National Science Development Board.

As a result of the surveys, an area of 2300 ha (5680 acres) was outlined as a potential reservoir at drillable depths. Fourteen wells were sunk inside the resistivity low, and confirmed the indications of the surveys. The wells produced a mixture of liquid and vapor at high flow rates, and revealed the nature of the reservoir. The Tiwi system is a liquid-dominated field in a reservoir of Quaternary andesites and subsidiary decites. It is believed that a system of microfractures lend permeability to the reservoir. These findings were reported by A. P. Alcaraz in 1976 and quoted by Ravenholt [Ravenholt, 1977 (A)].

A total of 20 wells have now been drilled, with 19 of these being producers; they extend to depths of between 760-2130 m (2500-7000 ft). The wells were drilled by Philippine Geothermal, Inc., a wholly owned subsidiary of the Union Oil Company, who subcontracted the actual drilling operations to Richter Drilling International Pty., Ltd., of Australia. Two rigs are kept active with three work shifts.

7.2 Energy conversion system

The preliminary design, equipment procurement, specifications and contract documents for the first two units at Tiwi were carried out by Rogers International. The Tokyo Shibaura Electric Company of Japan (Toshiba) holds orders for the turbo-generators for the first four units to be installed at Tiwi. Each of these are identical, 55 MW(e), single-cylinder, double-flow, 6 x 2 stage machines of the dual-admission type. The technical specifications for these units are given in Table 22 [Toshiba, 1977]. The generators for the units will be rated at 69,000 kVA at 13.8 kV and 60 Hz with 0.8 power factor. The stator will be conventionally hydrogen cooled; the rotor direct hydrogen cooled.

The energy conversion scheme is a separated-steam/hot-water flash ("double flash") system. A simplified schematic and thermodynamic state diagram would be the same as shown earlier for the Broadlands, New Zealand plant. (See Fig. 28.) Since the flow rate of steam required for plant operation is not known at this time, it is not possible to compute precisely the geothermal resource utilization efficiency for the plant. However, it is anticipated that 10 producing wells will be needed for each 55 MW unit, and using as a guide Units 9 and 10 at The Geysers, California [DiPippo, 1978 (C)], which are both 55 MW, condensing units manufactured by Toshiba, each unit will require roughly 454 Mg/h (1.0 x 10^6 lbm/h) of geothermal steam. For an average wellhead quality $\bar{x}$ = 25%, the resource utilization efficiency, η_u, would be approximately 41%; for x = 30%, $\eta_u \approx$ 49%; for $\bar{x}$ = 35%, $\eta_u \approx$ 57%. These estimates are all based on the available work of the geofluid at the wellhead.

Each unit of the power plant will produce about 1247 Mg/h (2.75 x 10^6 lbm/h) of waste liquid which will be disposed of by means of reinjection wells.

It was originally planned to have Units 1 and 2 on-line during 1978; this date, however, is doubtful. It is more likely that all four units will be operating by 1981.

8. Los Baños

Los Baños lies about 70 km (43 mi) southeast of Manila on the island of Luzon. It is part of a huge area with a geothermal potential of around 720 MW; the area extends over 153,000 ha (378,000 acres) in the Makiling-Banahaw volcanic region.

8.1 Well production

At least 14 wells have been drilled at the Los Baños thermal area. Bottom-hole temperatures are in the range 280-310°C (540-590°F), and geofluid qualities as high as 36% at the wellhead have been reported [Ravenholt, 1977 (A)]. Most of the wells are located about 450 m (1475 ft) above sea level near Mount Bulalo.

8.2 Energy conversion systems

A small wellhead auxiliary geothermal power unit has been operating at Los Baños since early 1977. It was supplied by Mitsubishi Heavy Industries, Ltd. (MHI); the technical particulars of this machine may be found in Table 23.

The main power units for Los Baños will consist of four identical units, each of 55 MW(e) capacity, of the single-cylinder, double-flow, mixed pressure, impulse-reaction design. The process flow diagram will be similar to that shown earlier in Fig. 28, i.e., a separated-steam/hot-water flash ("double flash") system. Table 24 contains the technical specifications for each of the first four units. According to these particulars, the geothermal resource utilization efficiency, η_u, will be as follows, depending on the actual quality, x, of the geofluid at the wellhead: η_u = 54% for x = 25%; η_u = 57% for x = 30%; η_u = 60% for x = 35%.

9. Tongonan

A 3 MW portable geothermal unit is operating at Tongonan on the island of Leyte. The unit consists of a noncondensing turbine (single Curtis stage) connected to a generator through a helical reduction gear. The entire unit is mounted on a platform to facilitate its transfer from one site to another. It was manufactured by MHI, Ltd. The technical specifications are given in Table 25; Figure 31(a) shows the power house and (b) the assembled power unit being tested in the MHI shop [Ravenholt, 1977 (A); MHI, 1977].

Small, "wellhead" units of this type in the 1-10 MW range are expected to find application in those cases where large units are either unnecessary or impractical, particularly on the smaller islands of the Philippines such as the Visayan group of Leyte, Cebu, Bohol, Negros and Panay. The electricity produced from them is cheaper than that generated by diesel engines. In any case, the use of wellhead units provides a source of revenue and local power during the early stages of development of a geothermal field. The revenue obtained helps to alleviate the cash flow problem faced by field developers.

10. Other Philippine geothermal areas with potential for power generation

The potential for geothermal development in the Philippines is significant; 1320 MW by 1985, as mentioned earlier. Table 26 gives a breakdown of the distribution of the expected generating capacity. In addition to the sites listed, initial investigations are underway at Mambucal in northern Negros. Resistivity surveys indicate that the potential of the fields included in the table exceeds 2200 MW.

Some idea of the scope of the effort that will be needed to achieve an installed capacity of 1320 MW in 1985 can be gotten from the fact that about 10 producing wells are needed for each 55 MW unit. Thus, 240 producing wells must be drilled; allowing 3 out of every 4 wells drilled to be producers, a total of 320 wells must be sunk. Assuming that each well costs $1,000,000 (current costs are $750,000), this will necessitate a capital investment, for wells alone, of $320,000,000. Taking into account both the time required to prove a field and the construction lead time for a power plant, it is difficult to imagine how such an enormous project can be accomplished within seven years. Simply to drill the required wells within that time would mean that roughly four wells would have to be drilled each month.

Nevertheless the opportunity exists for the Philippines to supply a significant percentage of its electrical needs from indigenous, geothermal energy. The high cost of imported petroleum products provides a great deal of motivation to get on with the development of the geothermal resources of the country.

Part III. Indonesia

11. Introduction

Indonesia's location at the junction of three tectonic plates with the associated volcanism and earthquake activity together with its average annual rainfall of 2000 mm (79 in) create a potentially valuable source of geothermal (hydrothermal) power. Exploration for geothermal energy began in 1926 and extensive geophysical, geological and geochemical surveys have been conducted by various teams of scientists from France, Japan, New Zealand, the United States, and the United Nations (UNESCO). A summary of these studies has recently been published [Radja, 1975]. Among the many promising thermal areas, the one at which a geothermal power plant is likely to appear first is Kawah Kamojang.

12. Kawah Kamojang

A 250 kW wellhead power generating unit has been purchased and will soon be operational at Kawah Kamojang. Fumaroles abound at this thermal site, the oldest to be discovered and explored in the Indonesian archipelago.

12.1 Exploration

The geothermal field of Kawah Kamojang, along with two other solfatara and fumarolic areas, Kawah Manuk and G. Wayang, is located in the southern Priangan thermal anomaly on the western side of the island of Java, about 42 km (26 mi) southeast of the city of Bandung. The area is marked by acid intrusions of quartz diorite and extrusions (dacites). Siliceous sinter has been deposited by several hot springs, leading one to believe that high temperatures exist at depth [Radja, 1975]. The area of the geothermal field is estimated to be about 1400 ha (3500 acres) [Hochstein, 1975]; the area enclosed within a 10 $\Omega \cdot m$ contour of a resistivity mapping is about 600 ha (1500 acres) [Radja, 1975].

Figure 32 shows the Kamojang area including the location of resistivity traverses, resistivity sounding profiles and temperature gradient holes [Hochstein, 1975]. Figure 33 gives a more detailed view and includes the location of exploratory shallow and deep wells [Hochstein, 1975].

Temperature gradients as high as 0.35°C/m (0.19°F/ft), or about 12 times normal, have been measured in the Pangkalan portion of the field. One of the earliest wells drilled is still producing; steam flows at 130°C (266°F) and 12.4 Mg/h (27.3 klbm/h). This particular well (Well No. 3) was drilled in 1926 [Stehn, 1929; Kartokusumo, et al., 1975]. The steam contains between 2-4% by weight of noncondensable gases; CO_2 makes up about 96.5% by volume, H_2S about 1.85%, with CH_4, H_2 and N_2 making up the bulk of the residuals [Kartokusumo, et al., 1975].

The findings indicate that Kawah Kamojang is a vapor-dominated field, perhaps a dry steam field, to shallow depths of at least 130 m (425 ft). The maximum temperature at these depths is about 238°C (460°F). Hochstein states that the reservoir is quite extensive, and is between 200-500 m (656-1640 ft) thick, with a power potential of between 100-250 MW for 50 years [Hochstein, 1975]. Furthermore, he concludes that vapor-dominated hydrothermal systems in young volcanic rocks may be much more common than previously believed.

12.2 Wellhead generator

Power production at Kamojang is expected to begin later this year. Geothermal Power Company of New York has supplied a 250 kW, noncondensing, wellhead turbo-generator to PERTAMINA, The State Oil and Natural Gas Mining Company [GR, 1978]. The unit is self-contained and consists of a turbine, generator, controls, gearbox and exhaust silencer diffuser mounted on a platform. GPC calls the unit a "Monoblok" system. The package cost just over $400/kW. The power generated will be used during the development phase of the project.

13. Other geothermal areas in Indonesia

A large number of thermal areas are evident throughout the Indonesian archipelago. Surface manifestations such as hot springs, boiling mud pools, solfataras and/or fumaroles are present at the sites listed below. Some surveys have been conducted at a few of them, and the reader is referred to other sources of information for more details [Akil, 1975; Muffler, 1975; Radja, 1975].

On the island of Java:

Danau (Banten) ... hot springs are abundant.

Dieng ... liquid-dominated reservoir, 5 wells drilled, maximum bottomhole temperature is 173°C (343°F) at 139 m (456 ft).

Ijen ... hot springs are present.

Kawah Cibeureum ... access to site is very difficult.

Kawah Derajat ... resistivity surveys are encouraging, located 12 km (7.5 mi) SE of Kamojang.

Kromong-Careme ... hot springs show high CO_2 content.

On the island of Sumatra:

Toba ... geological structure is favorable.

Padang Highlands ... strongly altered hydrothermal and dynamo metamorphism.

Pasumah ... thermal springs with temperatures up to 100°C (212°F), hydrothermally altered rock, deposits of siliceous travertines.

On the island of Borneo:

Kalimantan ... at least 10 thermal springs, one prospective geothermal area is located about 100 km (62 mi) NW of Amuntai.

On the island of Halmahera:

North Halmahera ... possible natural steam reservoir, needs much more study.

On the island of Sulawesi:

Minahasa ... young Quaternary volcanism.

Gorontalo ... little information available.

Central Sulawesi ... little information available.

South Sulawesi ... nine geothermal fields are located in this region (Parara, Mamasa, Somba, Sangala, Pambusuan, Sulili, Masepe, Sinjai and Malawa), temperature of hot springs is as high as 70°C (158°F).

On the islands of Nusa Tenggara:

Waikokor, Wai Pesih and Magekoba ... these three geothermal fields were studied in 1969 for possible electric power generation, hot springs exist at temperatures from 54-115°C (129-239°F), strong hydrothermal alterations.

In conclusion, since many of the geothermal regions of the Indonesian archipelago are nearly inaccessible on foot, aerial reconnaissance is often the only resort. On the basis of such surveys, there is evidence that Indonesia possesses a large store of geothermal energy. The demand for electric power is expected to reach 5100 MW in 1990; it was less than 1000 MW in 1975. Although there are large supplies of petroleum within Indonesia, it is often difficult to transport it to the places where power is needed and, besides, it is a very valuable export commodity. Thus, geothermal energy, with its low cost and indigenous advantages, figures to play an important role in meeting the growing demand for electrical power in Indonesia.

References

Note: The following three references are cited several times:

Proceedings of the United Nations Conference on New Sources of Energy: Solar Energy, Wind Power and Geothermal Energy, Aug. 21-31, 1961, Rome, Italy, Vols. 2 and 3, "Geothermal Energy"; United Nations, New York, 1964. (Referred to as Rome-1961, hereafter.)

Proceedings of the United Nations Symposium on the Development and Utilization of Geothermal Resources, Sept. 22-Oct. 1, 1970, Pisa, Italy; Geothermics, Spec. Issue 2, Vols. 1 and 2, Pergamon Press, Inc., New York, 1970. (Referred to as Pisa-1970, hereafter.)

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, DC, 1976. (Referred to as San Francisco-1975, hereafter.)

Akil, I., 1975, "Development of Geothermal Resources in Indonesia," San Francisco-1975, Vol. 1, pp. 11-15.

Armstead, H.C.H., 1961, "Geothermal Power Development at Wairakei, New Zealand," Rome-1961, Vol. 3, pp. 274-283.

Axtmann, R.C., 1974, "An Environmental Study of the Wairakei Power Plant," N. Z. Dept. Sci. Ind. Res., Phys. Eng. Lab. Rep. No. 445.

Axtmann, R.C., 1975(A), "Environmental Impact of a Geothermal Power Plant," Science, Vol. 187, pp. 795-803.

Axtmann, R.C., 1975(B), "Emission Control of Gas Effluents from Geothermal Power Plants," Environ. Letters, Vol. 8, No. 2, p. 135.

Bauer, H.E., Jones, E.M.E., Stirling, J.J., Willis, D.J. and Wu, P., 1977, "Environmental Impact Report for the Broadlands Geothermal Power Development," New Zealand Electricity Department, Power Development Section, Wellington, N.Z.

Bolton, R.S., 1970, "The Behaviour of the Wairakei Geothermal Field During Exploitation," Pisa-1970, Vol. 2, pp. 1426-1439.

Bolton, R.S., 1975, "Recent Developments and Future Prospects for Geothermal Energy in New Zealand," San Francisco-1975, Vol. 1, pp. 37-42.

Bolton, R.S., 1977, "Geothermal Energy in New Zealand," in Energy Technology Handbook, D. M. Considine, Ed.-in-Chief, McGraw-Hill, New York, pp. 7.14-7.33.

Browne, P.R.L., 1970, "Hydrothermal Alteration as an Aid in Investigating Geothermal Fields," Pisa-1970, Vol. 2, pp. 564-570.

Craig, S.B., 1961, "Geothermal Drilling Practices at Wairakei, New Zealand," Rome-1961, Vol. 3, pp. 121-133.

Dench, N.D., 1961, "Investigations for Geothermal Power at Waiotapu, New Zealand," Rome-1961, Vol. 2, pp. 179-191.

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.

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

Fisher, W.M., 1961, "Drilling Equipment Used at Wairakei Geothermal Power Project, New Zealand," Rome-1961, Vol. 3, pp. 154-168.

Fooks, A.C.L., 1961, "The Development of Casings for Geothermal Boreholes at Wairakei, New Zealand," Rome-1961, Vol. 3, pp. 170-183.

Glover, R.B., 1970, "Interpretation of Gas Compositions from the Wairakei Field over 10 Years," Pisa-1970, Vol. 2, pp. 1355-1366.

GR, 1978, Geothermal Report, R. A. Smith, Publisher-Editor, Vol. VII, No. 11, June 1, p. 4.

Grant, M.A., 1977, "Broadlands - A Gas-Dominated Geothermal Field," Geothermics, Vol. 6, pp. 9-29.

Grindley, G.W., 1961, "Geology of New Zealand Geothermal Steam Fields," Rome-1961, Vol. 2, pp. 237-245.

Grindley, G.W., 1970, "Subsurface Structures and Relation to Steam Production in the Broadlands Geothermal Field, New Zealand," Pisa-1970, Vol. 2, pp. 248-261.

Grindley, G.W. and Browne, P.R.L., 1975, "Structural and Hydrological Factors Controlling the Permeabilities of Some Hot-Water Geothermal Fields," San Francisco-1975, Vol. 1, pp. 377-386.

Haldane, T.G.N. and Armstead, H.C.H., 1962, "The Geothermal Power Development at Wairakei, New Zealand," Proc. Inst. Mech. Engrs., Vol. 176, No. 23, pp. 603-649.

Hitchcock, G.W. and Bixley, P.F., 1975, "Observations of the Effect of a Three-Year Shutdown at Broadlands Geothermal Field, New Zealand," San Francisco-1975, Vol. 3, pp. 1657-1661.

Hochstein, M.P., 1975, "Geophysical Exploration of the Kawah Kamojang Geothermal Field, West Java," San Francisco-1975, Vol. 2, pp. 1049-1058.

Hochstein, M.P. and Hunt, T.M., 1970, "Seismic, Gravity and Magnetic Studies, Broadlands Geothermal Field, New Zealand," Pisa-1970, Vol. 2, pp. 333-346.

Hunt, A.M., 1961, "The Measurement of Borehole Discharges, Downhole Temperatures and Pressures, and Surface Heat Flows at Wairakei," Rome-1961, Vol. 3, pp. 196-207.

Hunt, T.M., 1977, "Recharge of Water in Wairakei Geothermal Field Determined from Repeat Gravity Measurements," N.Z.J. Geol. Geophys., Vol. 20, No. 2, pp. 303-317.

Hunt, T.M. and Hicks, S.R., 1975, "Repeat Gravity Measurements at Broadlands Geothermal Field, 1967-1974," Geophys. Div. Rep. No. 113, Geophysics Division, DSIR, Wellington, N.Z.

Kartokusumo, W., Mahon, W.A.J. and Seal, K.E., 1975, "Geochemistry of the Kawah Kamojang Geothermal System, Indonesia," San Francisco-1975, Vol. 1, pp. 757-759.

Kestin, J., 1978, "Available Work in Geothermal Energy," Brown Univ. Rep. No. CATMEC/20, D.O.E. No. COO/4051-25, Providence, RI.

Lindal, B., 1973, "Industrial and Other Applications of Geothermal Energy," Geothermal Energy: Review of Research and Development, H.C.H. Armstead, ed., UNESCO, Paris, pp. 135-148.

Macdonald, W.J.P., 1975, "The Useful Heat Contained in the Broadlands Geothermal Field," San Francisco-1975, Vol. 2, pp. 1113-1119.

McLeod, N.C., 1977, Personal communication, August 8, Ministry of Works and Development, Wellington, New Zealand.

McNitt, J.R., 1965, "Review of Geothermal Resources," Terrestrial Heat Flow, W. H. K. Lee, ed., Geophysical Monograph Series No. 8, Amer. Geophy. Union of NAS-NRC, Pub. No. 1288.

MHI, 1977, "Portable Geothermal Power Plant - 3,000 kW Leyte Geothermal Power Plant in Philippines," Mitsubishi Heavy Industries, Ltd., Nagasaki Shipyard & Engine Works, Nagasaki, Japan.

Milora, S.L. and Tester, J.W., 1976, Geothermal Energy as a Source of Electric Power, MIT Press, Cambridge, MA.

Miner, S., 1969, "Preliminary Air Pollution Survey of Hydrogen Sulfide: A Literature Review," Nat. Air Poll. Cont. Adm., Raleigh, N.C.

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

NZED, 1974, "Wairakei - Power from the Earth," New Zealand Electricity Department, Pamphlet No. 50392H, A. R. Shearer, Gov. Printer, Wellington, N.Z.

NZED, 1975, "Wairakei Power Station," New Zealand Electricity Department, Pamphlet No. 60657H, A. R. Shearer, Gov. Printer, Wellington, N.Z.

Radja, V., 1975, "Overview of Geothermal Energy Studies in Indonesia," San Francisco-1975, Vol. 1, pp. 233-240.

Ravenholt, A., 1977(A), "Energy from Heat in the Earth - Philippines Taps Immense Resources of Pacific Fire Belt," Fieldstaff Reports, Southeast Asia Series, Vol. XXV, No. 5.

Ravenholt, A., 1977(B), "Wairakei and New Zealand's Geothermal Power," Fieldstaff Reports, Southeast Asia Series, Vol. XXV, No. 6.

Reay, P. F., 1972, "The Accumulation of Arsenic from Arsenic-Rich Natural Waters by Aquatic Plants," J. Appl. Ecol., Vol. 9, pp. 557-565.

Smith, J.H., 1961(A), "Casing Failures in Geothermal Bores at Wairakei," Rome-1961, Vol. 3, pp. 254-261.

Smith, J.H., 1961(B), "The Organization for and Cost of Drilling Geothermal Steam Bores," Rome-1961, Vol. 3, pp. 264-268.

Smith, J.H., 1970, "Geothermal Development in New Zealand," Pisa-1970, Vol. 2, pp. 232-247.

Smith, J.H. and McKenzie, G.R., 1970, "Wairakei Power Station New Zealand - Economic Factors of Development and Operation," Pisa-1970, Vol. 2, pp. 1717-1723.

Stehn, C.E,, 1929, "Kawah Kamojang," Fourth Pacific Science Congress, Java, Indonesia.

Stilwell, W.B., 1970, "Drilling Practices and Equipment in Use at Wairakei," Pisa-1970, Vol. 2, pp. 714-724.

Stilwell, W.B., Hall, W.K. and Tawhai, J., 1975, "Ground Movement in New Zealand Geothermal Fields," San Francisco-1975, Vol. 2, pp. 1427-1434.

Toshiba, 1977, "Toshiba Experience List on Geothermal Power Plant," Tokyo Shibaura Electric Company, Ltd., Heavy Apparatus Division, Tokyo, Japan.

Usui, T., and Aikawa, K., 1970, "Engineering and Design Features of the Otake Geothermal Power Plant," Pisa-1970, Vol. 2, pp. 1533-1545.

Wahl, E.F., 1977, Geothermal Energy Utilization, John Wiley & Sons, New York, NY.

Weissberg, B.G. and Zobel, M.G.R., 1973, Bull. Environ. Contam. Toxicology, Vol. 9, p. 148.

Wigley, D.M., 1970, "Recovery of Flash Steam from Hot Bore Water," Pisa-1970, Vol. 2, pp. 1588-1591.

Woods, D.I., 1961, "Drilling Mud in Geothermal Drilling," Rome-1961, Vol. 3, pp. 270-273.

Table 1

Drilling program for medium-depth wells at Wairakei

[Stilwell, 1970]

For 559 mm (22 in) O.D. casing:

Drill 311 mm (12.25 in) diameter pilot hole.
Open out to 660 mm (26 in) diameter.
Use 184 mm (7.25 in) O.D. drill collars.
Run and cement casing; Set up Stage 1 wellhead. (See Fig. 6.)

