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Geothermal Power Plants of Iceland:
A Technical Survey of Existing and Planned Installations

by

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Abstract

The technical features of the geothermal electric power plants of Iceland are described. Some description is given of the geology of the geothermal regions, and recent volcanic eruptions are discussed relative to their impact on the geothermal plant sites.

The 3 MW, single-flash plant at Námafjall, the 60 MW, double-flash plant at Krafla, and the 1 MW unit at Grindavik are included. Information is given on well arrangements, casing programs, energy conversion systems, capital investments, and operating experiences, where such information is available.

Acknowledgements

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Table of Contents

1. Introduction

Iceland is perhaps better known for its direct use of geothermal energy in space-heating applications than for geothermal electric power generation. Roughly 50 percent of the population of this island heats its homes with geothermal hot water. Essentially all of the capital city of Reykjavik is heated by means of geothermal water at about 86°C (187°F). It is intended to expand the use of geothermal hot water to provide up to 70% of the space-heating needs of the country within the next few years [Lindal, 1977].

There are only a few locations in Iceland where electric power is generated from geothermal resources. The centers of population are mainly along the southwest coast whereas most of the geothermal fields that have been exploited for power production lie inland and to the northeast. Exploration and the beginning of expoitation are now taking place on the Reykjanes peninsula in southwestern Iceland. Furthermore, while there is an ample supply of hydroelectric power to serve the 220,000 inhabitants of the island, the fluctuating nature of this resource may lead to shortfalls during periods of peak demand.

Iceland is situated astride the Mid-Atlantic ridge. The Icelandic graben which sweeps from the north to the southwest through the center of the island exhibits the great tension which exists in the crustal rift zone. Figure 1 shows this prominent geological feature along with the major cities and the existing geothermal power plants.

The structure of the island is relatively young, 10-50 million years old, having been formed by massive volcanic eruptions along the spreading ridge. It has been observed that the rift zone is separating at a rate of about 2 cm/yr. [Burke and Wilson, 1976; Dewey, 1976; Wilson, 1976]. The Icelandic geothermal power plants at Námafjall and Krafla are located within this rift zone at the northern end. A small plant near Grindavik is at the southwestern extremity of the west branch of the rift valley. The geological structure of the regions is highly unstable, creating serious problems related to well completions, reservoir engineering, and power production.

2. Námafjall

The geothermal resource at Námafjall is being put to use to process diatomaceous earth which is used as a filter aid. The diatomite plant at Kisilidjan is supplied with steam from wells at the Námafjall field [Birsic, 1977]. The power plant at the site is relatively small and supplies electrical power for the processing plant.

2.1. Geology

The Námafjall geothermal region is the site of several projects which make use of the thermal anomaly in the region. Wells had been used to extract sulfur from the hydrogen sulfide which constitutes a portion of the geofluid. This mining operation gave rise to the name Námafjall which means "the mountain of the mines" [Ragnars, et al, 1970].

As can be seen from Fig. 1, Námafjall lies on the western side of the rift valley in northern Iceland. An abundance of surface thermal manifestations are found there including boiling mud pools, steaming ground, and fumaroles. The Námafjall thermal area covers about 400 - 500 ha (988 - 1235 acres), but is part of a much larger thermal region, including Krafla, which extends over 5000 ha (12,350 acres).

The area is highly fractured with fissures and faults trending north-northeast/south-southwest. The rocks found there are of the silicic volcanic type and range in composition from basaltic andesites to rhyolites. Most of the volcanic fissures are inactive, having last erupted at least 1000 years ago. One of them, however, was last known to erupt in 1728 [Ragnars, et al, 1970].

2.2. Well programs and gathering system

The arrangement of the wells relative to the power plant and the adjacent diatomite plant is shown in Fig. 2. A number of shallow wells (not shown) were drilled during 1947 - 1953 for sulphur mining. The present production wells were begun in 1963, with the first of these, N1, being completed in 1966, followed by N2 and N3 in 1968. The wells are located along two faults and are separated by about 90 m (295 ft).

Since the uppermost 180 m (590 ft) of the formation are permeable, loss of circulation is often encountered during the shallow drilling phase. Repeated cementing is required to prevent the wells from collapsing. The newest wells are cased as follows: (1) Surface casing of 406 mm (16 in) to a depth of 30 - 40 m (100 - 130 ft); (2) Anchor casing of 244 mm (9 5/8 in) to 200 m (656 ft); (3) Production casing of 194 mm (7 5/8 in) to 600 m (1970 ft). If needed, 152 mm (6 in) slotted liners are installed below the production casing [Ragnars, et al, 1970].

The wellhead equipment is shown schematically in Fig. 3. It was found necessary to install a U-pipe separator on the wellhead because of sand, mud, pebbles and other solid material which is ejected occasionally from the wells. A conventional cyclone separator is used to separate the vapor and liquid phases of the geofluid. The wellhead equipment is housed in a small shed to shelter it from the effects of the severe Icelandic winters.

The steam pipelines are run 2 m (6.6 ft) above ground level to avoid being buried in snow during winter and being inundated during thaws. The pipes are 250 mm (10 in) in diameter and carry 50 mm (2 in) of glass wool insulation which is protected by a waterproof sheathing of aluminum. Thermal expansion loops are provided along the lines to allow for temperature differences are large as 220°C (396°F) which amounts to a movement of about 0.26 m/100 m.

2.3. Geofluid characteristics

The wells produce a mixture of liquid and vapor plus an amount of noncondensable gases equal to about 1% (by weight) of the steam flow. The composition (by volume) of the noncondensable gases is roughly as follows: hydrogen sulfide, 52%; carbon dioxide, 32%; hydrogen, 12%; other gases such as nitrogen, methane, argon, etc., 4% [Bjornsson, 1968].

Down-hole temperatures of nearly 300°C (572°F) have been observed; normal steam delivery temperature is about 183°C (361°F). Each well produces about 25 Mg/h (55,000 lbm/h) of separated steam at a pressure of 1078 kPa (156 lbf/in^2). The total dissolved solids in the liquid (down-hole) is about 1000 ppm, nearly 60% of which is silica. At 25°C (77°F) the liquid has a pH $\approx$ 7.

2.4. Energy conversion system

The power plant is of the noncondensing type with a nominal capacity of 3.0 MW. The original turbine-alternator was manufactured by British Thomson-Houston and had a rating of 2.5 MW. It was purchased second-hand by the Laxa Power Works so as to reduce construction time. The plant was, in fact, designed and built in seven working months [Ragnars, et al, 1970]. Recently the turbine was upgraded to 3.0 MW.

The configuration of the power generation equipment is shown in Fig. 4. A final cyclone separator is required at the power house to remove moisture which condenses out of the steam during the transmission from the wells to the power plant. The exhaust stack/silencer stands beside the building, rising about 9 m (29 ft) above ground level. The power house is quite compact, having dimensions 12.5 m (w) × 8 m (ℓ) × 7.5 m (h) (41 × 26 × 21 ft). Because of the climate, the transformer is located inside the power house.

Since the plant is of the noncondensing type, it has a low resource utilization efficiency. On the assumption that 20% of the geofluid is vapor at the wellhead, and that the appropriate ambient sink temperature for the region is 11°C (51.8°F), then the utilization efficiency is 14% and the plant consumes 82.5 kg of geofluid/kW·h (182 lbm/kW·h).

The technical specifications for the Námafjall unit are contained in Table 1.

2.5. Economic data

Preliminary cost estimates made in 1967 showed that electricity could be generated at between 4.5 - 5.5 US mill/kW·h at a 91% capacity factor [Ragnars, et al, 1970]. The capital costs have been computed [Leardini, 1974] as follows:

Power station	US $ 50/kW
Wells and gathering systems	US $ 73/kW
Total	US $123/kW

It should be noted, however, that the power station cost included a second-hand, recommissioned steam turbine. Had a new machine been purchased at that time, i.e., in 1968, the total capital cost for the plant would have been about US $147/kW.

2.6. Operating experience

It was learned that the power station had sustained serious damage recently caused by an earthquake at the site, but that the plant has been repaired and is operating once again [Kuwada, 1978].

3. Krafla

The geothermal power plant at Krafla is the first major power station of its type in Iceland. It is an advanced design and uses a secondary flash process to generate additional steam for power generation from liquid which would otherwise be wasted.