For 406 mm (16 in) O.D. casing:

Drill 311 mm (12.25 in) diameter pilot hole.
Open out to 533 mm (21 in) diameter with expanding hole opener.
Use 184 mm (7.25 in) O.D. drill collars and 168 mm (6.625 in) O.D. drill pipe.
Run and cement casing; Set up Stage 2 wellhead. (See Fig. 6.)

For 298 mm (11.75 in) O.D. casing:

Drill 381 mm (15 in) diameter hole.
Use 184 mm (7.25 in) O.D. drill collars and 168 mm (6.625 in) O.D. drill pipe.
Run and cement casing; Set up Stage 3 wellhead. (See Fig. 6.)

For 219 mm (8.625 in) O.D. casing:

Drill 270 mm (10.625 in) diameter hole.
Use 184 mm (7.25 in) O.D. drill collars and 89 mm (3.5 in) O.D. drill pipe.
Run and cement casing; Set up Stage 4 wellhead. (See Fig. 6.)

For 168 mm (6.625 in) O.D. slotted liner:

Drill 194 mm (7.625 in) diameter hole.
Use 146 mm (5.75 in) O.D. drill collars and 89 mm (3.5 in) O.D. drill pipe.
Run liner with "J" slot.

Table 2

Drilling program for deep wells at Wairakei

[Stilwell, 1970]

For 559 mm (22 in) O.D. casing:

Drill 311 mm (12.25 in) diameter pilot hole.
Open out to 660 mm (26 in) diameter.
Use 229 mm (9 in) and 203 mm (8 in) O.D. drill collars.
Run and cement casing; Set up Stage 1 wellhead. (See Fig. 7.)

For 457 mm (18 in) O.D. casing:

Drill 311 mm (12.25 in) diameter pilot hole.
Open out to 533 mm (21 in) diameter with expanding hole opener.
Use 229 mm (9 in) and 203 mm (8 in) O.D. drill collars, and 114 mm (4.5 in) O.D. drill pipe.
Run and cement casing; Set up Stage 2 wellhead. (See Fig. 7.)

For 340 mm (13.375 in) O.D. casing:

Drill 311 mm (12.25 in) diameter pilot hole.
Open out to 419 mm (16.5 in) diameter with hole opener.
Use 229 mm (9 in) and 203 mm (8 in) O.D. drill pipes, and 114 mm (4.5 in) O.D. drill pipe.
Run and cement casing; Set up Stage 3 wellhead. (See Fig. 7.)

For 244 mm (9.625 in) O.D. casing:

Drill 311 mm (12.25 in) diameter hole.
Use 203 mm (8 in) O.D. drill collars and 114 mm (4.5 in) O.D. drill pipe.
Run and cement casing; Set up Stage 4 wellhead. (See Fig. 7.)

For 194 mm (7.625 in) slotted lines:

Drill 216 mm (8.5 in) diameter hole.
Use 159 mm (6.25 in) O.D. drill collars and 114 mm (4.5 in) O.D. drill pipe.
Run liner with "J" slot.

Table 3

Country	New Zealand
Unit name	Wairakei: Station A, HP Units (2 units)
Owner	New Zealand Electricity Department
Year of start-up	1958, 1959
Plant type	Separated steam/multiple flash

Turbine characteristics/unit

Manufacturer	British Thomson-Houston	
Type	Single-cylinder, single-flow, noncondensing	
Rated capacity	6.5 MW	
Maximum capacity	6.5 MW	
Speed	3000 rev/min	
Steam inlet pressure (1)	910 kPa	132 lbf/in^2
Steam inlet temperature	175.8°C	348.5 °F
Noncondensable gas content	0.5 % by weight of inlet steam	
Exhaust pressure	∿ 441 kPa	∿ 64 lbf/in^2
Turbine steam flow rate	(NA)(2) Mg/h	(NA) lbm/h
Maximum allowable pressure	(NA) kPa	(NA) 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

(1) Original pressure was 1338 kPa (194 lbf/in^2), but has been reduced owing to deterioration of reservoir pressure. Note that Bolton [1977] reported 1009 kPa (146 lbf/in^2) in his Fig. 12, but gave the values shown above in the text.

(2) Original flow rate was 144.7 Mg/h (0.319 x 10^6 lbm/h), per unit.

Table 4

Country	New Zealand
Unit name	Wairakei: Station A, HP Units (2 units)
Owner	New Zealand Electricity Department
Year of start-up	1962
Plant type	Separated steam/multiple flash

Turbine characteristics/unit

Manufacturer	British Thomson-Houston	
Type	Single-cylinder, single-flow, noncondensing	
Rated capacity	11.2 MW	
Maximum capacity	11.2 MW	
Speed	3000 rev/min	
Steam inlet pressure (1)	910 kPa	132 lbf/in^2
Steam inlet temperature	175.8 °C	348.5 °F
Noncondensable gas content	0.5 % by weight of inlet steam	
Exhaust pressure	∿ 441 kPa	∿ 64 lbf/in^2
Turbine steam flow rate	(NA)(2) Mg/h	(NA) lbm/h
Maximum allowable pressure	(NA) kPa	(NA) 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

(1) Original pressure was 1338 kPa (194 lbf/in^2), but has been reduced owing to deterioration of steam reservoir pressure.

(2) Original flow rate was 258.0 Mg/h (0.569 × 10^6 lbm/h), per unit.

Table 5

Country	New Zealand
Unit name	Wairakei: Station A, IP Units (2 units)
Owner	New Zealand Electricity Department
Year of start-up	1959
Plant type	Separated steam/multiple flash

Turbine characteristics/unit

Manufacturer	British Thomson-Houston	
Type	Single-cylinder, single-flow, noncondensing	
Rated capacity	11.2 MW	
Maximum capacity	11.2 MW	
Speed	3000 rev/min	
Steam inlet pressure	441 kPa	64.0 lbf/in^2
Steam inlet temperature	147 °C	297 °F
Noncondensable gas content	~ 0.4 % by weight of inlet steam	
Exhaust pressure	106.7 kPa	15.5 lbf/in^2
Turbine steam flow rate	~ 209 Mg/h	~ 0.46 $\times 10^6$ lbm/h
Maximum allowable pressure	(NA) kPa	(NA) 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 6

Country	New Zealand
Unit name	Wairakei: Station A, LP Units (4 units)
Owner	New Zealand Electricity Department
Year of start-up	1959, 1960
Plant type	Separated steam/multiple flash

Turbine characteristics/unit

Manufacturer	British Thomson-Houston	
Type	Single-cylinder, single-flow, condensing	
Rated capacity	11.2 MW	
Maximum capacity	11.2 MW	
Speed	3000 rev/min	
Steam inlet pressure	∿ 103.4 kPa	∿ 15.0 lbf/in^2
Steam inlet temperature	∿ 100.6°C	∿ 213 °F
Noncondensable gas content	∿ 0.4 % by weight of inlet steam	
Exhaust pressure	5.1 kPa	1.5 in Hg
Turbine steam flow rate	∿ 130 Mg/h	∿ 0.287 × 10^6 lbm/h
Maximum allowable pressure	(NA) kPa	(NA) lbf/in^2
Last stage blade height	(NA) mm	(NA) in

Condenser characteristics/unit

Type	Spray jet, barometric	
Pressure	5.1 kPa	1.5 in Hg
Cooling water temperature	15.0 °C	59.0 °F
Outlet water temperature (1)	29.5 °C	85.1 °F
Cooling water flow rate (1)	∿ 5,039 Mg/h	∿ 11.1 × 10^6 lbm/h

(1) Average values.

Table 6 (cont.)

Gas extractor characteristics

Type	Steam jet ejector	
Number of stages or sets	3	
Suction pressure	5.1 kPa	1.5 in Hg
Capacity	(NA) m^3/h	(NA) ft^3/min
Steam consumption	(NA)	

Heat rejection system characteristics/unit

Type	Waikato River	
Number of cells	-	
Water inlet temperature	15.0 °C	59.0 °F
Water outlet temperature	29.5 °C	85.1 °F
Design wet-bulb temperature	- °C	- °F
Water flow rate	∿ 6.04 Gg/h	∿ 11.1×10^6 lbm/h
Water pump power	100 kW	
Draft fan type	(None)	
Air flow rate/fan	- m^3/s	- ft^3/min
Fan motor power	- kW	

Table 7

Country	New Zealand
Unit name	Wairakei: Station B, MP Units (3 units)
Owner	New Zealand Electricity Department
Year of start-up	1962, 1963
Plant type	Separated steam/ multiple flash

Turbine characteristics/unit

Manufacturer	Asociated Electrical Industries	
Type	Single-cylinder, single-flow, pass-in, condensing	
Rated capacity	30.0 MW	
Maximum capacity	30.0 MW	
Speed	1500 rev/min	
Main steam inlet pressure	441 kPa	64 lbf/in^2
Main steam inlet temperature	147 °C	297 °F
Secondary steam pressure	∿ 103.4 kPa	∿ 15 lbf/in^2
Secondary steam temperature	∿ 100.6 °C	∿ 213 °F
Noncondensable gas content	∿ 0.4% by weight of main steam	
Exhaust pressure	5.1 kPa	1.5 in Hg
Main steam flow rate	∿ 181.3 Mg/h	∿ 0.4×10^6 lbm/h
Secondary steam flow rate	∿ 45.3 Mg/h	∿ 0.1×10^6 lbm/h
Maximum allowable pressure	(NA) kPa	(NA) lbf/in^2
Last stage blade height	(NA) mm	(NA) in

Condenser characteristics/unit

Type	Spray jet, barometric	
Pressure	5.1 kPa	1.5 in Hg
Cooling water temperature	15.0 °C	59.0 °F
Outlet water temperature	29.5 °C	85.1 °F
Cooling water flow rate	∿ 7,460 Mg/h	∿ 16.4×10^5 lbm/h

Table 7 (cont.)

Gas extractor characteristics

Type	Steam jet ejector	
Number of stages or sets	3	
Suction pressure	5.1 KPa	1.5 in Hg
Capacity	(NA) m^3/h	(NA) ft^3/min
Steam consumption	(NA)	

Heat rejection system characteristics/unit

Type	Waikato River	
Number of cells	-	
Water inlet temperature	15.0 °C	59.0 °F
Water outlet temperature	29.5 °C	85.1 °F
Design wet-bulb temperature	- °C	- °F
Water flow rate	∿ 7.46 Gg/h	∿ 16.4×10^6 lbm/h
Water pump power	∿ 2 kW	
Draft fan type	(None)	
Air flow rate/fan	- m^3/s	- ft^3 min
Fan motor power	- kW	

Table 8

Geothermal resource utilization efficiency calculation

(See Fig. 14 for state designations)

	Mg/h	lbm/h
Steam flow rate per 6.5-MW HP unit.	144.7	319,000
Steam flow rate per 11.2-MW HP unit	258.1	569,000
Total H.P. steam flow rate.	805.6	1,776,000
Total H.P. liquid flow rate(1).	3222.4	7,104,000
Steam flow rate at state d(2)	28.4	62,660
Steam flow rate per 11.2-MW IP unit	208.7	460,000
Steam flow rate per 30-MW MP unit(3). . . .	181.4	400,000
Total I.P. steam at state d'.	127.6	281,340
Total I.P. liquid at state h(4)	191.4	422,010
Enthalpy:	kJ/kg	Btu/lbm
State a	212.6	494.56
State h	232.3	540.34
State o(5).	12.1	28.06
Entropy:	kJ/kg·K	Btu/lbm·R
State a	0.55489	0.71704
State h	0.62040	0.80170
State o	0.04295	0.05550
Availability rate:	GJ/h	10^6 Btu/h
State a	1147.7	1087.8
State h	116.1	110.0
Total availability entering plant	1263.8	1197.8
Power output:	693.4	657.2
Resource utilization efficiency, η_u	0.549	

(1) Dryness fraction at state a assumed to be 20%.
(2) Assumes 15% of H.P. geofluid is used with multiflash units.
(3) Main steam flow rate.
(4) Dryness fraction at state h assumed to be 40%.
(5) Sink condition; T_o = 289 K (520 R)

Table 9

Impurities in geothermal fluid at Wairakei

[Armstead, 1961]

Noncondensable gases in steam	ppm (by weight)	
	H.P. wells[1]	I.P. wells[2]
Carbon dioxide, CO_2	4857	3467
Hydrogen sulfide, H_2S	132	70
Nitrogen, N_2	7	17
Methane, CH_4	3	5
Hydrogen, H_2	1	1
Total	5000	3560

Constituents in hot liquid	ppm (by weight)
Chloride, Cl	2318
Silica, SiO_2	300
Metaboric acid, $H_2B_2O_4$	116
Bicarbonate, HCO_3	39
Sulphate, SO_4	34
Fluoride, F	10
pH of condensate	8.6

(1) For pressure of 1.48 MPa (214 lbf/in^2).

(2) For pressure of 0.58 MPa (84 lbf/in^2).

Table 10

Effect of liquid discharge from Wairakei power plant on chemical nature of Waikato River [Axtmann, 1975 (A)]

Constituent (1)	Increment in river concentration, ppm
Chloride, Cl	20.8
Sodium, Na	12.0
Silica, Si	6.3
Potassium, K	1.9
Boron, B	0.27
Sulfate, SO_4	0.24
Calcium, Ca.	0.17
Lithium, Li.	0.13
Fluoride, F.	0.077
Bromide, Br.	0.055
Arsenic, As.	0.039
Rubidinum, Rb.	0.029
Cesium, Cs	0.026
Iodide, I.	0.0047
Ammonium, NH_4.	0.0014
Magnesium, Mg.	0.000047
Mercury, Hg.	0.0000015

(1) Discharge flow rate = 6500 Mg/h (14.3 x 10^6 lbm/h); river flow rate = 127 m^3/s (2 x 10^6 gal/min).

Table 11

Capital costs for the Wairakei geothermal power station

[Smith and McKenzie, 1970]

Item	Cost/NZ $000
Land acquisition	nil
Site preparation	278
Establishment items (camps, temporary housing, workshops, offices, site levelling)	1,688
Permanent Village (Wairakei Village)	1,318
Power Stations:	
Foundations, cooling water culverts, offices, workshops, roads and landscaping.	4,674
Cooling water pump house (pumps, mains, valves).	1,881
Turbines and generators.	8,874
Steam piping and valves.	967
Electrical work (400 V and 11 kV switchgear, panels, control room, transformers other than generator transformers).	840
Generator transformers	576
Outdoor structure and switchgear, high-tension circuit breakers	662
General services (electrical, air, telephones, etc.)	115
Workshop tools	18
Borefield:	
Well drilling (including exploration and unproductive wells)	7,643
Wellhead equipment	1,638
Branch pipelines	971
Main pipelines	5,258
Roads.	462
Main drainage.	1,641
Water supply	446
Landscaping.	405
General services	17
Pilot Hot Water Scheme (later abandoned):	
Modifications to wellhead equipment.	213
Hot water pipeline	732
Flash plant and controls	925
No. 10 turbo-alternator.	591
Work for plant expansion (not completed)	293
Miscellaneous charges and adjustments.	241
Total	43,367

Table 12

Average annual operating and maintenance expenses at Wairakei: 1965-1969

[Smith and McKenzie, 1970]

Item	Cost/NZ $000
Borefield:	
Mineral rights	nil
Land and roads	9.4
Services	6.9
Hot water drains	16.8
Well servicing and modifications	84.8
New wells (to maintain production)	295.4
Measurements	60.3
Main pipeline servicing and modifications	53.7
New pipelines	30.9
Branch pipelines	15.0
Steam traps	7.6
Buildings (in steamfield)	0.5
Hot water equipment	1.0
Mechanical equipment	2.1
General workshop	2.6
Salaries of operating personnel	25.5
Supervision	8.2
Miscellaneous	1.0
Borefield total	621.7
Power station:	
Land and roads	9.8
Services	3.8
Buildings (power stations)	19.1
Permanent Village	22.6
Information Center (3 years)	6.2
Ministry of Works buildings (3 years)	65.0
Cooling water system	12.6
Gas extractor system	7.1
Steam lines	36.5
Turbo-alternators	108.0
Electrical equipment	25.0
Miscellaneous mechanical equipment	22.0
Operating costs (salaries plus other charges)	194.6
Supervision	12.6
Miscellaneous	43.6
Power station total	588.5
Total working expenses	1210.2

Table 13

Annual production of electricity at the Wairakei power plant

[After Smith and McKenzie, 1970]

Year(1)	Generation GW·h (net)	Max. Load MW	Capacity factors, % Field-limited(3)	Installed(4)
1959	6.4	test runs	—	—
1960	169	50.6	37.9	27.9
1961	384	64.0	68.5	63.5
1962	491	65.6	85.5	81.3
1963	761	131	66.3	45.1
1964	1004	149	77.0	59.6
1965	1194	175	78.8	71.6
1966	1255	166	86.6	74.6
1967	1268	171	84.7	75.2
1968	1058(2)	167	72.2	78.4
1969	1207	166	83.1	71.6

(1) For the year ended March 31.

(2) Low generation caused by cut-back in geofluid flow for aquifer pressure-recovery test over 4 months during which the maximum plant capacity was 75 MW.

(3) Based on a borefield-limited effective maximum capacity, i.e., maximum load from col. 3.

(4) Based on an installed capacity of 69 MW for 1960-1962 and 192.6 MW thereafter, except for an effective installed capacity of 153.4 MW for 1968.

Table 14

Production characteristics of wells KA1 and KA4 at Kawerau during 1952-1955 [After Smith, 1970]

Wellhead Pressure		Steam Flow		Liquid Flow		Total Flow		Quality
kPa	lbf/in^2	Mg/h	klbm/h	Mg/h	klbm/h	Mg/h	klbm/h	%
				Well KA1				
446	64.7	8.16	18.0	9.07	20.0	17.23	38.0	47.3
515	74.7	7.71	17.0	9.48	20.9	17.19	37.9	44.8
653	94.7	6.67	14.7	10.07	22.2	16.74	36.9	39.9
791	114.7	5.62	12.4	10.25	22.6	15.87	35.0	35.4
929	134.7	4.63	10.2	9.66	21.3	14.29	31.5	32.4
1067	154.7	3.63	8.0	8.48	18.7	12.11	26.7	30.0
1205	174.7	2.63	5.8	6.58	14.5	9.21	20.3	28.6
				Well KA4				
432	62.7	3.6	8.0	7.7	17.0	11.3	25.0	32.0
515	74.7	3.6	8.0	8.2	18.0	11.8	26.0	30.8
584	84.7	3.2	7.0	7.7	17.0	10.9	24.0	29.2
653	94.7	2.7	6.0	7.3	16.0	10.0	22.0	27.3
722	104.7	2.3	5.0	6.8	15.0	9.1	20.0	25.0

Table 15

Country	New Zealand
Unit name	Kawerau
Owner	Tasman Pulp and Paper Company
Year of start-up	1961
Plant type	Separated steam ("single flash")/process heating

Turbine characteristics

Manufacturer	(NA)	
Type	single-cylinder, single-flow, noncondensing	
Rated capacity	10.0 MW	
Maximum capacity	10.0 MW	
Speed	3000 rev/min	
Steam inlet pressure	790.9 kPa	114.7 lbf/in^2
Steam inlet temperature	169.9°C	337.9 °F
Noncondensable gas content	< 2.5% by weight of inlet steam	
Exhaust pressure	∿ 101.6 kPa	∿ 30 in Hg
Turbine steam flow rate	144.7 Mg/h	0.319×10^6 lbm/h
Maximum allowable pressure	(NA) kPa	(NA) lbf/in^2
Last stage blade height	(NA) mm	(NA) in

Condenser characteristics

Type	(None) (1)	
Pressure	- kPa	- in Hg
Cooling water temperature	- °C	- °F
Outlet water temperature	- °C	- °F
Cooling water flow rate	- Mg/h	- lbm/h

(1) Up to 45 Mg/h (100 klbm/h) of exhaust steam is condensed in a black liquor pre-evaporator.

Table 16

Technical information on wells BR1-16 at Broadlands

[After Smith, 1970]

Well No.	Date Drilled	Wellhead Elevation m	Depth Drilled m	Depth Cased m	Max. W.H. Pressure MPa	Bottomhole Temperature °C
BR 1	12-65	293	1396	607	3.37	275
BR 2	7-66	301	1034	417	5.30	278
BR 3	2-67	299	912	469	5.21	275
BR 4	8-67	313	1019	517	5.74	263
BR 5	9-67	317	1268	842	0.1(1)	243
BR 6	9-67	293	1082	653	1.55	143
BR 7	12-67	306	1119	538	7.20	277
BR 8	12-67	302	776	444	4.94	270
BR 9	3-68	308	1368	500	5.72	289
BR 10	4-68	302	1087	496	5.40	278
BR 11	5-68	311	760	484	4.79	270
BR 12	10-68	294	1369	653	6.16	275
BR 13	7-68	292	1080	813	0.79	254
BR 14	12-68	297	1282	587	3.99	293
BR 15	9-69	304	2418	1801	4.63	297
BR 16	6-69	303	1404	626	5.84	273

(1) Non-flowing well.

Notes: 1 m = 3.28 ft; 1 MPa = 145 lbf/in^2; 1°C = (°F-32)/1.8.

Table 17

Mass flow rates from selected wells at Broadlands

[After Smith, 1970]

	Wellhead Pressure/MPa					
Well No.	0.44	0.79	1.13	1.48	1.82	2.17
	Steam flow rate/(Mg/h)					
BR 2	102	98	93	88	80	72
BR 3	65	59	55	47	38	25
BR 4	30	28	24	19	15	11
BR 7	36	35	33	30	28	24
BR 8	93	89	86	82	78	73
BR 9	25	24	20	17	14	11
BR 11	103	96	90	86	77	66
BR 13	40	36	32	27	22	17
Steam Total	494	465	433	396	352	299
	Liquid flow rate/(Mg/h):					
BR 2	105	110	114	115	114	109
BR 3	112	118	120	114	113	88
BR 4	26	27	27	26	24	21
BR 7	10	10	10	10	10	10
BR 8	86	90	93	87	80	74
BR 9	40	42	44	45	46	46
BR 11	151	158	163	168	163	146
BR 13	94	98	98	99	99	99
Liquid Total	624	653	669	664	649	593
Total	1118	1118	1102	1060	1001	892
Avg. Quality/%	44	42	39	37	35	34

Notes: 1 MPa = 145 lbf/in^2; 1 Mg/h = 2205 lbm/h.

Table 18

Composition of steam from selected wells at Broadlands

[Bauer, *et al*, 1977]

Well No.	Date	Max. W.H. Pressure MPa	Constituents in steam		
			CO_2 (1) % (wt.)	H_2S (1) % (wt.)	NH_3 ppm
BR 8	10-76	0.95	3.4	0.037	33.5
BR 11	10-76	2.06	1.3	0.031	29.5
BR 17	9-76	0.99	1.2	0.022	22.8
BR 18	9-76	0.79	6.8	0.077	49.0
BR 22	9-76	3.14	2.3	0.039	43.1
BR 23	9-76	0.79	2.4	0.035	41.5
BR 25	10-76	2.74	4.1	0.045	26.0
BR 27	10-76	3.89	10.8	0.071	41.5
BR 28	10-76	1.03	4.4	0.053	28.0

(1) For a wellhead pressure of 0.79 MPa (114.6 lbf/in^2).