The project got under way officially in April 1974 when the Icelandic Parliament passed an act calling for the construction of a geothermal power plant at Krafla. A number of agencies and organizations have been involved in the planning, design, construction, and operation of the plant. These include:

- Krafla Geothermal Project Executive Committee - Overall responsibility for planning and construction of plant.
- National Energy Authority of Iceland (OS) - Well drilling, steam winning, design and construction of steam gathering system, and liquid waste disposal system.
- Nature Conservation Council - Consent and supervision of plant design, especially waste water disposal, as it impacts the environment, specifically Lake Mývatn and River Laxá.

A large number of subcontractors have been commissioned for the actual operations, including the Rogers Engineering Co., Inc. of San Francisco as architects/engineers for the power plant.

3.1. Geology

As can be seen from Fig. 1, Krafla lies in the same volcanic rift zone as Námafjall. This area is extremely active, with twenty volcanic eruptions having occurred there during the last 10,000 years. A series of massive eruptions took place during the period 1724-1728, when mixtures of basalt and rhyolite poured forth from craters. The activity culminated in an enormous steam explosion, so gigantic that it was visible to inhabitants of southern Iceland over 300 km (185 mi) away.

The Krafla area was most recently subjected to another series of strong seisic events. In July 1975 earthquake tremors was detected. Gradually these increased in strength, and on December 20, 1975 lava burst out in Leirhnjúkur, only 3 km (2 mi) from the site of the Krafla plant. Although the lava flow lasted only a few hours, steam continued to erupt until the end of the year. During this period, 2000 - 4000 earth tremors were recorded each day.

During the first three months of 1976, there occurred seven earthquakes of magnitude greater than 4.0 on the Richter scale, with two of these exceeding magnitude 5.0. All of these were centered within a few kilometers of the plant site. By June 1976 most of the activity had ceased, but continuous vigilance is carried out by means of seismic monitors and field observations [Sólnes, 1976].

This recent activity has resulted in the formation of a large number of new fissures which traverse the geothermal fields in the Krafla area. These trend mostly north-south through the southern border of the caldera in which Krafla is located. A number of new hot springs and boiling mud pools were also created [Pálmason, et al, 1975].

3.2. Well programs and gathering system

A series of exploratory surveys were conducted from 1970-1973 in the Krafla area. These included geological, geochemical, and geophysical (electrical resistivity and magnetic) surveys. As a result of the magnetic low (caused by hydrothermal alteration of magnetite) and the delineation of the field by the resistivity survey, two exploratory wells were sited and drilled to depths of about 1100 m (3600 ft).

One of these was quite hot, with a bottomhole temperature of 298°C (568°F), but was a poor producer (low permeability). It was estimated that a temperature of 330°C (626°F) would be encountered at a depth of 2 km (6560 ft), the depth of the proposed production wells.

The other exploratory well was an excellent producer, but yielded relatively cool geofluid. The low temperatures were caused by an influx of cool water from a shallow aquifer at a depth of about 340 m (1100 ft). Although a high-temperature reservoir lies at deeper depths, the cold water from the shallow reservoir resulted in bottomhole temperatures of only 210°C (410°F).

In the case of production wells which intercept the shallow reservoir, the upper zone will be sealed off to prevent the degradation of fluid temperature which ensues from the mixing of the fluids from the hot and cold producing zones [Kuwada, 1978].

A plan view of the power station site is given in Fig. 5 which shows the locations of the power house, cooling tower, cooling pond, and proposed wells. The locations of the wells are tentative and subject to change. Also shown in the figure are the sites of recent volcanic activity, Leirhnjúkur, mentioned earlier, and Víti ("Hell") a crater which was formed at the beginning of the "Fires of Mývatn" in 1724. The proximity of these centers of volcanic action to the Krafla bore field is evident.

Figure 6 shows a typical casing program for a production well. The wells are capped by a 254 mm (10 in) gate valve rated at 6.2 - 10.3 MPa (900 - 1500 lbf/in^2).

3.3. Energy conversion system

The plant is of the separated/single-flash (or so-called "double-flash") steam type. Each well is equipped with a high-pressure cyclone separator, the steam from which is piped to the power house while the liquid is directed to a flash tank located 400 - 500 m (1312 - 1640 ft) from the plant. The liquid from all the wellhead separators is collectively flashed to generate a flow of secondary, low-pressure steam.