Table 19

Composition of separated bore liquid at Broadlands

[Bauer, *et al*, 1977]

Constituent	Concentration/ppm
Chloride, Cl.	1488
Sodium, Na.	997
Silica, SiO_2.	771
Bicarbonate, HCO_3	175
Potassium, K.	175
Boron, B.	43.7
Sulfate, SO_4.	26.8
Lithium, Li	10.7
Arsenic, As	3.3
Calcium, Ca	1.68
Cesium, Cs.	1.63
Rubidinum, Rb	1.62
Hydrogen sulfide, H_2S	1.0
Aluminum, Al.	0.8
Antimony, Sb.	0.5
Tungsten, W	0.24
Total others.	0.212-0.218

Table 20

Country	New Zealand
Unit name	Broadlands Units 1, 2 and 3
Owner	New Zealand Electricity Department
Year of start-up	1983 (Unit 1), 1984 (Units 2 and 3)
Plant type	Separated steam/flash ("double flash")

Turbine characteristics

Manufacturer	(NA)			
Type	Dual-admission, condensing			
Rated capacity/unit	50.0 MW			
Maximum capacity/unit	55.0 MW			
Speed	3000 rev/min			
Main steam inlet pressure	650.0	kPa	94.3	lbf/in^2
Main steam inlet temperature	162.0	°C	323.6	°F
Secondary steam pressure	200.0	kPa	29.0	lbf/in^2
Secondary steam temperature	120.0	°C	248.0	°F
Noncondensable gas content	∿ 2.4 % by weight of main steam			
Exhaust pressure	(NA)	kPa	(NA)	in Hg
Main steam flow rate/unit	413.7	Mg/h	0.913×10^6	lbm/h
Secondary steam flow rate/unit	93.3	Mg/h	0.206×10^6	lbm/h
Maximum allowable pressure	(NA)	kPa	(NA)	lbf/in^2
Last stage blade height	(NA)	mm	(NA)	in

Condenser characteristics

Type	(NA)			
Pressure	(NA)	kPa	(NA)	in Hg
Cooling water temperature	30.0	°C	86.0	°F
Outlet water temperature	43.0	°C	109.4	°F
Cooling water flow rate	59,200	Mg/h	130.5×10^5	lbm/h

Table 20 (cont.)

Gas extractor characteristics

Type	Steam jet ejector or radial blower	
Number of stages or sets	(NA)	
Suction pressure	(NA) kPa	(NA) in Hg
Capacity	∿ 22,000 m^3/h	∿ 13,000 ft^3/min
Power consumption	(NA)(1)	

Heat rejection system characteristics

Type	Mechanical, induced draft cooling tower	
Number of cells	14 (total 3 units)	
Water inlet temperature	43.0 °C	109.4 °F
Water outlet temperature	30.0 °C	86.0 °F
Design wet-bulb temperature	(NA) °C	(NA) °F
Water flow rate	60.6 Gg/h	133.7 $\times 10^6$ lbm/h
Water pump power	(NA)(1) kW	
Draft fan type	Vertical, axial	
Air flow rate/fan	(NA) m^3/s	(NA) ft^3/min
Fan motor power	(NA)(1) kW	

(1) Total auxiliary power requirements are estimated to be 5 MW/unit.

Table 21

Composition and quantity of exhauster stack gas discharge

[After Bauer, *et al*, 1977]

Gas	Concentration		Flow Rate	
	ppm (wt.)	ppm (vol.)	Mg/h	lbm/h
CO_2	92.5	84.6	35	77,000
H_2S	1.2	1.4	0.45	992
CH_4	0.8	2.1	0.3	661
N_2	0.7	1.1	0.3	661
H_2	0.0	0.2	0.0	0
H_2O (vapor)	4.8	10.6	1.8	3,970

Note: Assumes no emissions controls upstream of plant and condenser is of the shell-and-tube type.

Table 22

Country	Philippines
Unit name	Tiwi, Units 1-4
Owner	National Power Corporation
Year of start-up	1978(?)(Units 1 and 2), 1981(Units 3 and 4)
Plant type	Separated steam/flash ("double flash")

Turbine characteristics/unit

Manufacturer	Tokyo Shibaura Electric Company, Ltd. (Toshiba)	
Type	Single-cylinder, double-flow, pass-in, 6 × 2 stages	
Rated capacity	55.0 MW	
Maximum capacity	55.0 MW	
Speed	3600 rev/min	
Main steam inlet pressure	699.4 kPa	101.4 lbf/in^2
Main steam inlet temperature	165.0 °C	329.0 °F
Secondary steam pressure	184.7 kPa	26.8 lbf/in^2
Secondary steam temperature	118.0 °C	244.4 °F
Noncondensable gas content	5.0% by weight of main steam	
Exhaust pressure	13.5 kPa	4.0 in Hg
Main steam flow rate	(NA) Mg/h	(NA) lbm/h
Secondary steam flow rate	(NA) Mg/h	(NA) lbm/h
Maximum allowable pressure	(NA) kPa	(NA) lbf/in^2
Last stage blade height	584.2 mm	23.0 in

Condenser characteristics/unit

Type	Spray jet, barometric	
Pressure	13.5 kPa	4.0 in Hg
Cooling water temperature	30.6 °C	87.1 °F
Outlet water temperature	48.9 °C	120.0 °F
Cooling water flow rate	12,600 Mg/h	27.8 × 10^6 lbm/h

Table 22 (cont.)

Gas extractor characteristics/unit

Type	Blower and steam jet ejector	
Number of stages or sets	2	
Suction pressure	∿ 12.7kPa	∿ 3.76 in Hg
Capacity	(NA) m^3/h	(NA) ft^3/min
Power consumption	(NA)	

Heat rejection system characteristics/unit

Type	Cross-flow, mechanical-draft cooling tower	
Number of cells	6	
Water inlet temperature	48.9 °C	120.0 °F
Water outlet temperature	30.6 °C	87.1 °F
Design wet-bulb temperature	26.7 °C	80.1 °F
Water flow rate	∿ 15.2 Gg/h	∿ 33.5×10^6 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 23

Country	Philippines
Unit name	Los Baños, Wellhead Unit
Owner	National Power Corporation
Year of start-up	1977
Plant type	Separated steam ("single flash")

Turbine characteristics

Manufacturer	Mitsubishi Heavy Industries, Ltd.	
Type	Single Curtis stage, geared, noncondensing	
Rated capacity	1.2 MW	
Maximum capacity	1.3 MW	
Speed, turbine/generator	7129/1800 rev/min	
Steam inlet pressure	658.3 kPa	95.5 lbf/in^2
Steam inlet temperature	162.3 °C	324.1 °F
Noncondensable gas content	5.0 % by weight of inlet steam	
Exhaust pressure	102.9 kPa	30.4 in Hg
Turbine steam flow rate	22.3 Mg/h	0.0492×10^6 lbm/h
Maximum allowable pressure	1,572.1 kPa	228.0 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 24

Country	Philippines
Unit name	Los Baños, Units 1-4
Owner	National Power Corporation
Year of start-up	1978(?)(Unit 1), 1979(Unit 2), 1981(Unit 3), 1982(Unit 4)
Plant type	Separated steam/flash ("double flash")

Turbine characteristics/unit

Manufacturer	Mitsubishi Heavy Industries, Ltd.	
Type	Single-cylinder, double-flow, pass-in, 5 × 2 stages	
Rated capacity	55.0 MW	
Maximum capacity	68.75 MW	
Speed	3600 rev/min	
Main steam inlet pressure	653.4 kPa	94.8 lbf/in^2
Main steam inlet temperature	162.3 °C	324.1 °F
Secondary steam pressure	171.0 kPa	24.8 lbf/in^2
Secondary steam temperature	115.6 °C	240.1 °F
Noncondensable gas content	5.0% by weight of main steam	
Exhaust pressure	13.5 kPa	4.0 in Hg
Main steam flow rate	352.0 Mg/h	0.776 × 10^6 lbm/h
Secondary steam flow rate	125.0 Mg/h	0.276 × 10^6 lbm/h
Maximum allowable pressure	1,072.0 kPa	155.5 lbf/in^2
Last stage blade height	635.0 mm	25.0 in

Condenser characteristics/unit

Type	Spray jet, barometric	
Pressure	13.5 kPa	4.0 in Hg
Cooling water temperature	30.6 °C	87.1 °F
Outlet water temperature	48.9 °C	120.0 °F
Cooling water flow rate	13,200 Mg/h	29.1 × 10^6 lbm/h

Table 24 (cont.)

Gas extractor characteristics/unit

Type	Blower and steam jet ejector	
Number of stages or sets	2	
Suction pressure	12.7 kPa	3.76 in Hg
Capacity	138,240 m^3/h	4.88×10^6 ft^3/min
Power consumption; steam	1.55 MW (blower); 79.1 Mg/h (0.174×10^6 lbm/h)	

Heat rejection system characteristics/unit

Type	Cross-flow, mechanical-draft cooling tower	
Number of cells	6	
Water inlet temperature	48.9 °C	120.0 °F
Water outlet temperature	30.6 °C	87.1 °F
Design wet-bulb temperature	26.7 °C	80.1 °F
Water flow rate	15.2 Gg/h	33.5×10^6 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 25

Country	Philippines
Unit name	Leyte Portable Power Unit
Owner	Philippine National Oil Co., Energy Dev. Corp.
Year of start-up	1977
Plant type	Separated steam ("single flash")

Turbine characteristics

Manufacturer	Mitsubishi Heavy Industries, Ltd.	
Type	Single Curtis stage, geared, noncondensing	
Rated capacity	3.0 MW	
Maximum capacity	3.0 MW	
Speed, turbine/generator	7554/1800 rev/min	
Steam inlet pressure	787.7 kPa	114.2 lbf/in^2
Steam inlet temperature	170.0 °C	338.0 °F
Noncondensable gas content	5.0 % by weight of inlet steam	
Exhaust pressure	127.5 kPa	37.6 in Hg
Turbine steam flow rate	53.0 Mg/h	0.117×10^6 lbm/h
Maximum allowable pressure	1,572.1 kPa	228.0 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 26

Potential geothermal power generation in the Philippines

[Ravenholt, 1977 (A)]

Geothermal Field	1978	1979	1980	1981	1982	1983	1984	1985	Est. Max. Capacity
Tiwi	110	-	55	55	-	55	55	-	560
Los Baños	55	55	-	55	55	-	55	55	720
Tongonan	-	-	55	55	-	55	55	-	(NA)
S. Negros	-	-	-	55	55	-	55	55	425
Manat-Masara	-	-	-	55	55	-	55	55	500
Total Annual	165	55	110	275	165	110	275	165	
Cumulative	165	220	330	605	770	880	1155	1320	

Notes: All values in megawatts. Wellhead units not included.

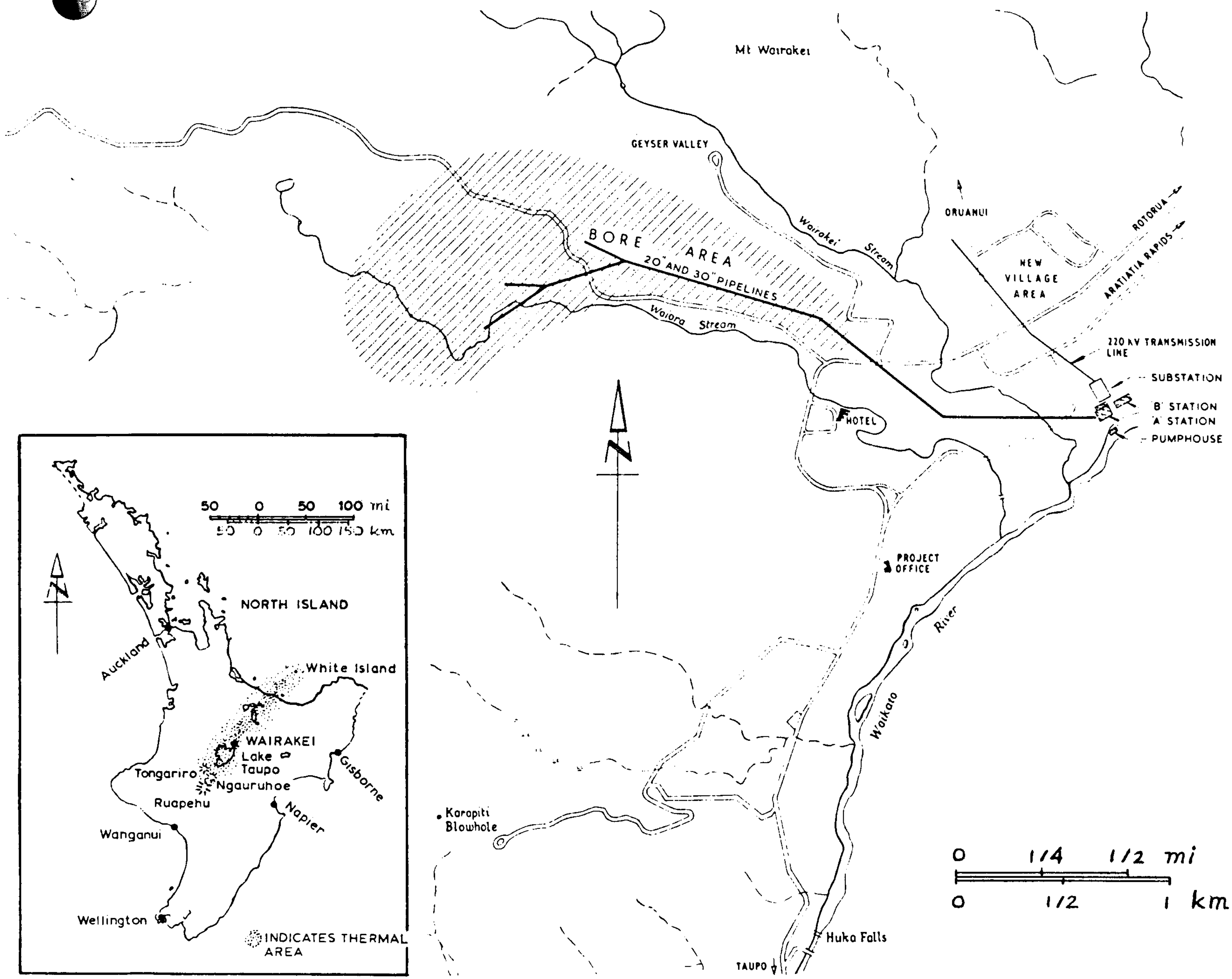


Fig. 1 Location of Wairakei geothermal field, North Island, New Zealand [Armstead, 1961].

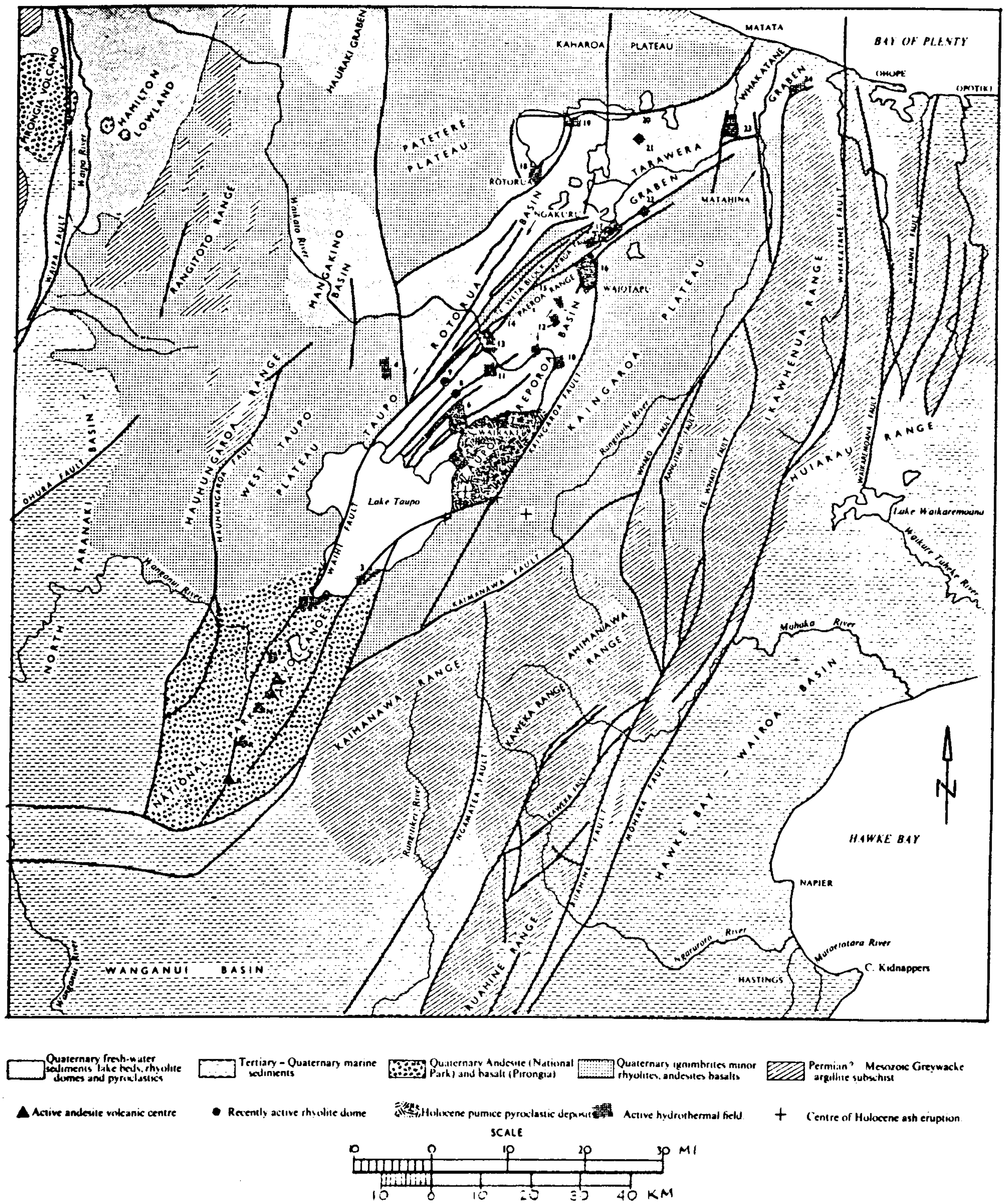
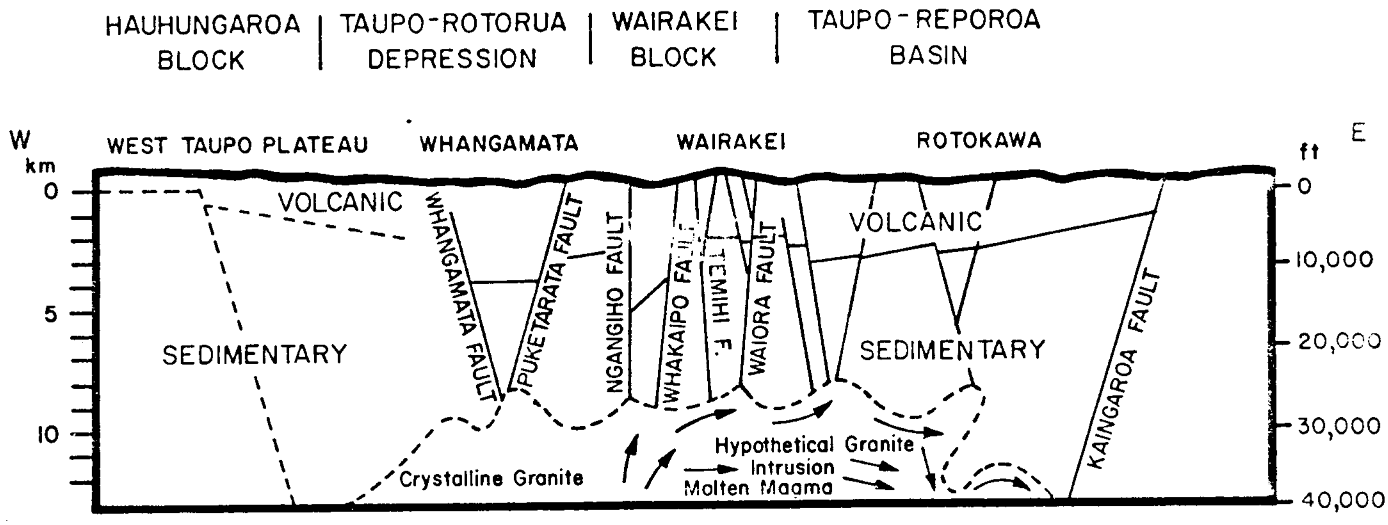
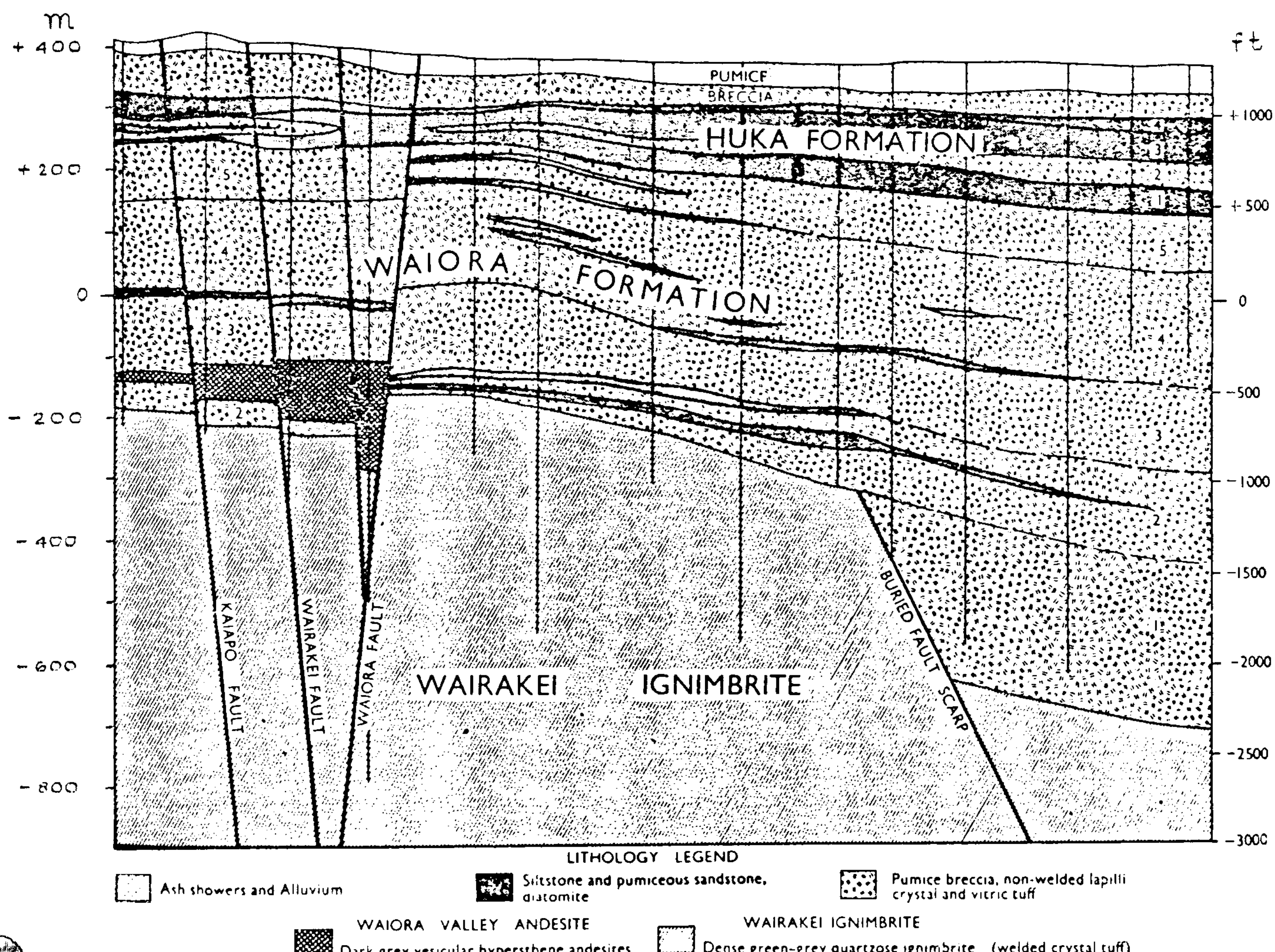


Fig. 2 Generalized geological map of Taupo volcanic zone, New Zealand [Grindley, 1961].



(a)



(b)

Fig. 3 (a) Geologic cross-section of Taupo thermal zone at Wairakei [McNitt, 1965]; (b) Detailed cross-section of Wairakei reservoir [Grindley, 1961].

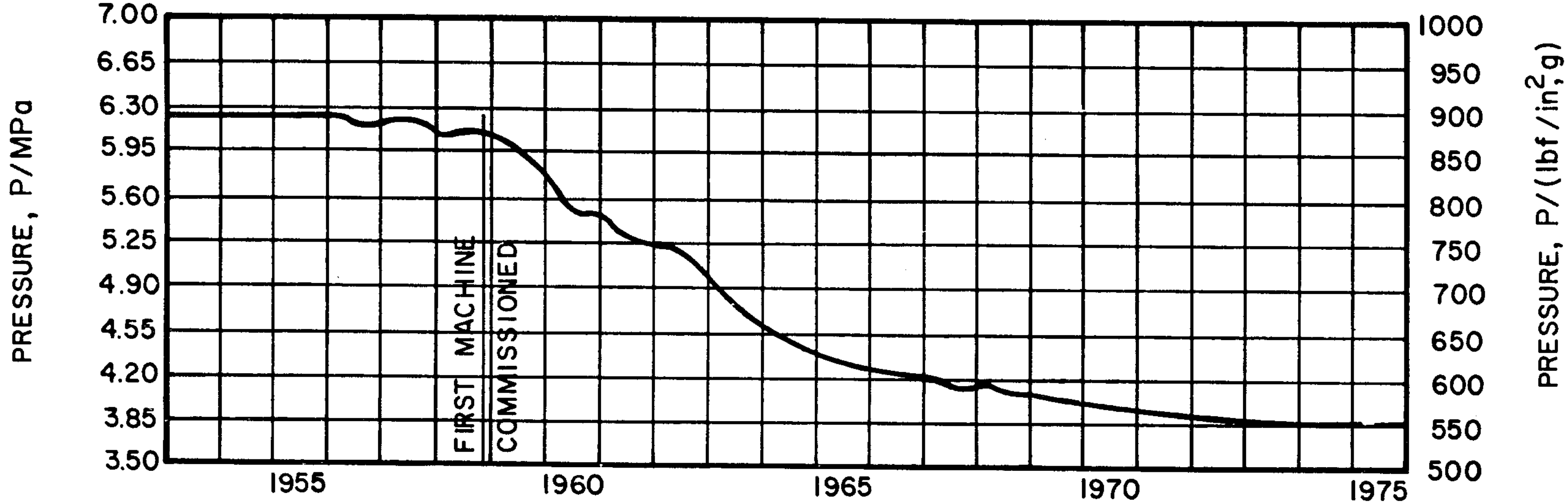


Fig. 4 Reservoir pressure history at Wairakei [after Bolton, 1970 and 1977; Hunt, 1977].

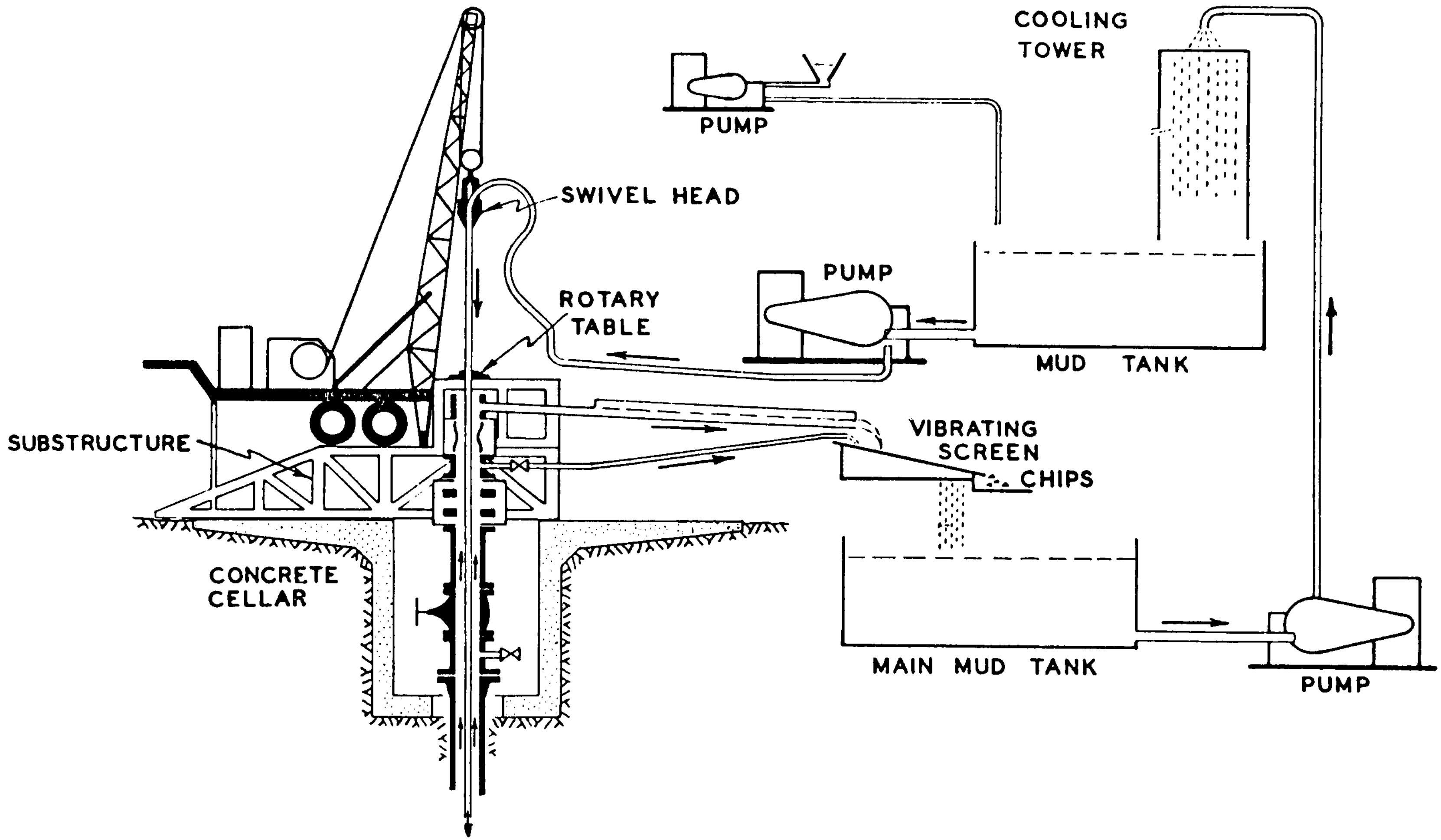


Fig. 5 Typical drilling rig and drilling fluid circulation layout at Wairakei [Craig, 1961].

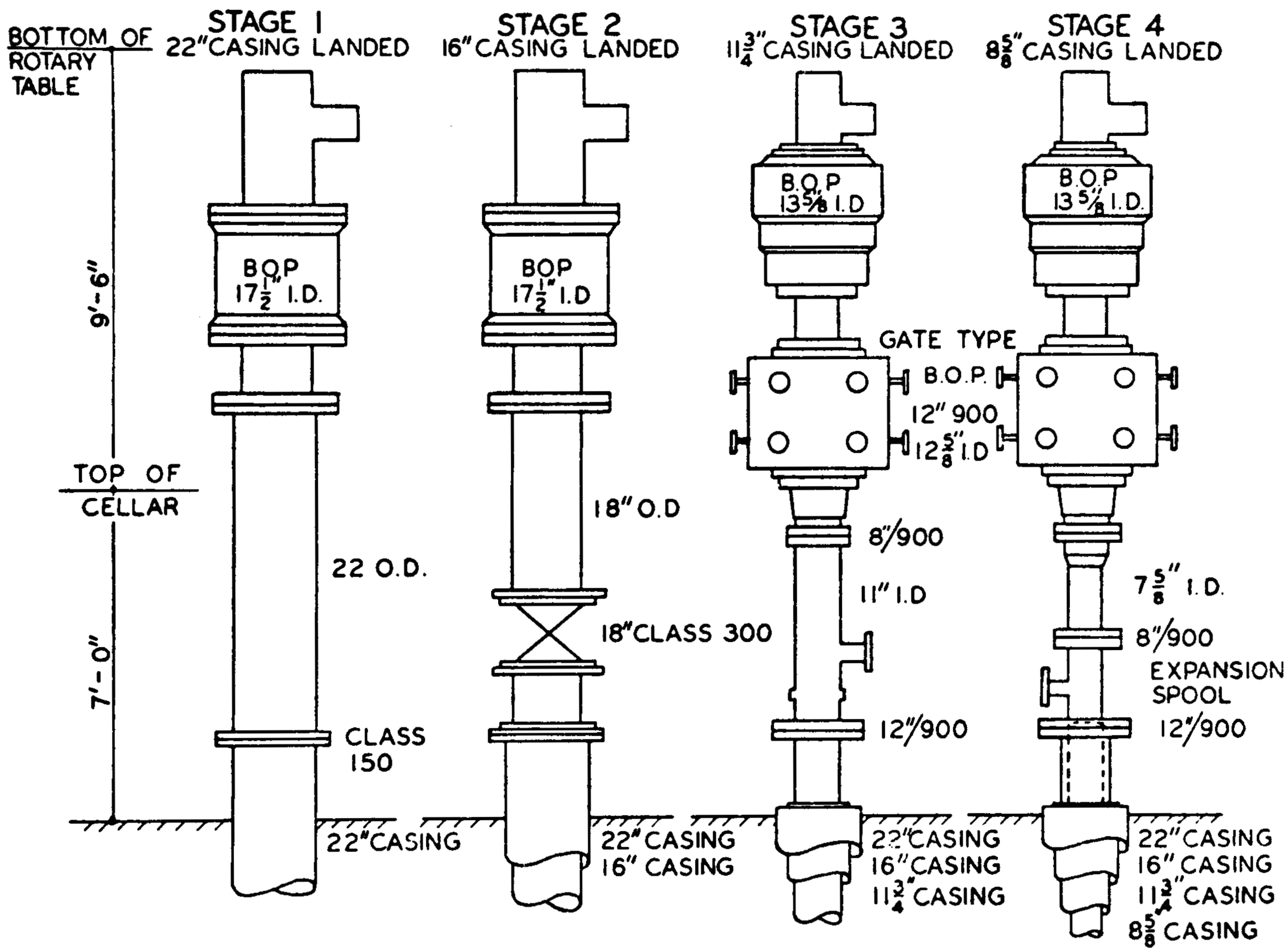


Fig. 6 Wellheads for various stages of drilling program - medium-depth wells at Wairakei [Stilwell, 1970].

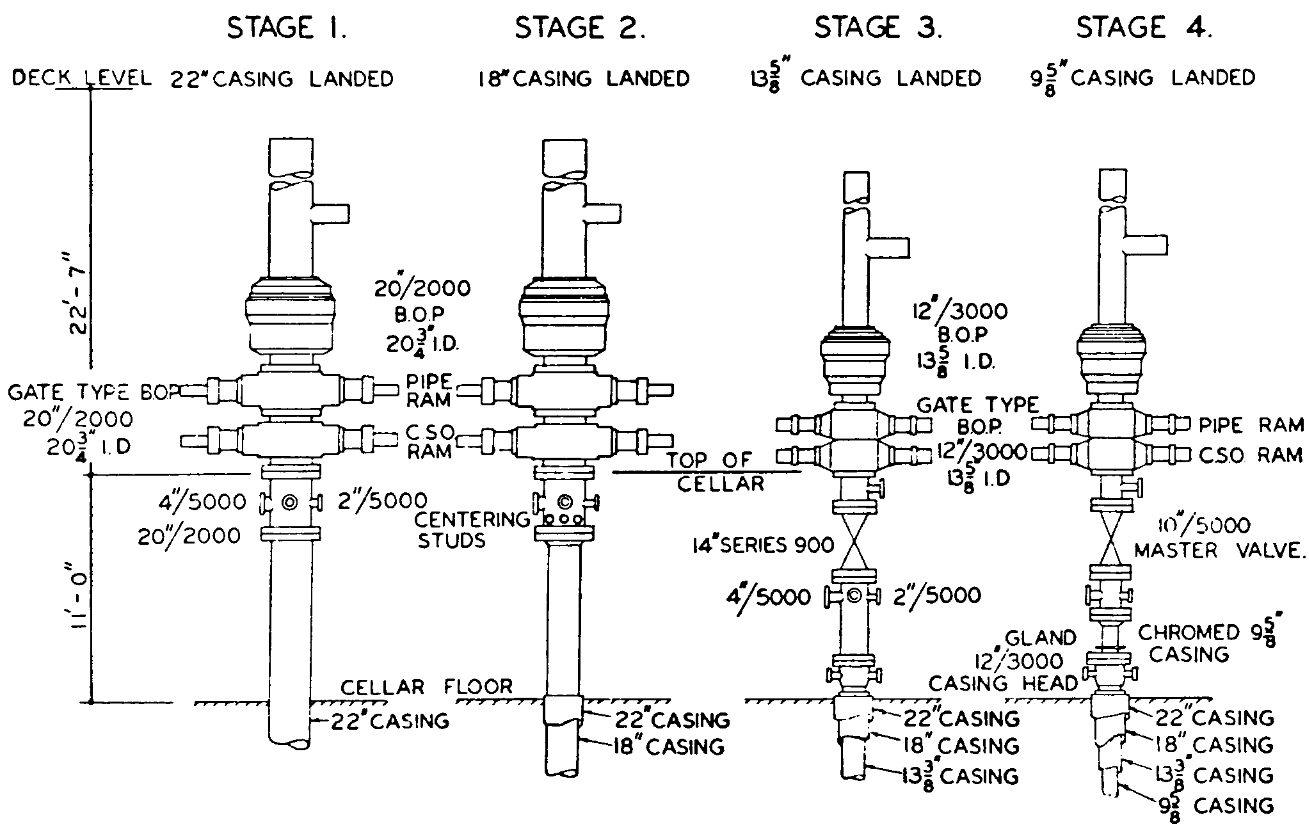


Fig. 7 Wellheads for various stages of drilling program - deep wells at Wairakei [Stilwell, 1970].

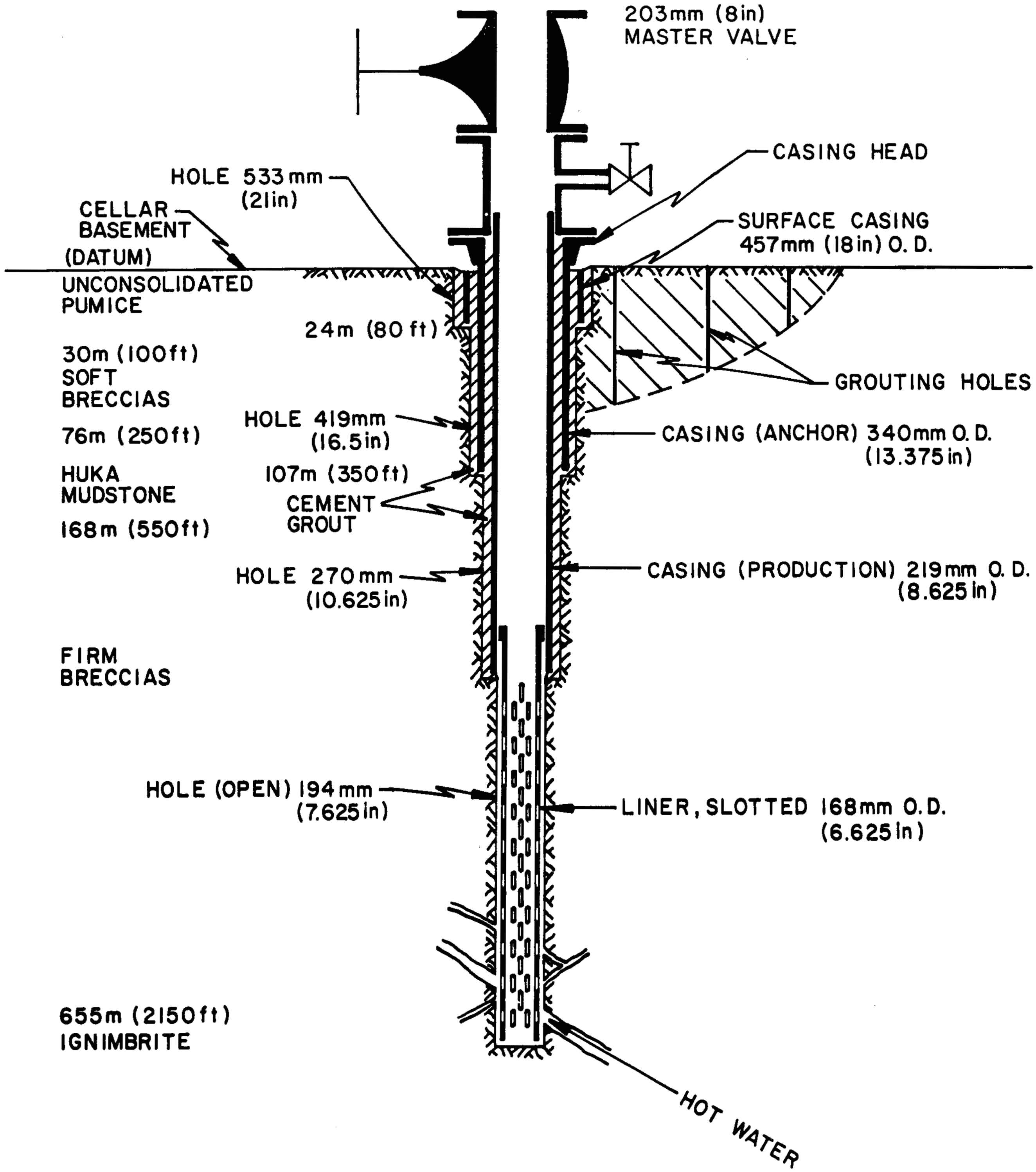


Fig. 8 Typical completed well at Wairakei [after Craig, 1961; Stilwell, 1970].

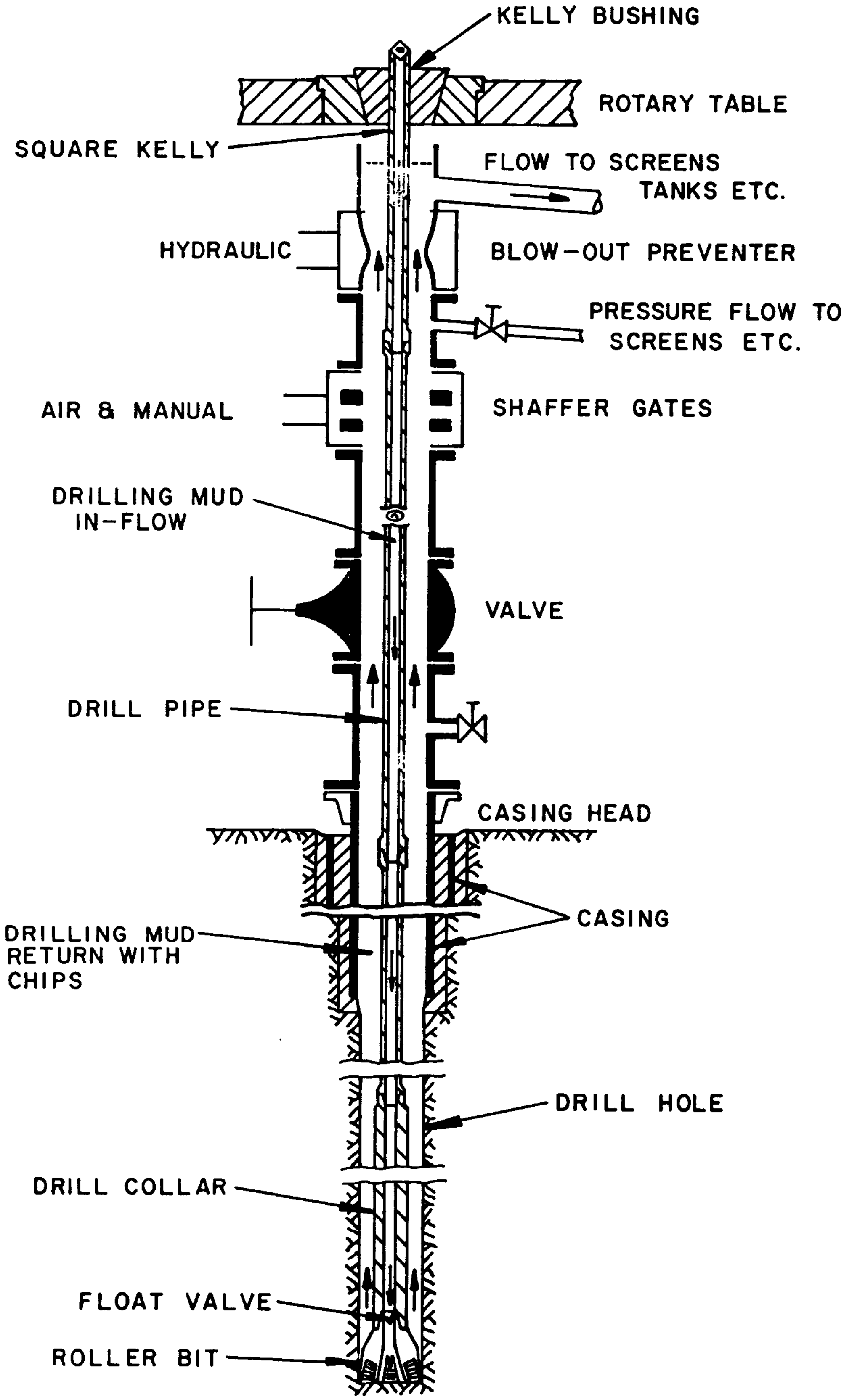


Fig. 9 Typical drill string and blowout preventer equipment at Wairakei [Craig, 1961].