The turbine is a single-cylinder, double-flow, dual-pressure unit manufactured by the Mitsubishi Heavy Industries, Ltd. It has five stages in each flow, with the secondary steam admitted to the machine through pass-in sections on each side where it mixes with the primary steam before expanding in the last stages.

A highly-simplified flow diagram for the plant is shown in Fig. 7. Only one typical wellhead setup is depicted; there may be 5 or 6 wells required for each turbo-generator unit. There are two 30 MW units currently installed at Krafla although there is insufficient steam available at this time to supply even one unit fully. The technical specifications for the Krafla units are listed in Table 1 [MHI, 1978].

The cooling pond can hold about 120,000 m^3 (32 × 10^6 gal); a 4-day hold-up time can be provided to allow for cooling of the waste water from about 90°C (194°F) to 10 - 20°C (50 - 68°F). During this time, hydrogen sulfide will have escaped to the atmosphere and silica will have polymerized and settled out. The effluent will then be discharged into the Skarosels stream for eventual disposal in the Búrfell lava field [Sólnes, 1976].

3.4. Economic data

The capital investment figures given below are projected values made in 1976; it is quite likely that the cost of the wells and steam transmission system will exceed the figures given below.

Item	Capital Cost, $	$/kW
Power house, energy conversion equipment, substation, staff housing, etc.	26,000,000	433
Production wells and complete steam gathering system	10,000,000	167
Transmission line from Krafla to Akureyri	3,300,000	55
Total capital cost	39,300,000	655

The cost per installed kilowatt is based on the full 60,000 kW station capacity. Since it is not likely that this will be achieved in the near future, these figures should increase accordingly.

3.5. Operating experience

Very little information is available on the operation of the plant. It is known that trouble has been encountered with the production wells. Although the geofluid is relatively clean (TDS $\approx$ 1000 ppm with about 650 ppm silica), the wells have been subject to clogging. Two plugs seem to develop: a deep plug at about 1550 m (5085 ft) which consists of iron sulfide, and a calcium carbonate plug at about 700 m (2300 ft). In a short period of time, the 187 mm (7 3/8 in) diameter hole in the slotted liner is reduced to about 38 mm (1 1/2 in). One of the two production zones lies between the two plugs, and it is possible that the calcium carbonate plug may be eliminated by blocking off the upper production zone [Kuwada, 1978]. In any event, it now seems evident that the cause of the poor production from the wells is the presence of these deposits in the boreholes, rather than the collapsing of the formation from earthquake activity as was earlier thought to be the case.

4. Grindavik

It has been learned that a 1 MW geothermal power unit is located at Svartsengi near Grindavik on the Reykjanes peninsular in southwestern Iceland [Gudmundsson, 1978].

The bottomhole temperature is 235°C (455°F); the temperature of the steam at the separator is 155°C (311°F). Presumably the plant is of the non-condensing type and makes use of a single well. It is expected that the capacity at the site will be increased as field development takes place and justifies the expansion of the plant.

Table 1 contains what little information is known about the power plant.