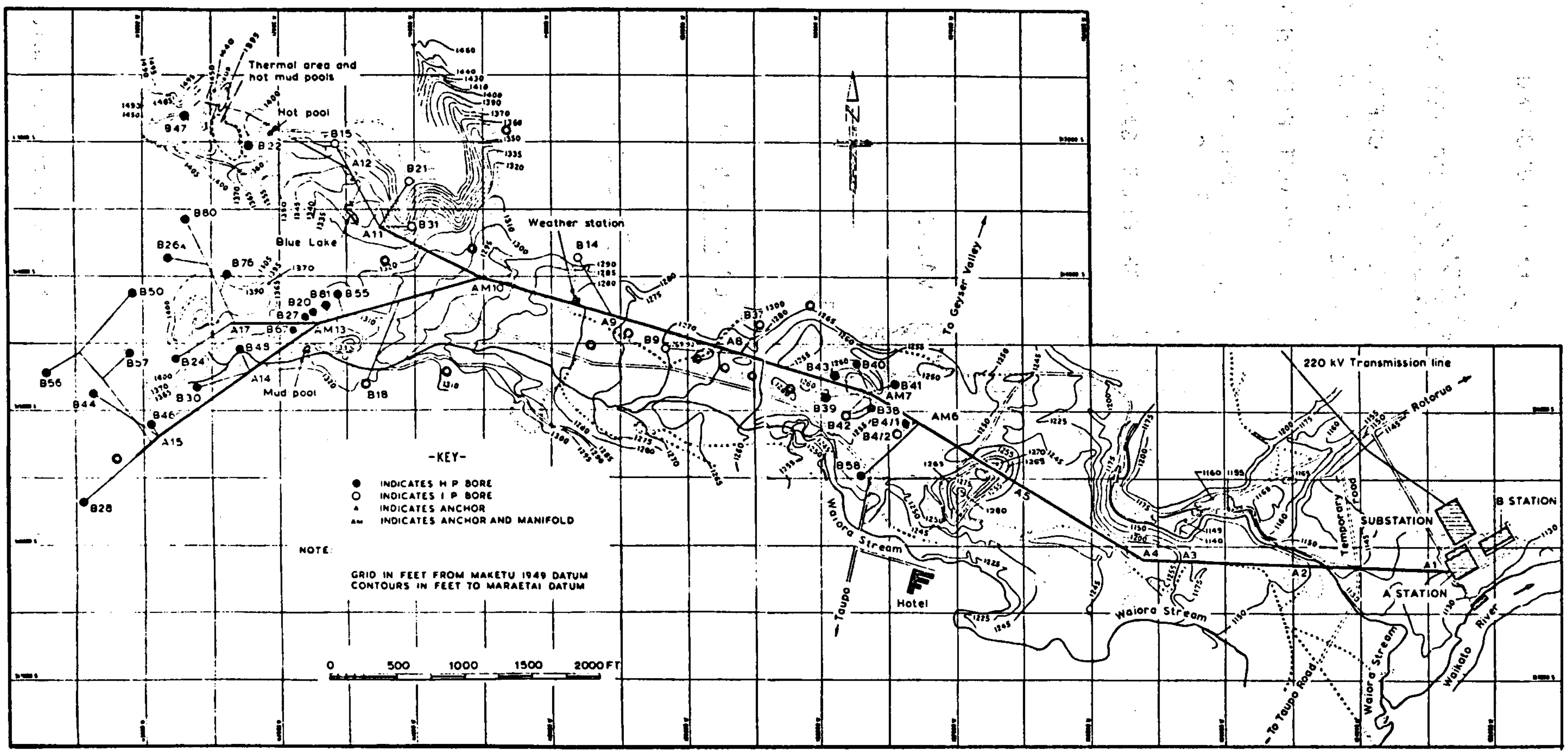


Fig. 10 Arrangement of wells at Wairakei [after Haldane and Armstead, 1962; Bolton, 1977; Grindley, 1961].

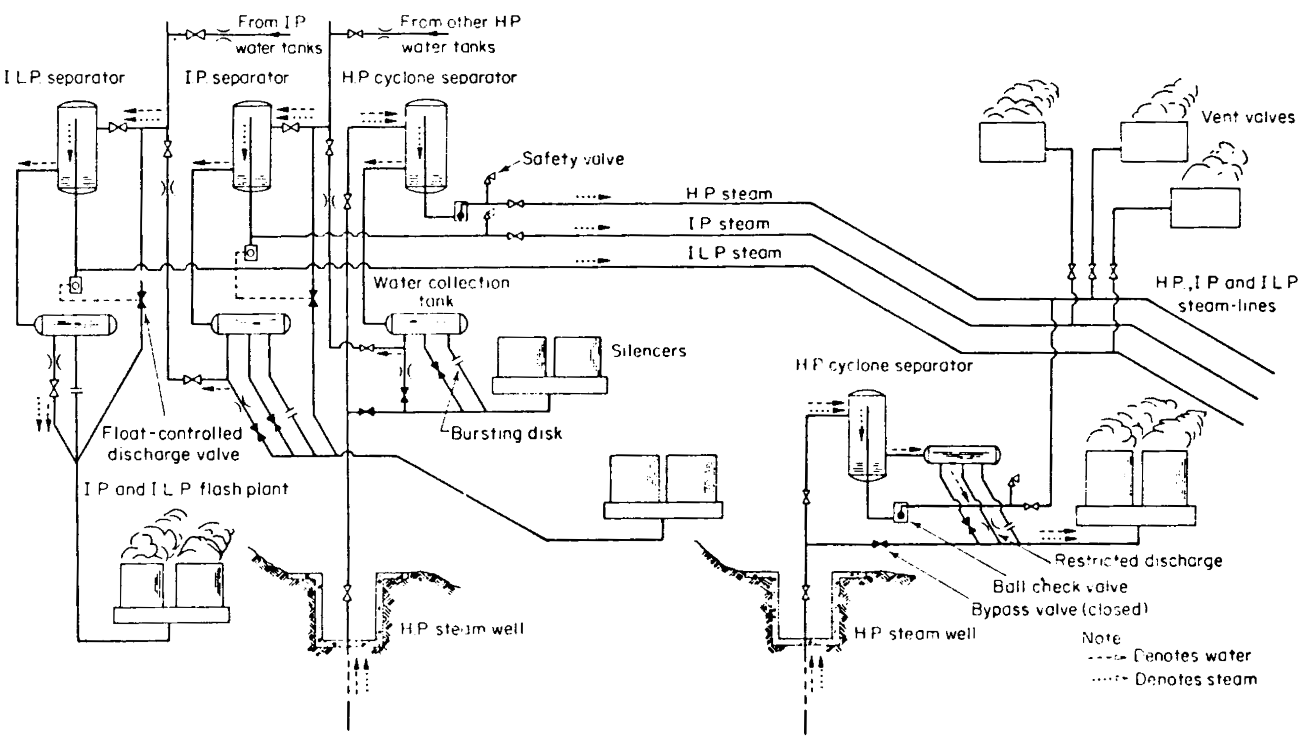
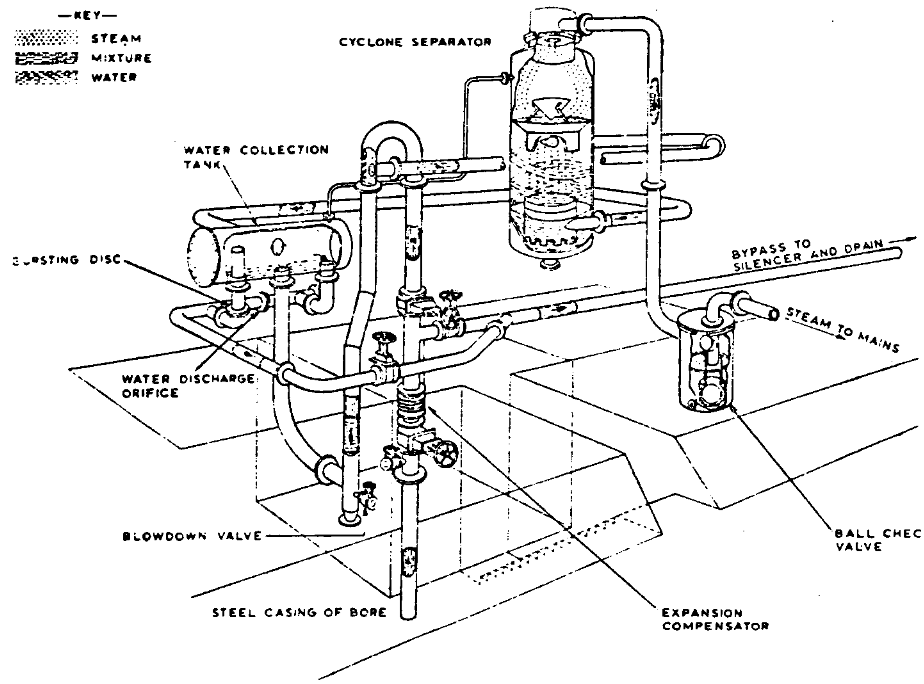
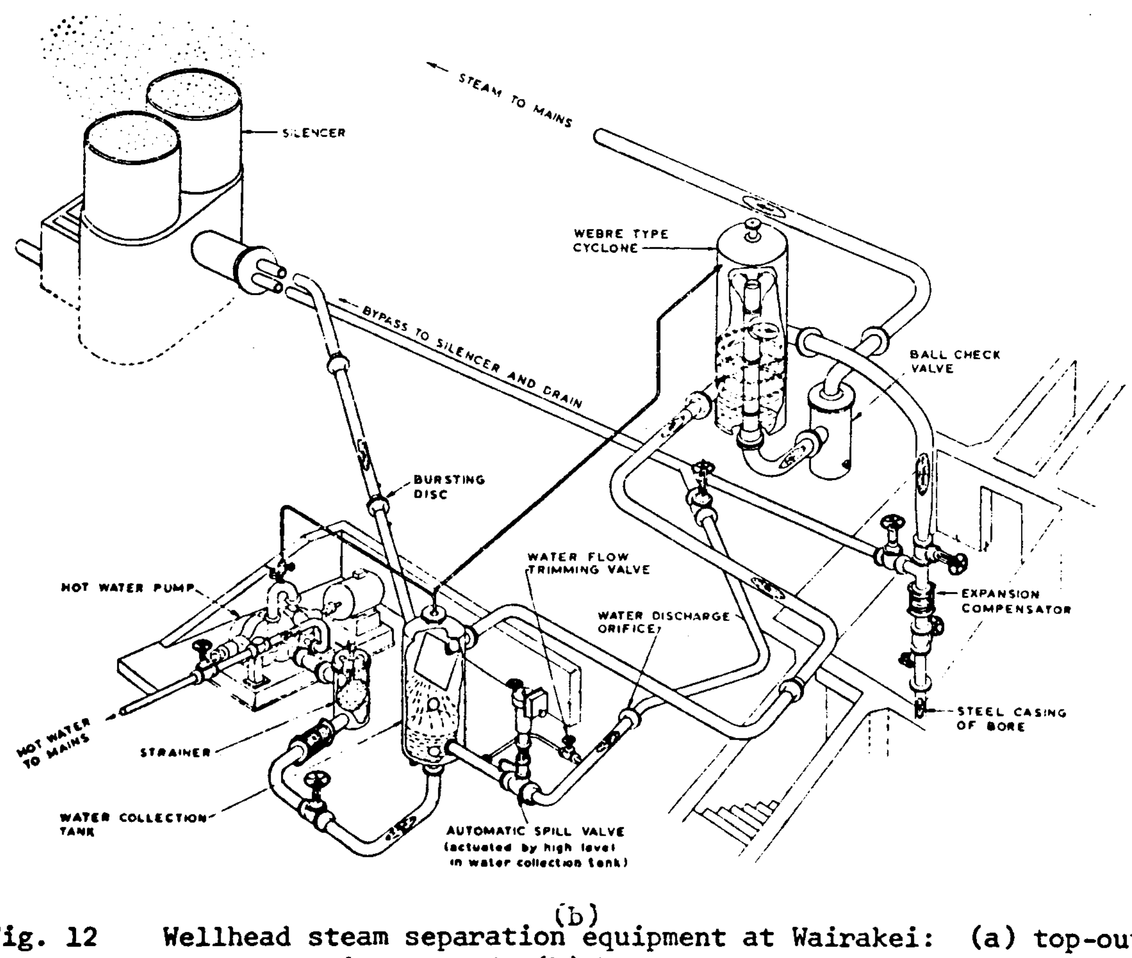


Fig. 11 Steam separation equipment at Wairakei [Bolton, 1977].



(a)



(b)

Fig. 12 Wellhead steam separation equipment at Wairakei: (a) top-outlet separator with U-bend, (b) bottom-outlet separator with hot-water pump (pump no longer used) [Haldane and Armstead, 1962; Bolton, 1977].

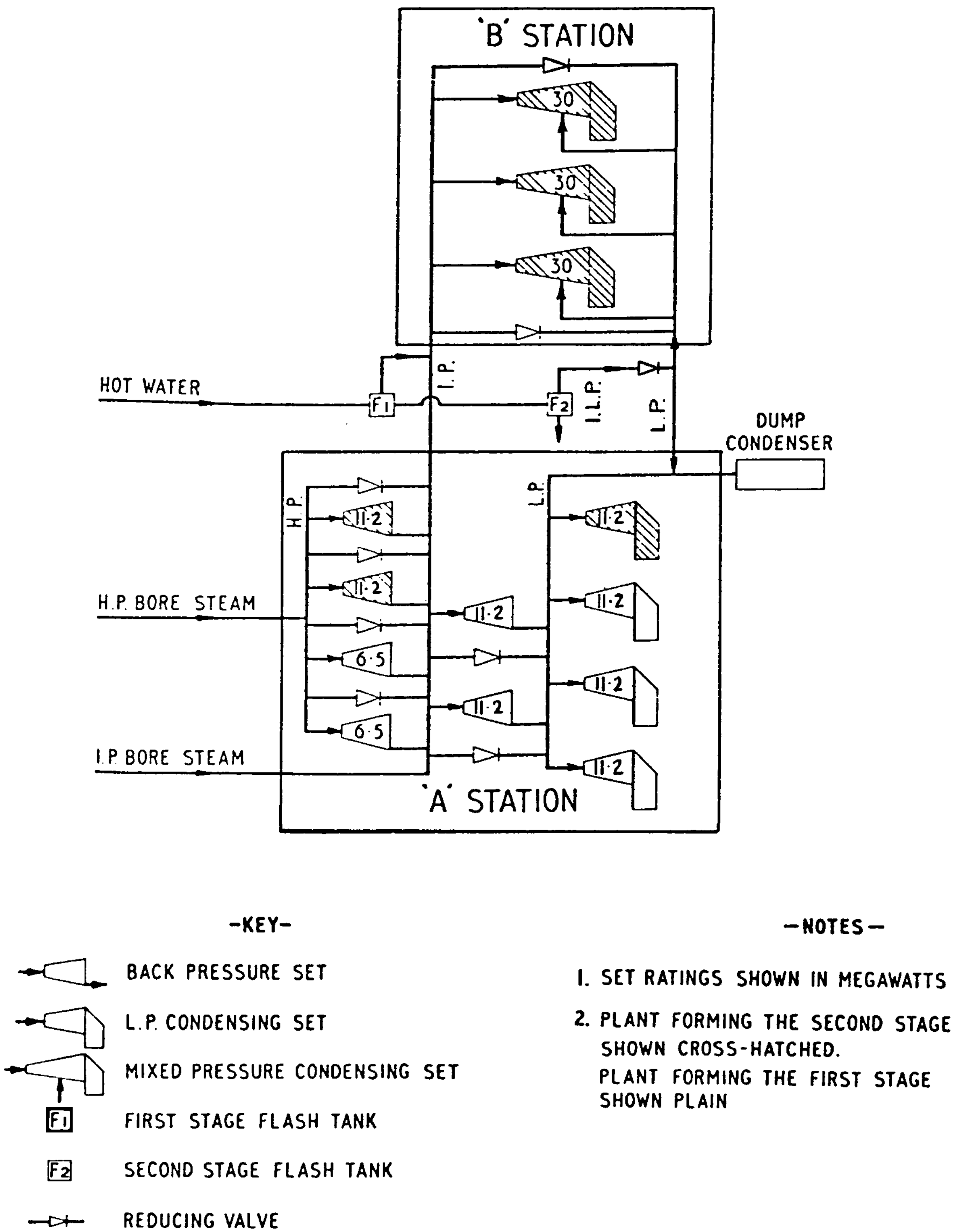


Fig. 13 Turbine arrangements at Wairakei [after Armstead, 1961].

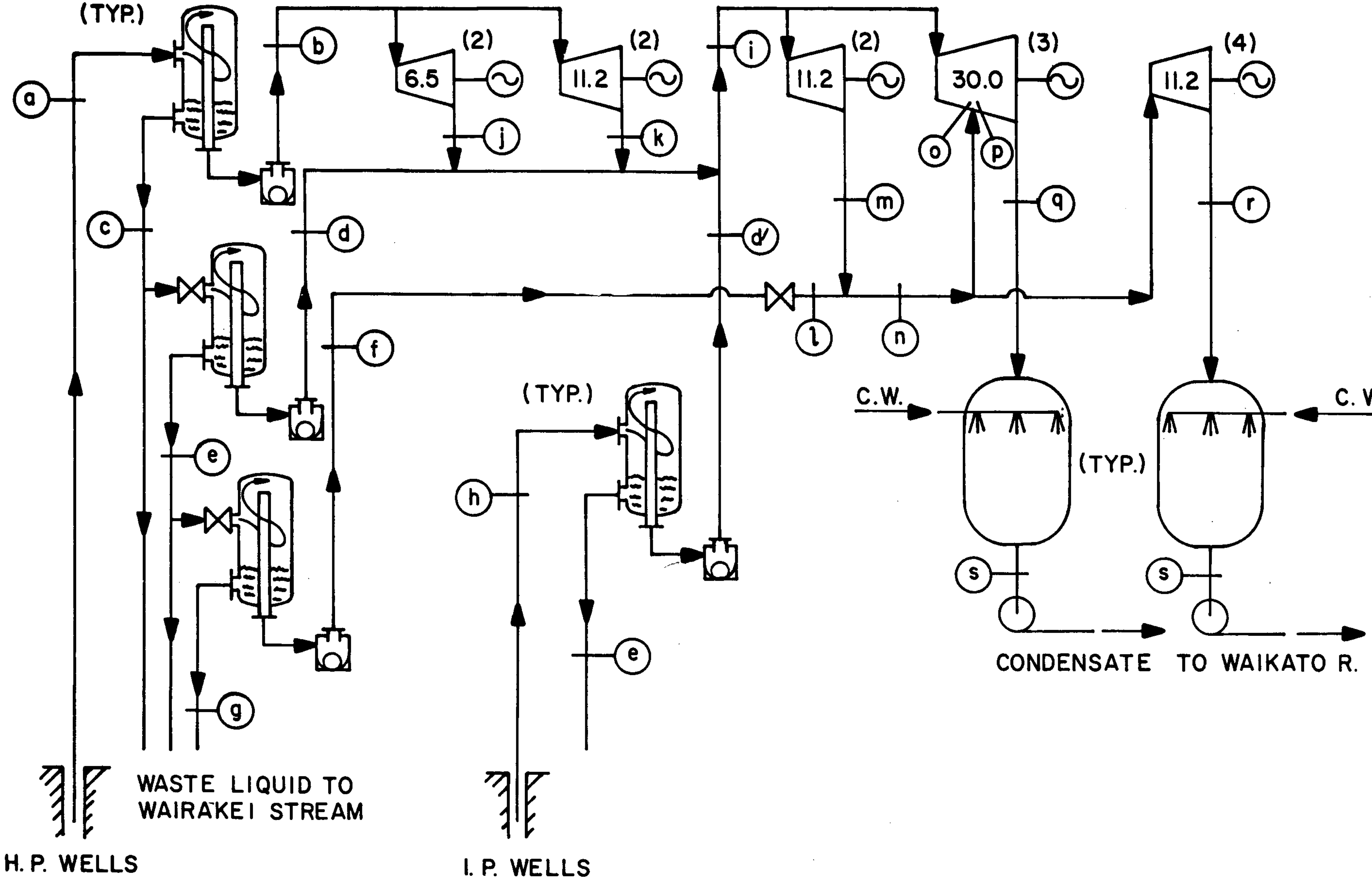


Fig. 14 Simplified flow diagram for Wairakei power plant.

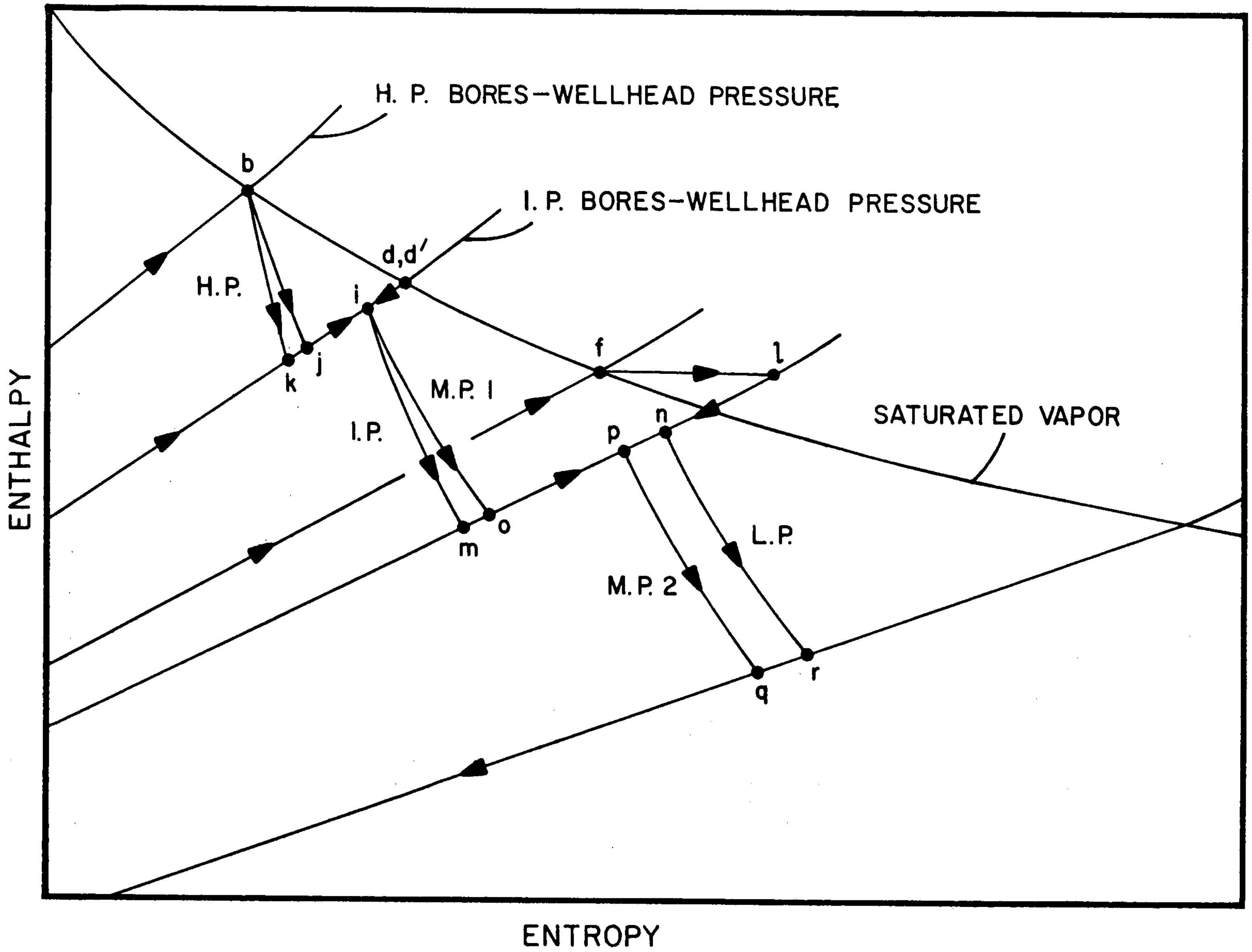


Fig. 15 Mollier diagram showing expansion processes for Wairakei power cycle (not to scale).

Fig. 16 General view of Wairakei power houses: "A" station in foreground, "B" station at left back. The bank of I.P. safety valves appear along the right side of "A" station [NZED, 1974].

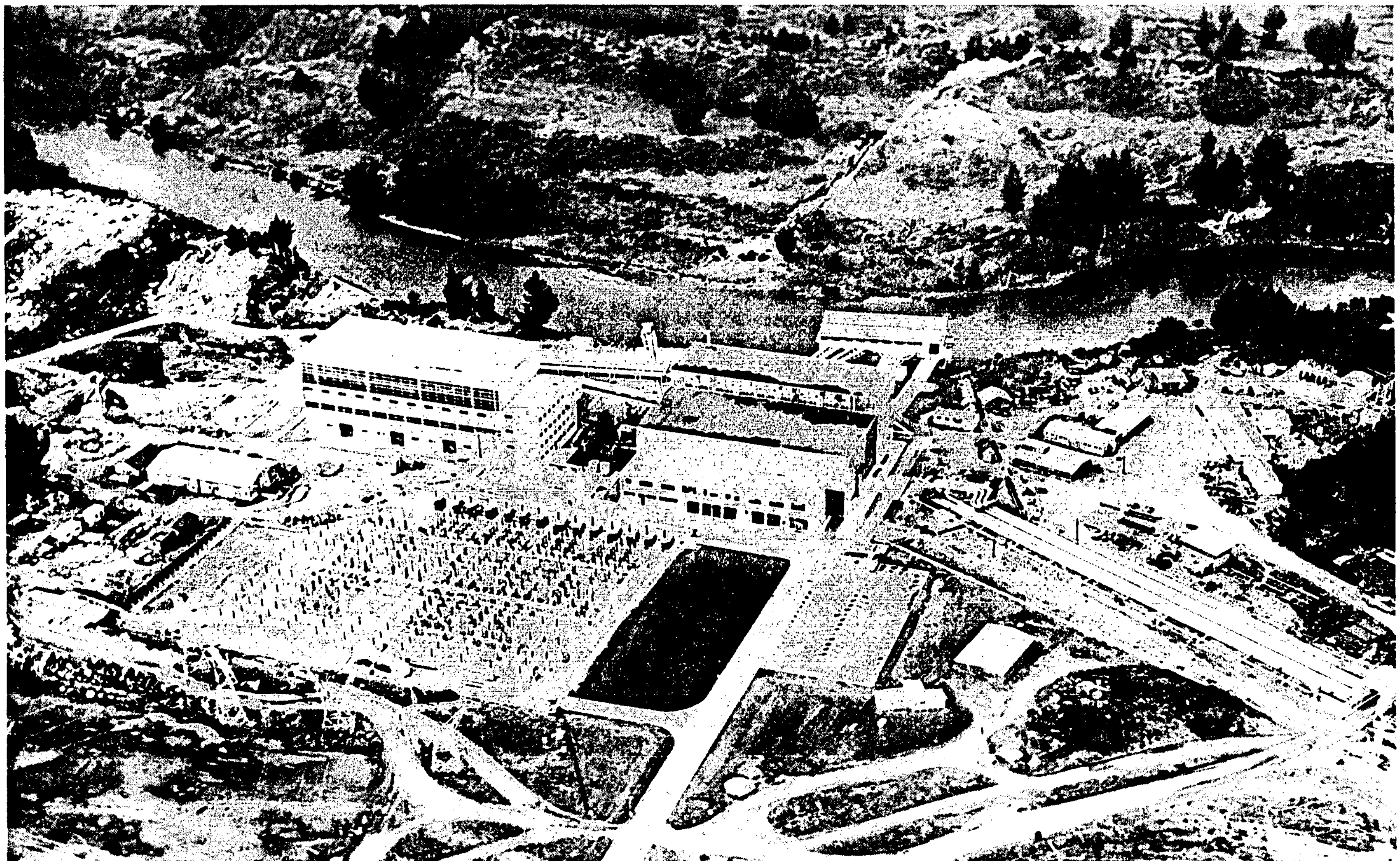


Fig. 17 Aerial view of Wairakei power station. The steam lines enter from the right, the switchyard is at the left center, the cooling water pump house is located behind "A" station on the Waikato River, with the outfall seen to the left of the plant [NZED, 1974].

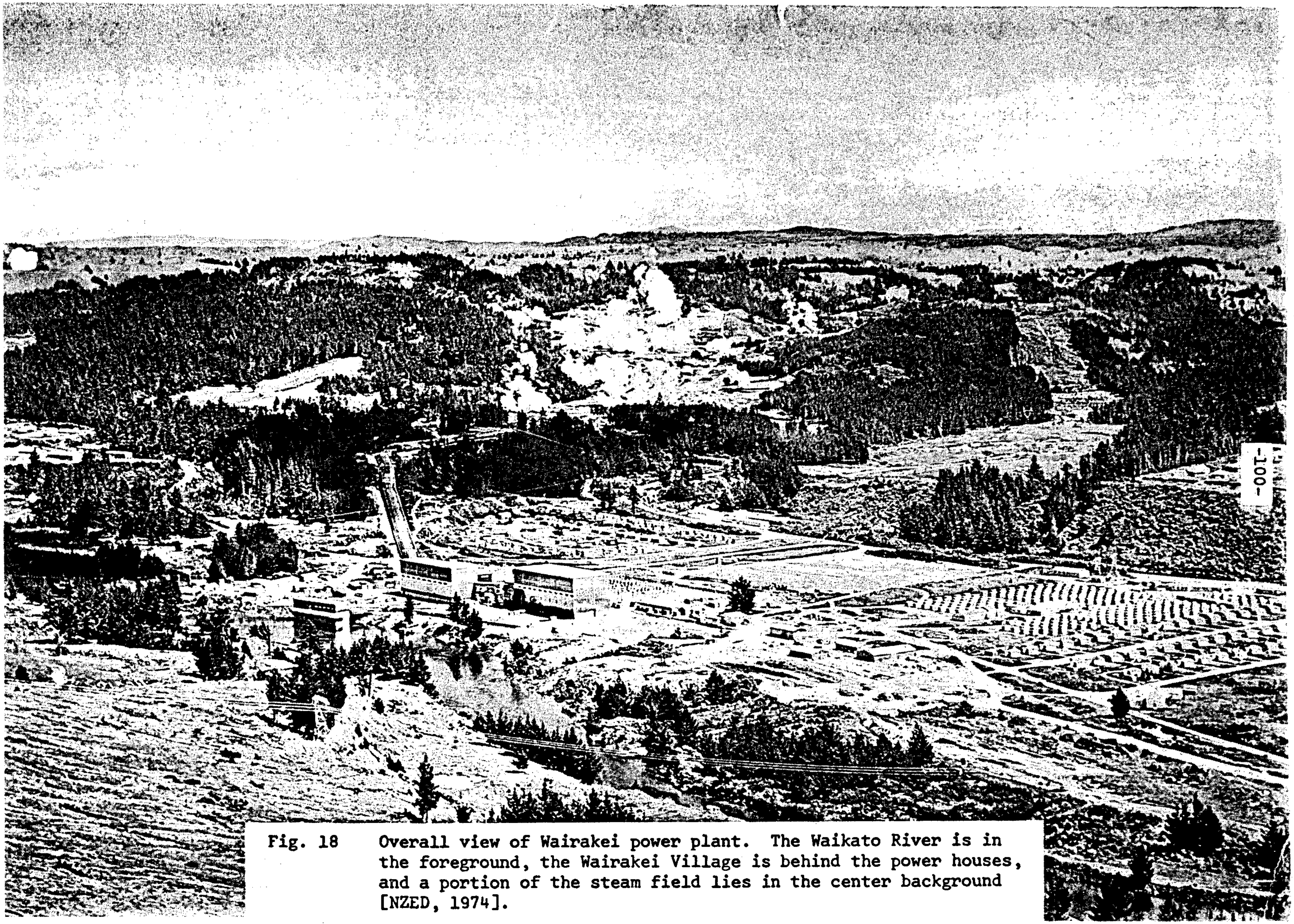


Fig. 18 Overall view of Wairakei power plant. The Waikato River is in the foreground, the Wairakei Village is behind the power houses, and a portion of the steam field lies in the center background [NZED, 1974].

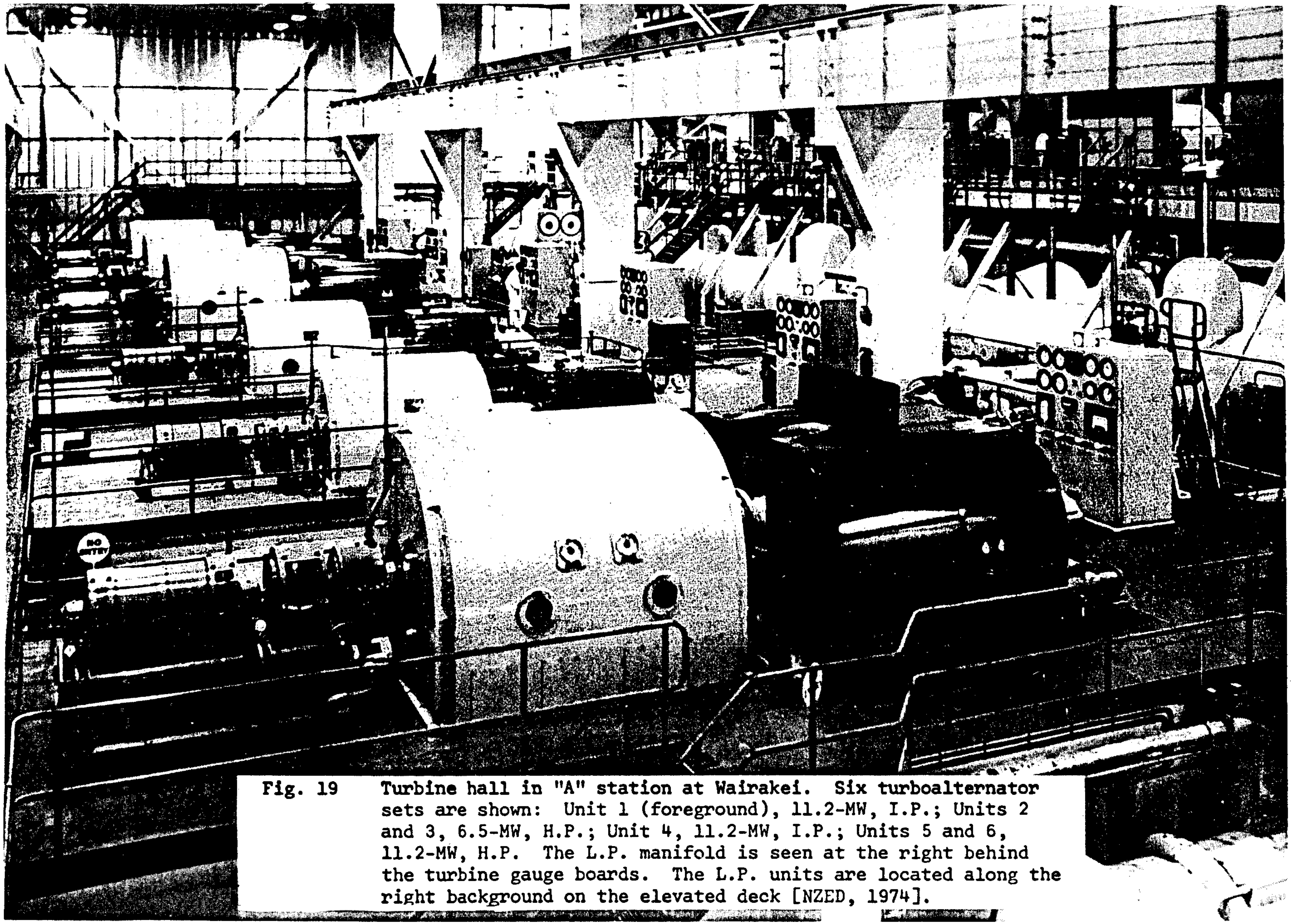


Fig. 19 Turbine hall in "A" station at Wairakei. Six turboalternator sets are shown: Unit 1 (foreground), 11.2-MW, I.P.; Units 2 and 3, 6.5-MW, H.P.; Unit 4, 11.2-MW, I.P.; Units 5 and 6, 11.2-MW, H.P. The L.P. manifold is seen at the right behind the turbine gauge boards. The L.P. units are located along the right background on the elevated deck [NZED, 1974].

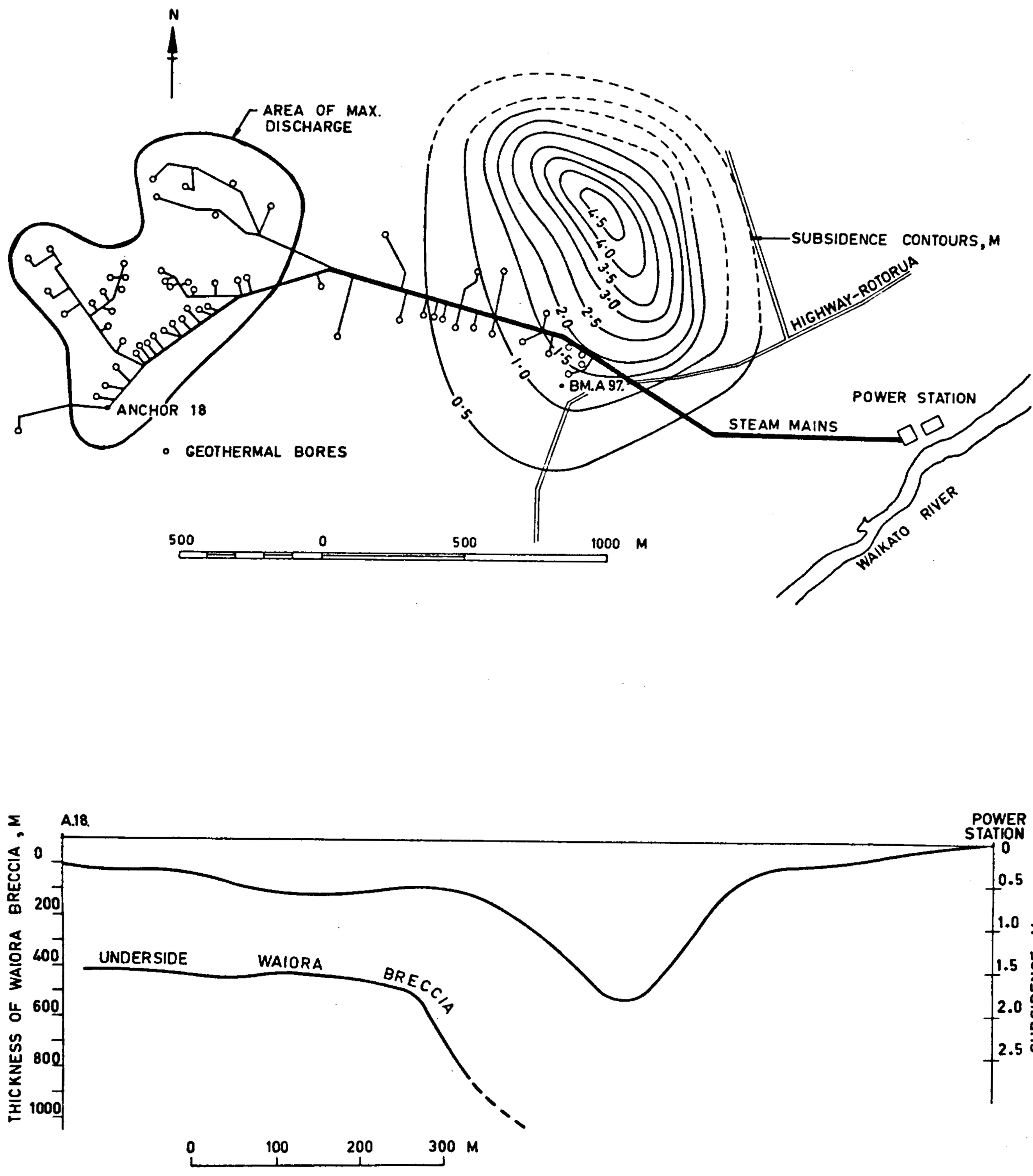


Fig. 20 (a) Total subsidence at Wairakei (relative to BM TH7 in the power house) for the period 1964-1974; (b) Total subsidence and Waiora breccia thickness measured along the main steam pipelines from 1964-1974 [Stilwell, et al., 1975].

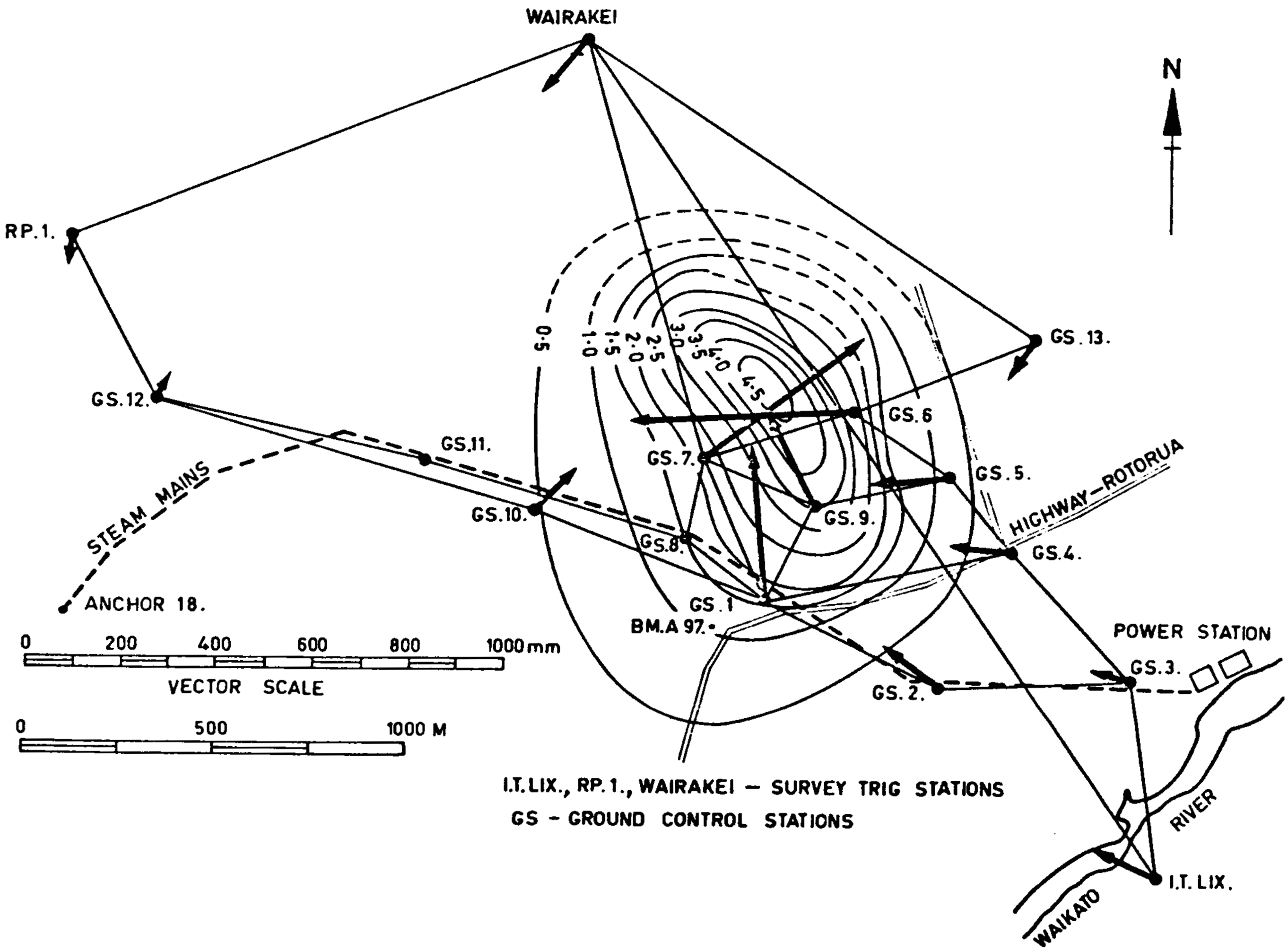


Fig. 21 Vector diagram of horizontal ground movement at Wairakei from 1966 to 1974 [Stilwell, et al., 1975].