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Table 1

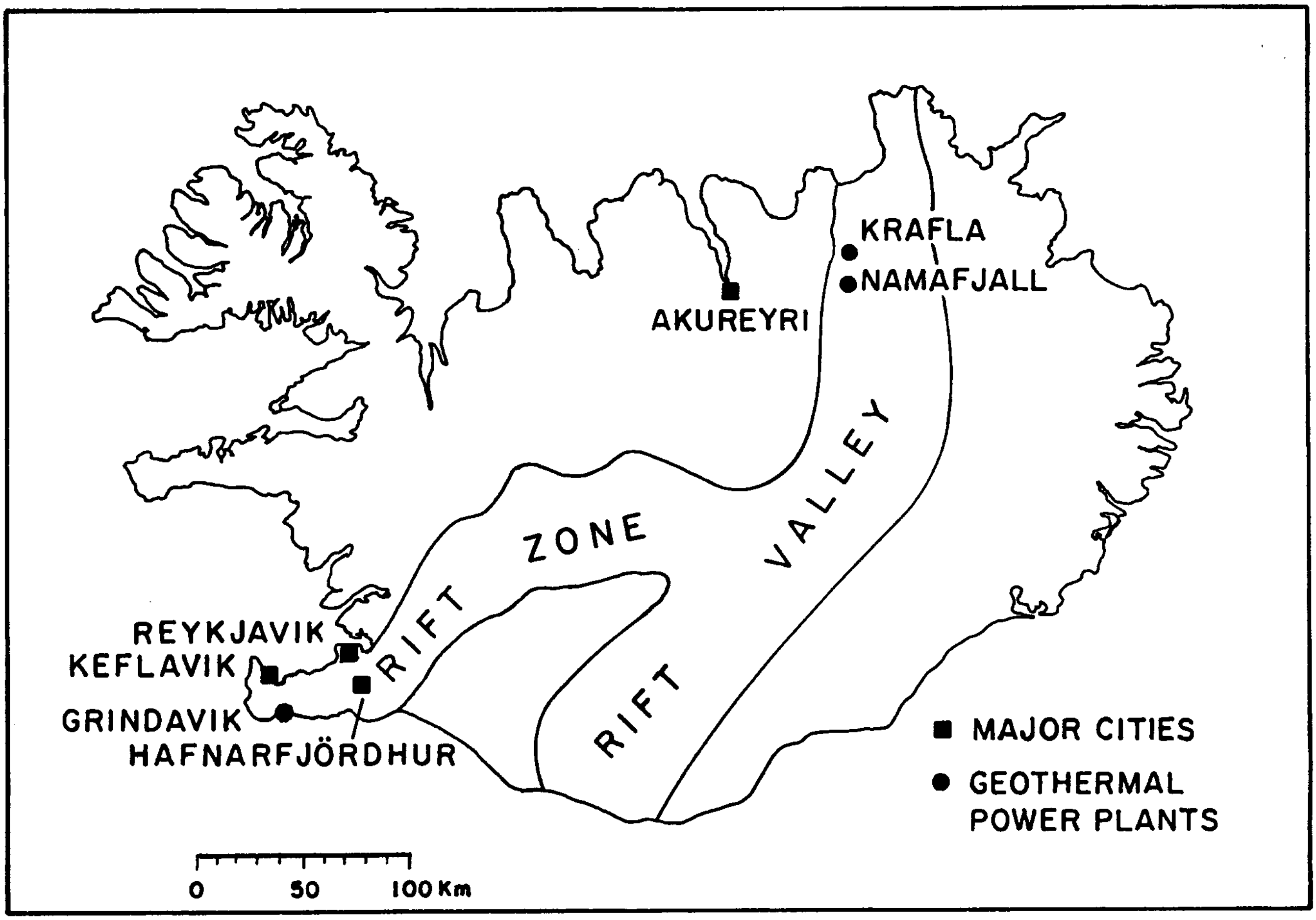
Technical specifications for Icelandic geothermal power stations

	Námafjall	Krafla Unit 1[a]	Grindavik
Year of start-up	1969	1977	1978
Turbine data:			
Type	Single cylinder, one Curtis stage, noncondensing	Single cylinder, double-flow, dual-admission, impulse-reaction	(NA)
Rated capacity, MW	3.0	30.0	1.0
Maximum capacity, MW	3.4	35.0	1.0
Speed, rpm	3000	3000	(NA)
Main steam pressure, lbf/in^2	142.7	110.0	78.8
Main steam temperature, °F	354.5	334.4	311.0
Secondary steam pressure, lbf/in^2	—	27.5	—
Secondary steam temperature, °F	—	244.4	—
Exhaust pressure, in Hg	31.4	3.5	∿31.4
Main steam flow rate, 10^3 lbm/h	109	417	(NA)
Secondary steam flow rate, 10^3 lbm/h	—	142	(NA)
Condenser data:			
Type	(None)	low-level, direct-contact, tray type	(NA)
Cooling water temperature, °F	—	71.6	(NA)
Outlet water temperature, °F	—	115.2	(NA)
Cooling water flow rate, 10^6 lbm/h	—	12.4	(NA)

(a) Krafla Unit 2 is identical to Unit 1 and is under construction.