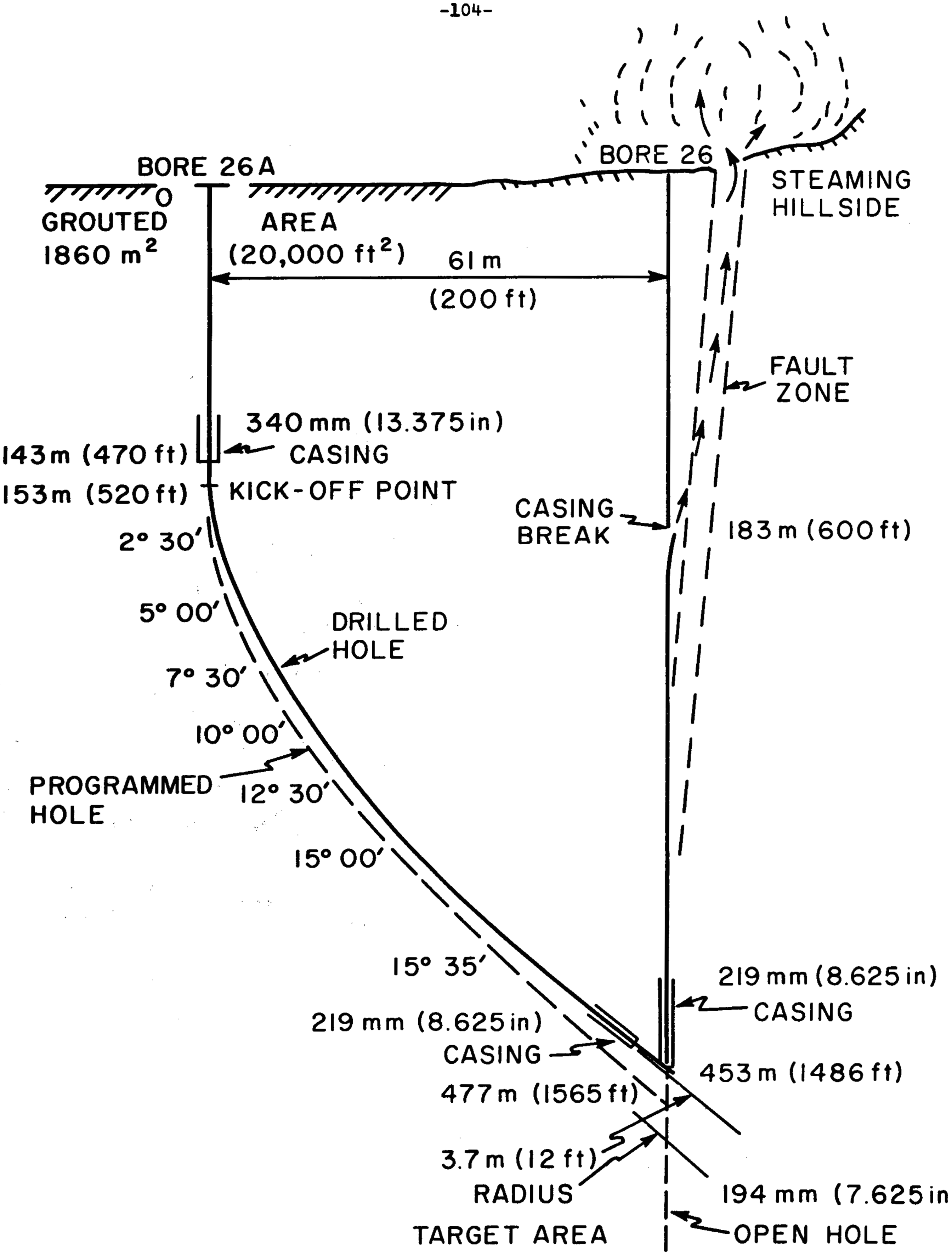


Fig. 22 **The drilling of deviated Bore 26A to control blowout of well Bore 26 [after NZED, 1974 and Craig, 1961].**

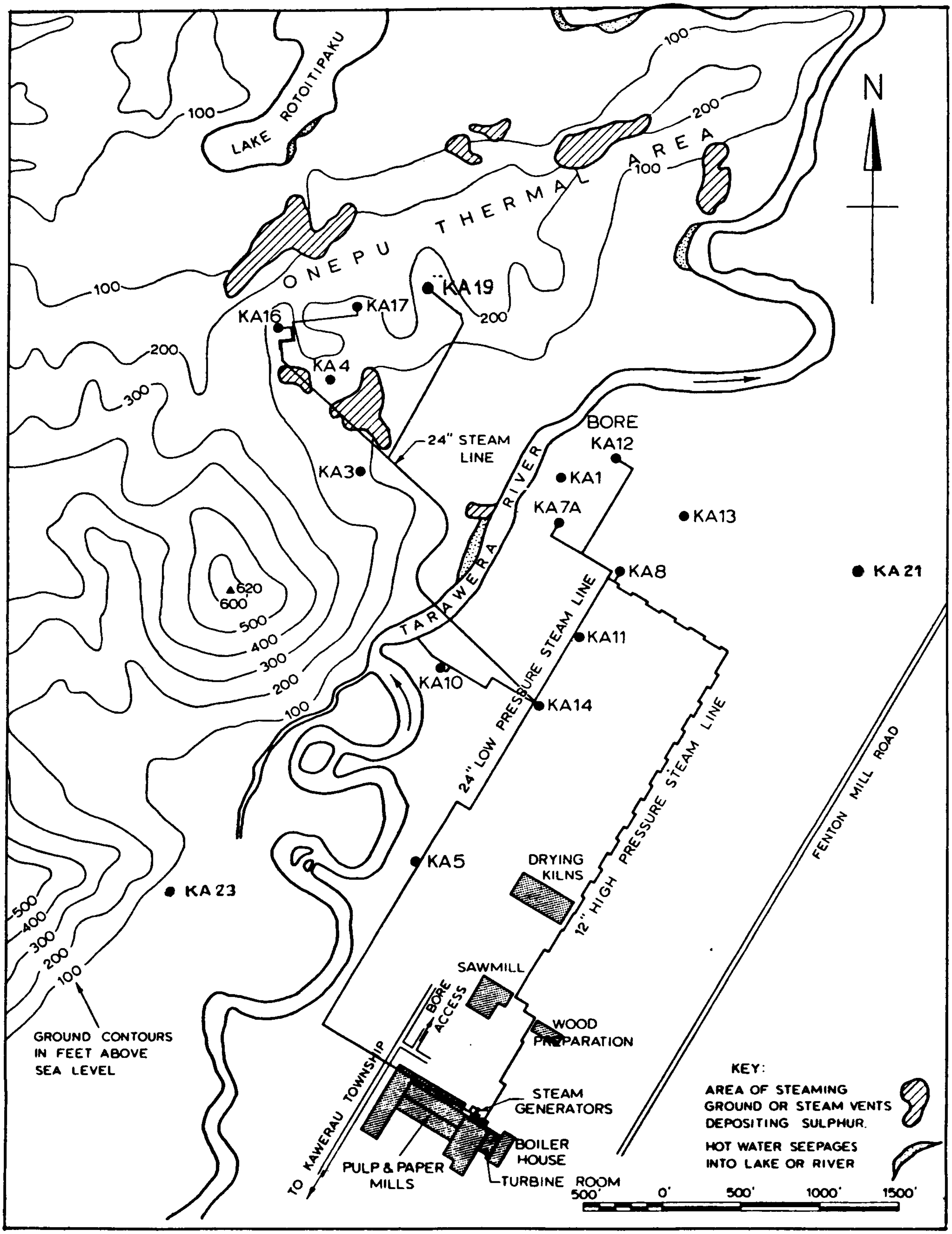


Fig. 23 Steam field layout at Kawerau [after Smith, 1970 and Bolton, 1977].

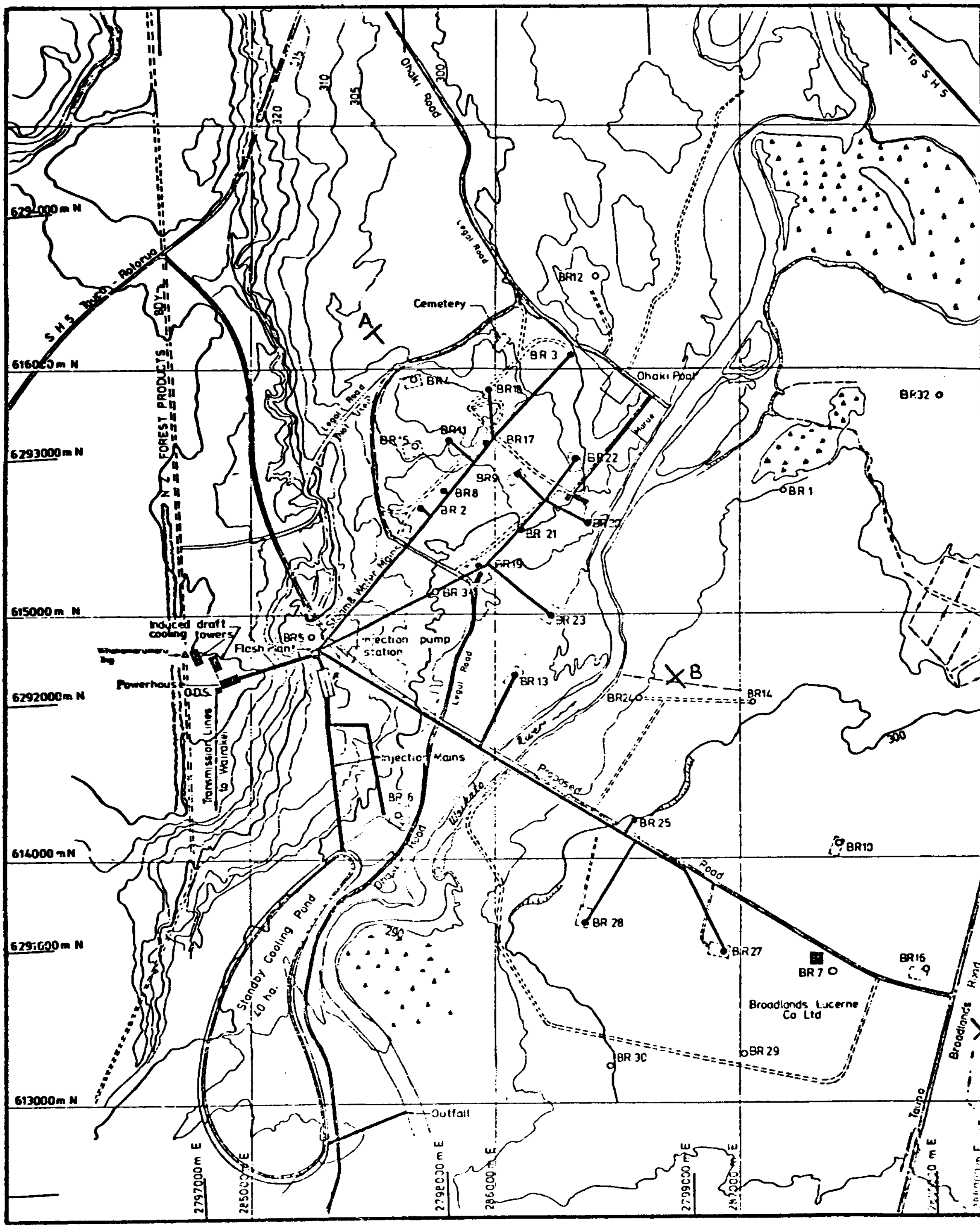


Fig. 24 Preliminary layout of the Broadlands geothermal power plant, steam field and gathering system [Bauer, et al., 1977]. Key: • BR28, producing well; o BR30, nonproducing well.

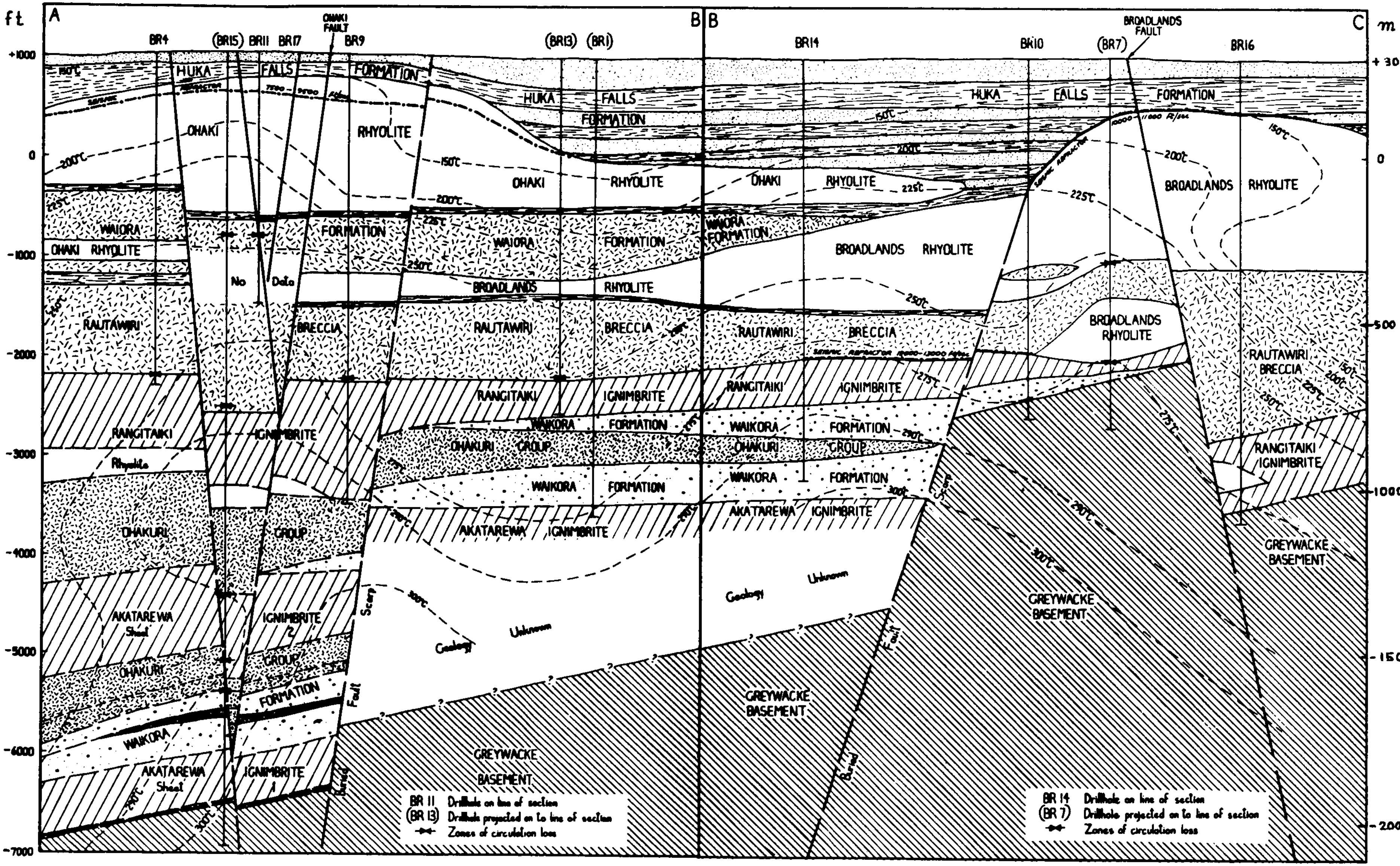


Fig. 25 Geologic cross-section through the Broadlands geothermal field with Ohaki thermal area at left and Broadlands thermal area at right [after Browne, 1970; Grindley, 1970].

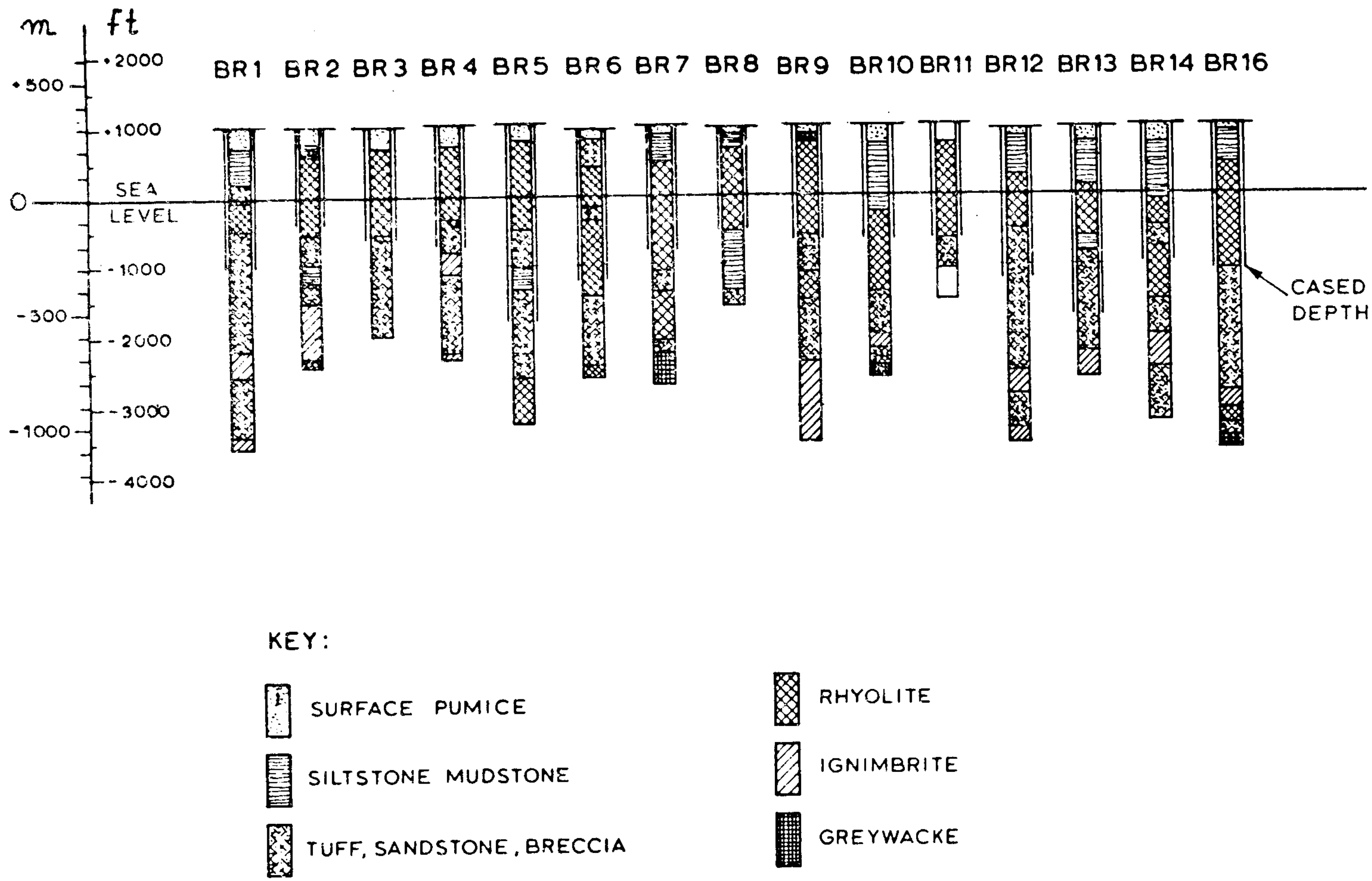


Fig. 26 Geologic logs for wells BR1-16 at Broadlands [after Smith, 1970].

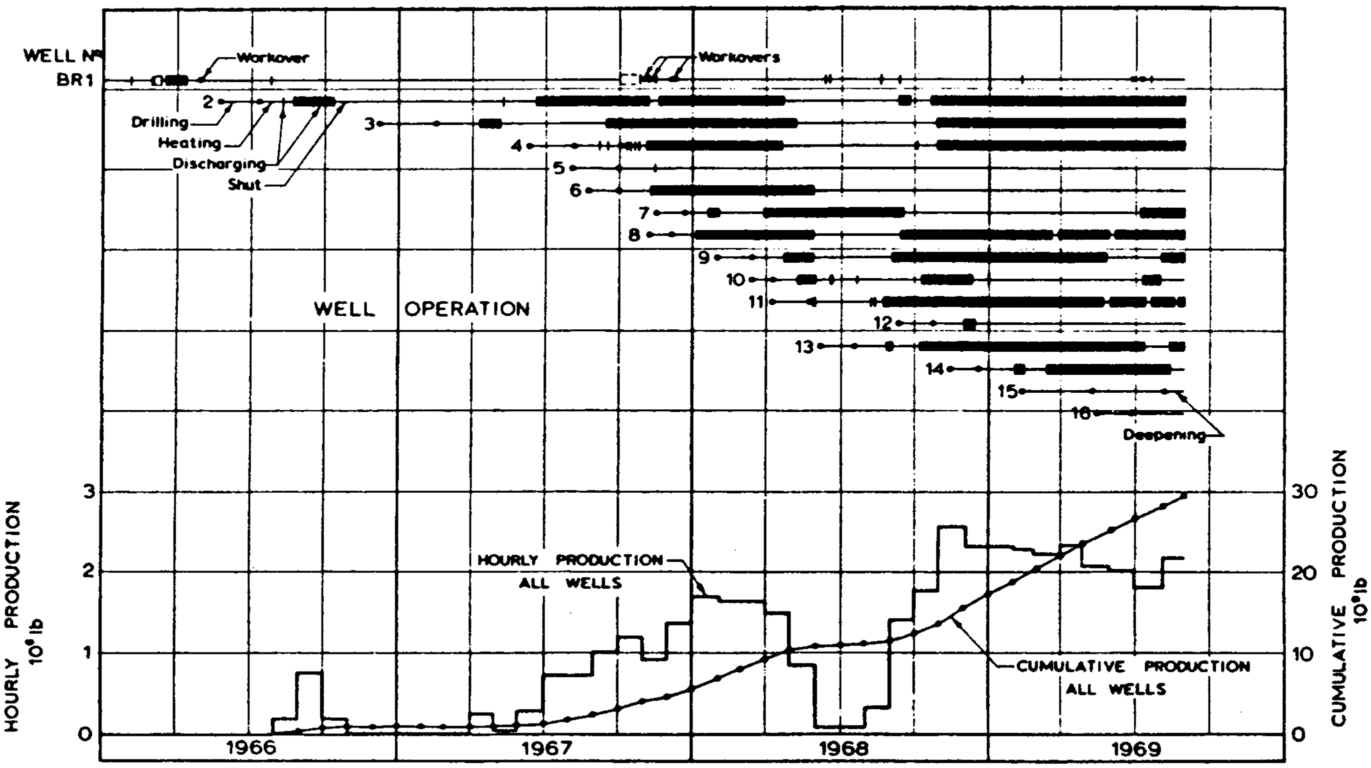


Fig. 27 Log of well operations for wells BR1-16 for the period 1966-1969 [after Smith, 1970].

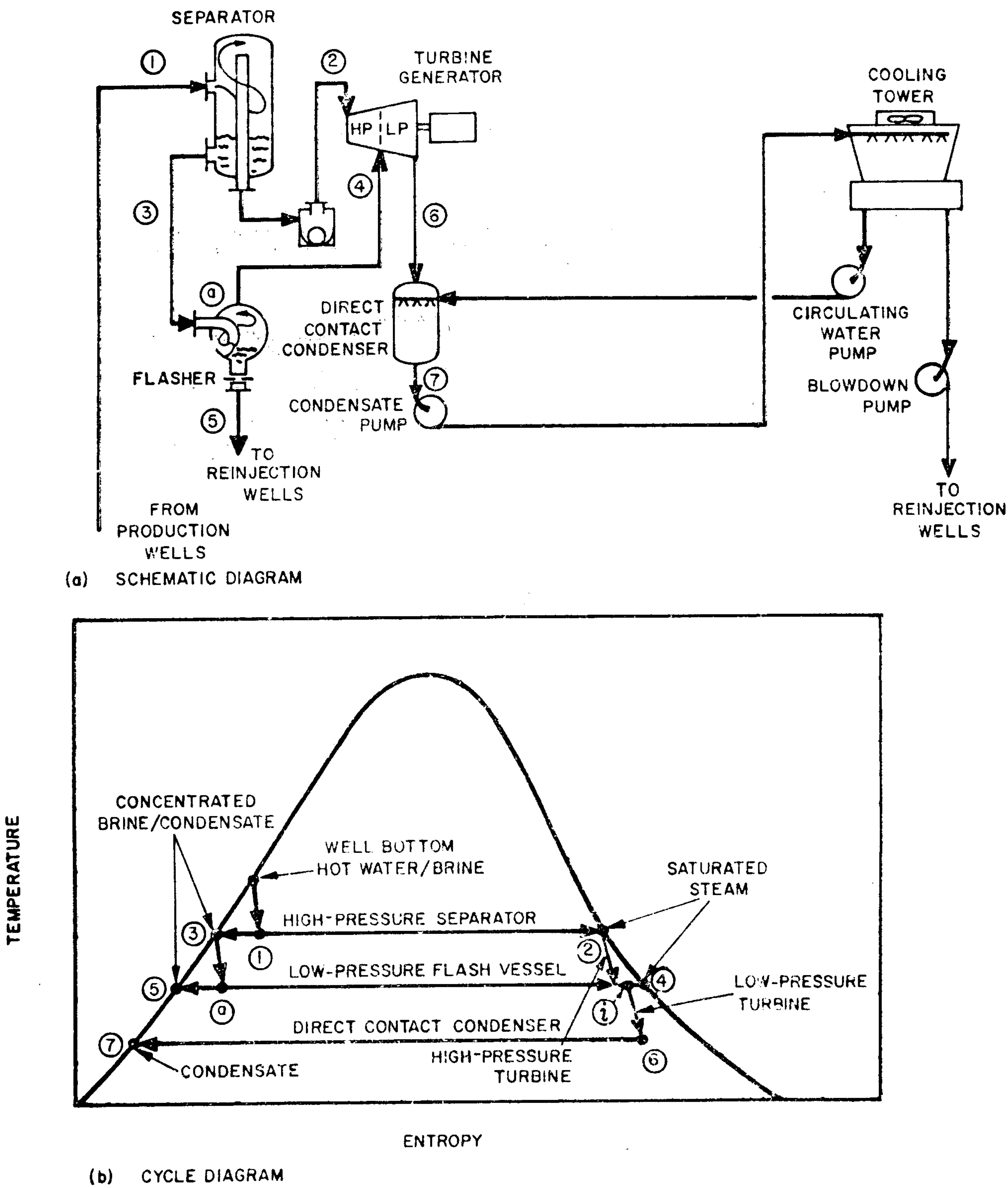


Fig. 28 (a) Generalized plant schematic and (b) cycle diagram for proposed Broadlands geothermal power plant.

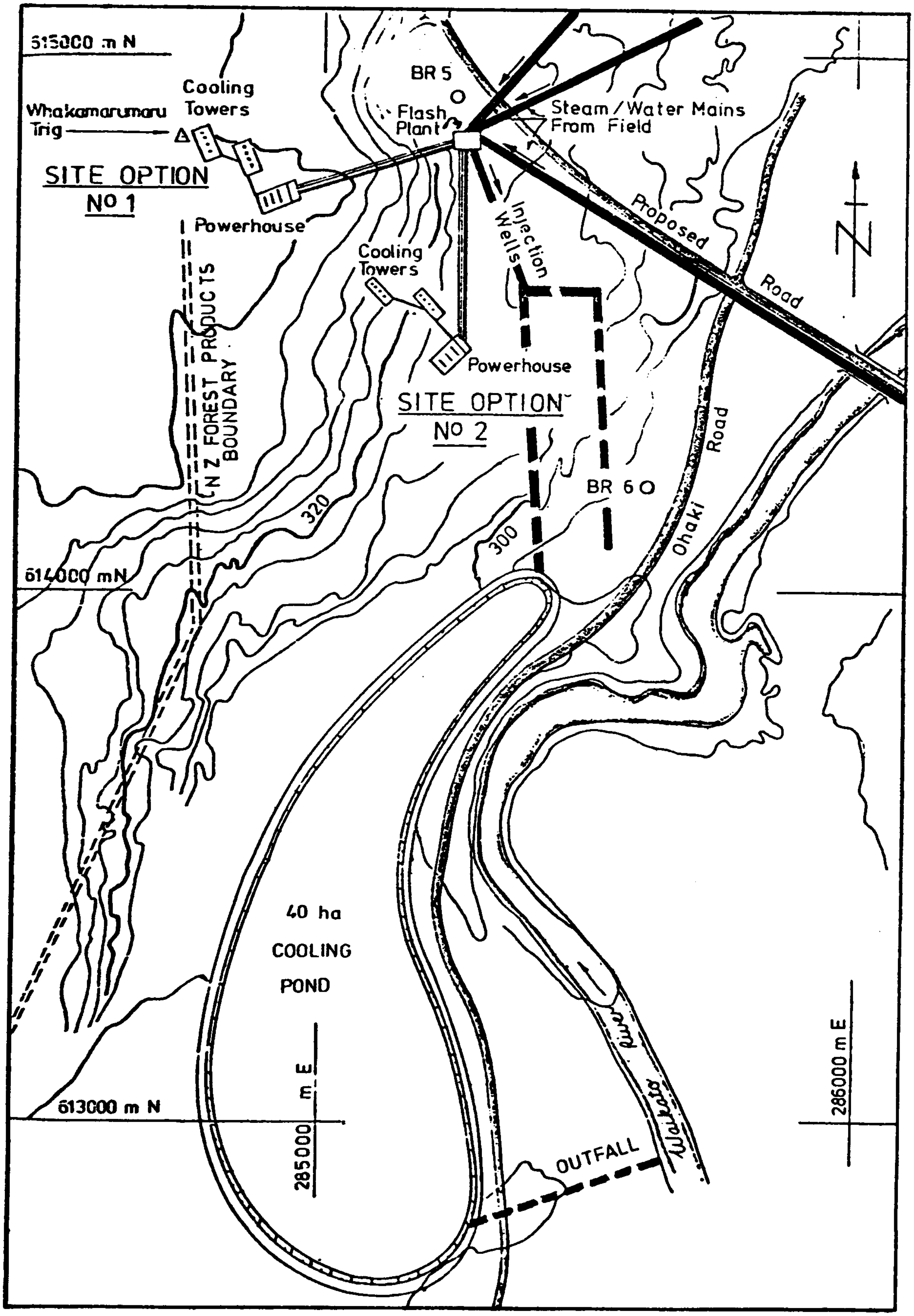


Fig. 29 Location of cooling pond for Broadlands geothermal power plant [Bauer, et al., 1977].

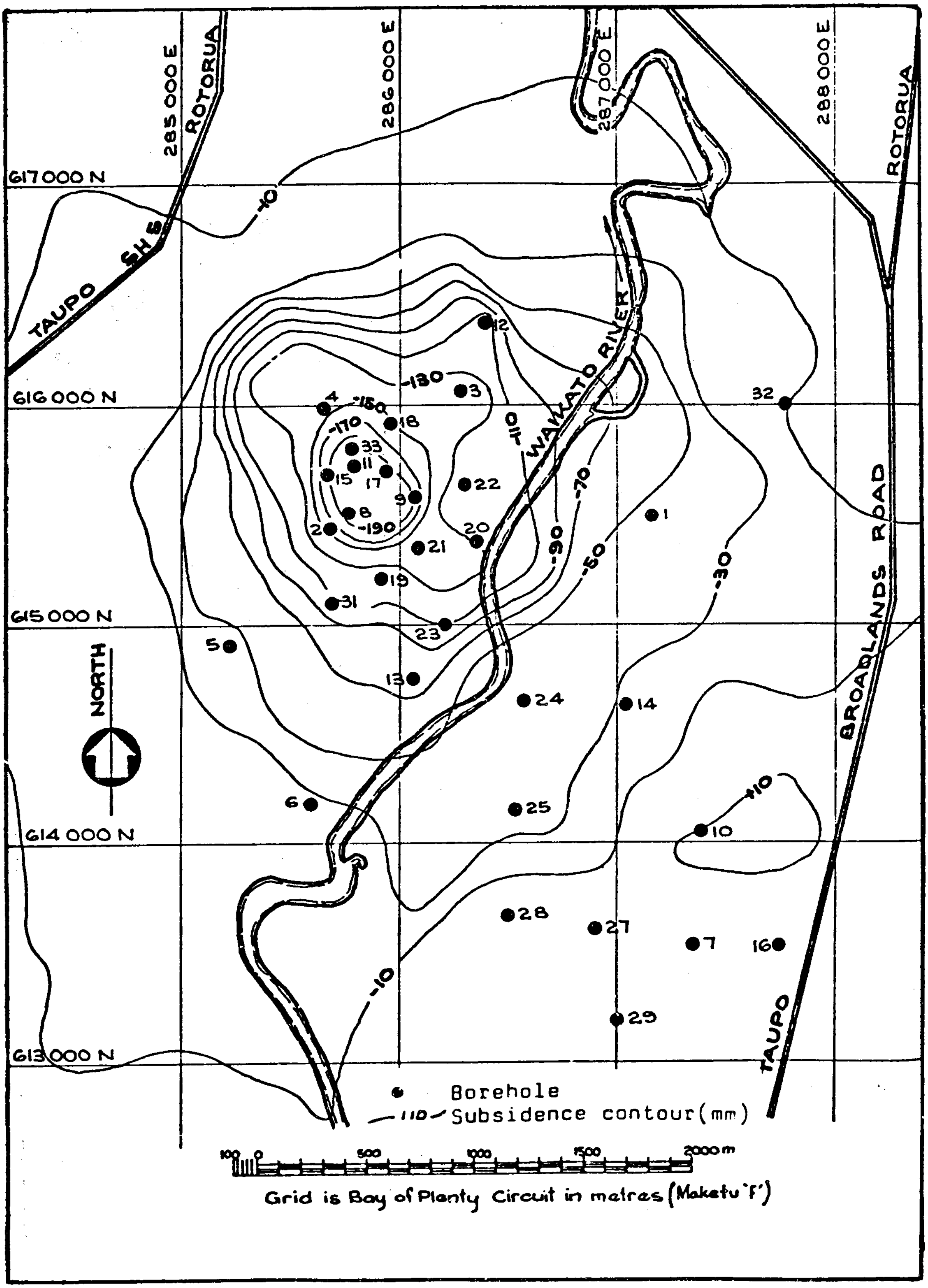
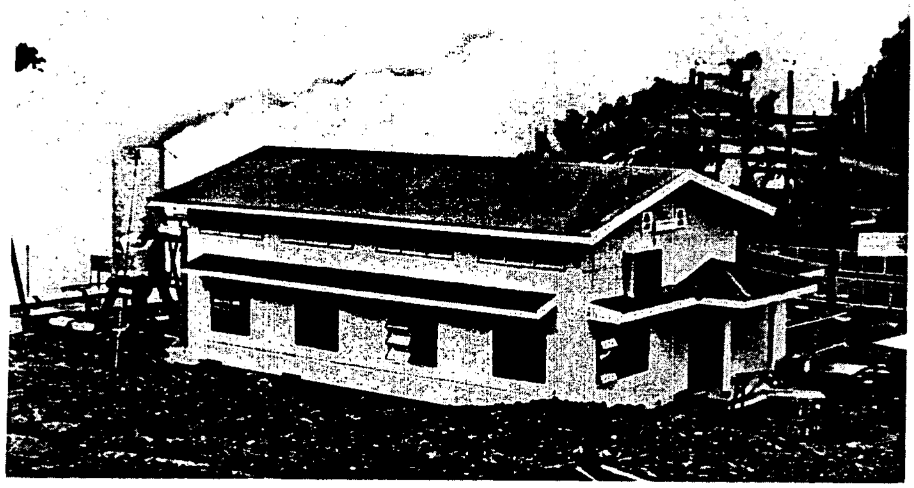
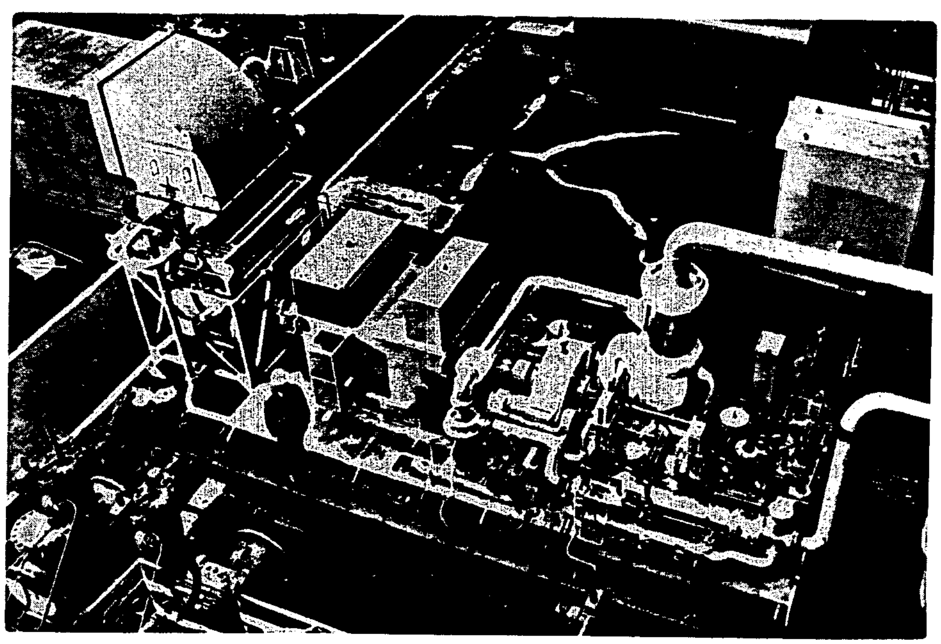


Fig. 30 Subsidence contours at Broadlands for the period May 1968 - March 1974 [after Bauer, et al., 1977].



(a)



(b)

Fig. 31 (a) Portable geothermal power station at Tongonan, Leyte, and (b) turbo-generator and auxiliaries on test in MHI shop [MHI, 1977].

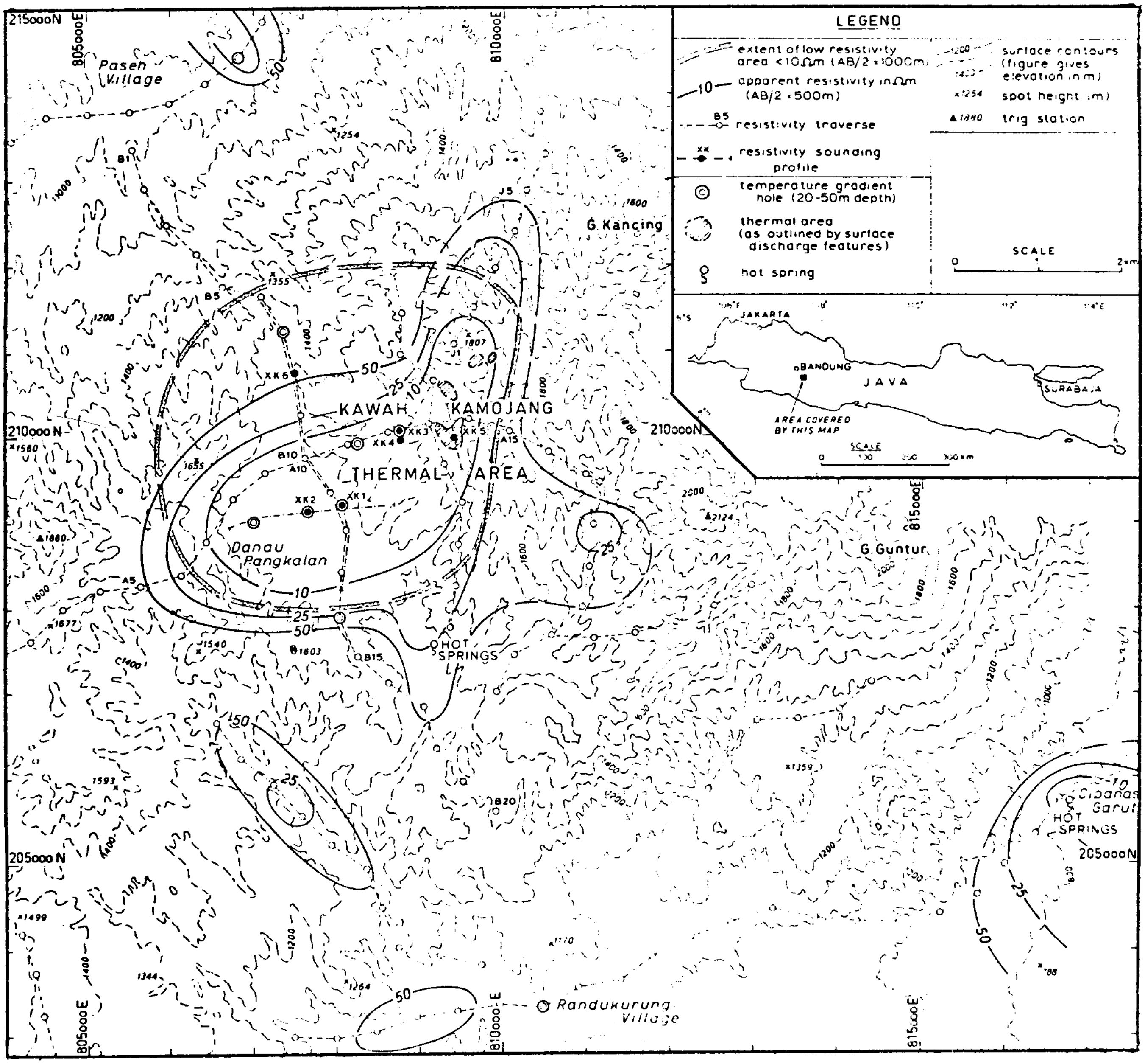


Fig. 32 Exploration of Kawah Kamojang geothermal field, Indonesia [Hochstein, 1975].

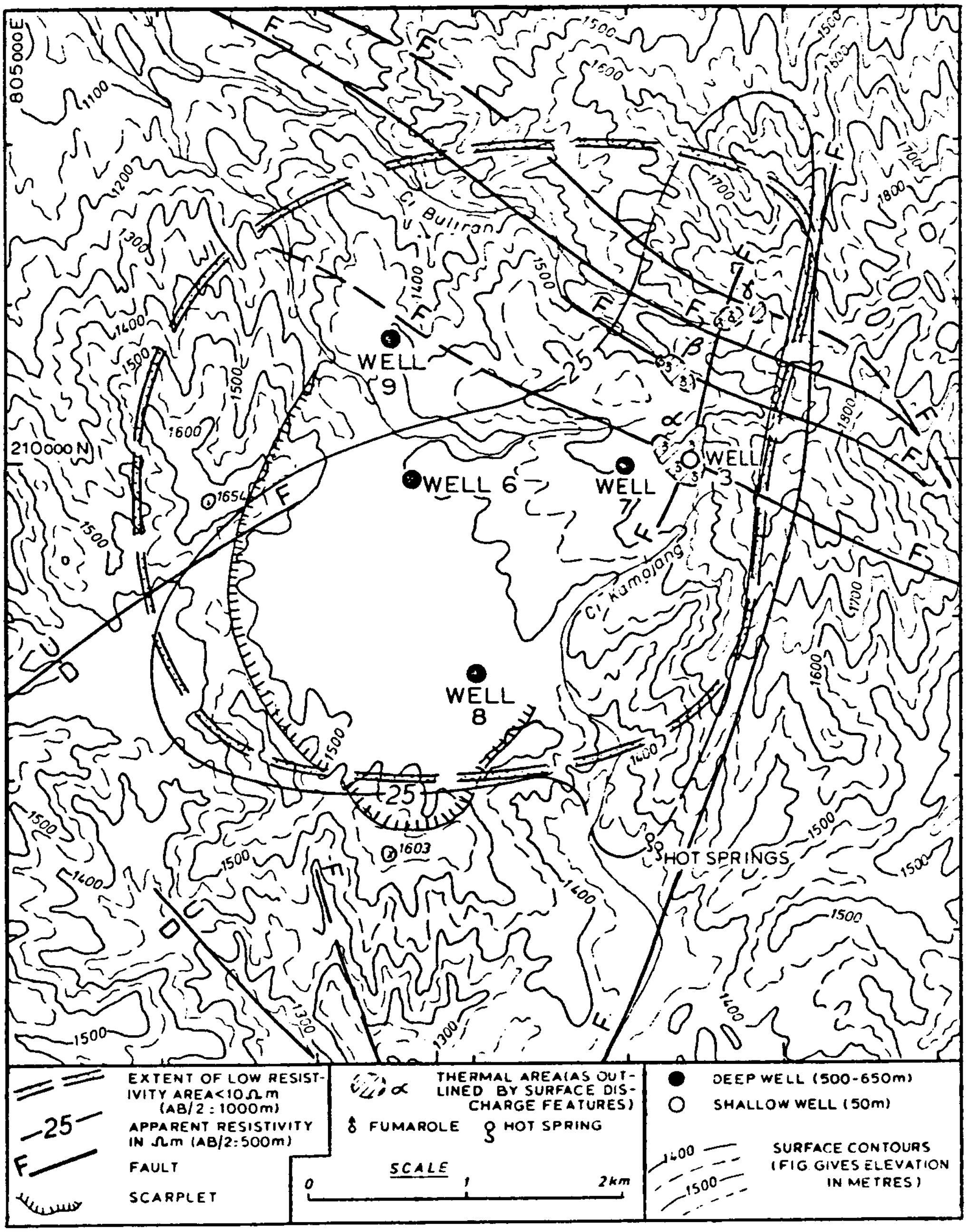


Fig. 33 Exploration wells at Kawah Kamojang, Indonesia [Hochstein, 1975].

☆U.S. GOVERNMENT PRINTING OFFICE: 1979-640-092/526