Figure captions

Fig. 1.	Map of Iceland showing rift zones, major cities, and sites of geothermal power plants.
Fig. 2.	Arrangement of wells at Námafjall to serve diatomite processing plant and 3.0 MW, noncondensing power unit [after Ragnars, *et al*, 1970].
Fig. 3.	Typical wellhead equipment at Námafjall [Ragnars, *et al*, 1970].
Fig. 4.	Layout of 30 MW geothermal power plant at Námafjall [Ragnars, *et al*, 1970].
Fig. 5.	Arrangement of Krafla geothermal power plant and steam wells [after Sólnes, 1976].
Fig. 6.	Typical casing program for production well at Krafla [after Sólnes, 1976]. (Not to scale.)
Fig. 7.	Simplified flow diagram for Krafla geothermal power station.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NAMAFJALL
AKUREYRI
RIFT VALLEY
RIFT ZONE
RIFT
REYKJAVIK
KEFLAVIK
GRINDAVIK
HAFNARFJÖRDHUR
■ MAJOR CITIES
● GEOTHERMAL POWER PLANTS
0
50
100 Km

Figure 1

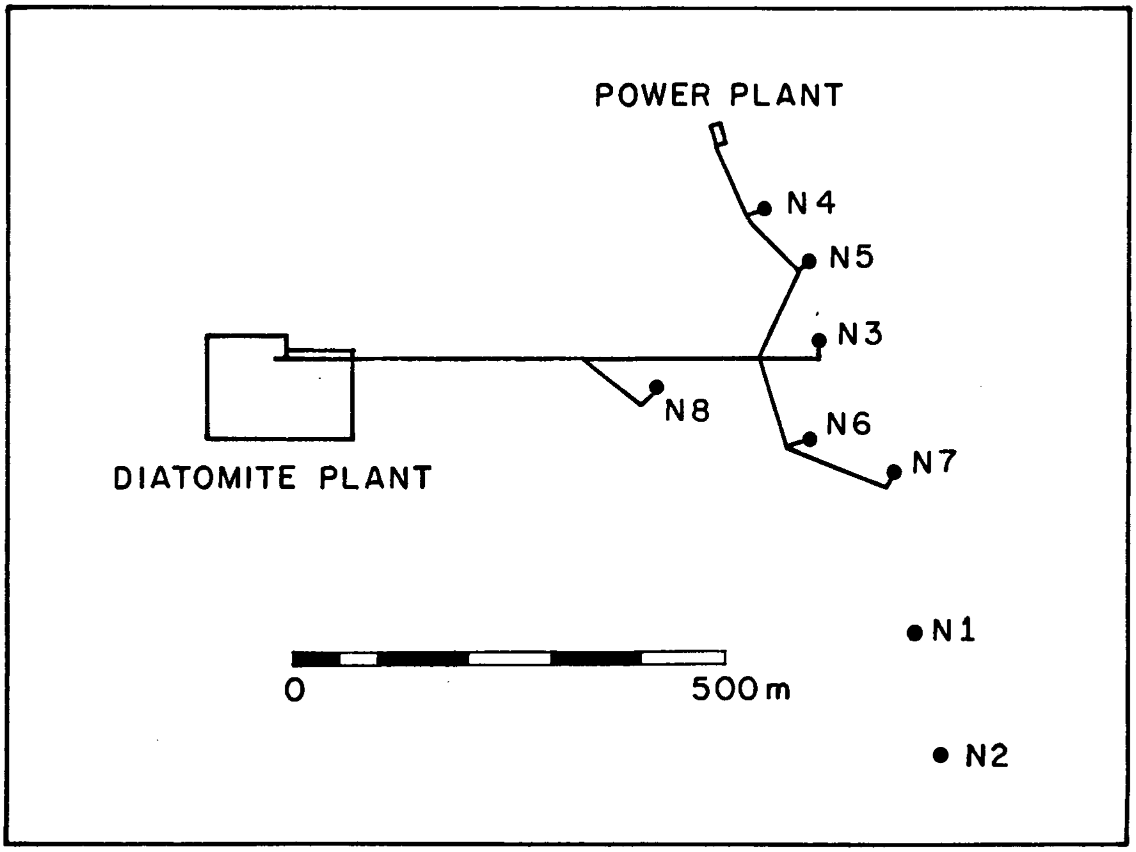
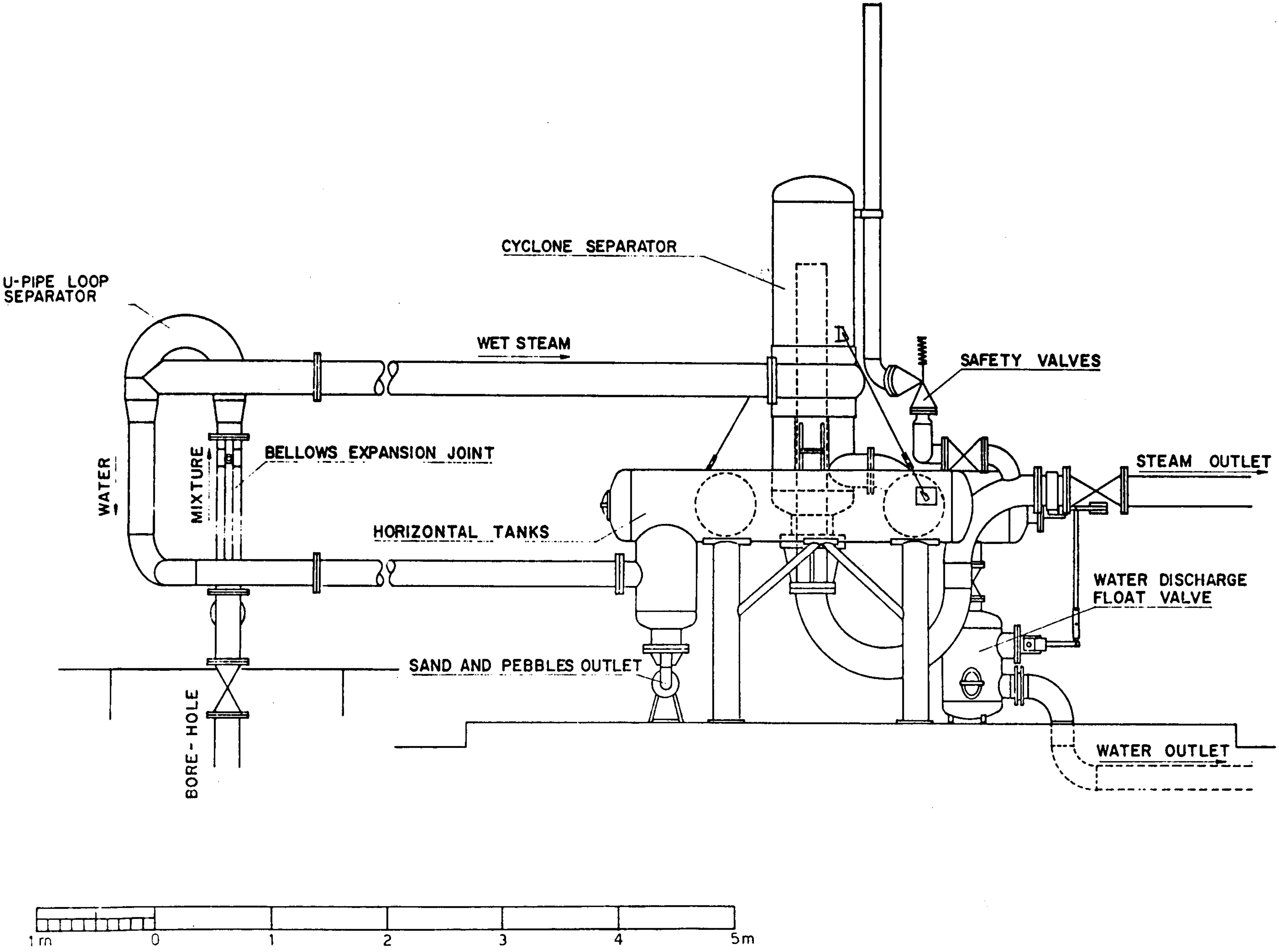


Figure 2


CYCLONE SEPARATOR
U-PIPE LOOP SEPARATOR
WET STEAM
SAFETY VALVES
BELLOWS EXPANSION JOINT
WATER
MIXTURE
STEAM OUTLET
HORIZONTAL TANKS
WATER DISCHARGE FLOAT VALVE
SAND AND PEBBLES OUTLET
BORE-HOLE
WATER OUTLET
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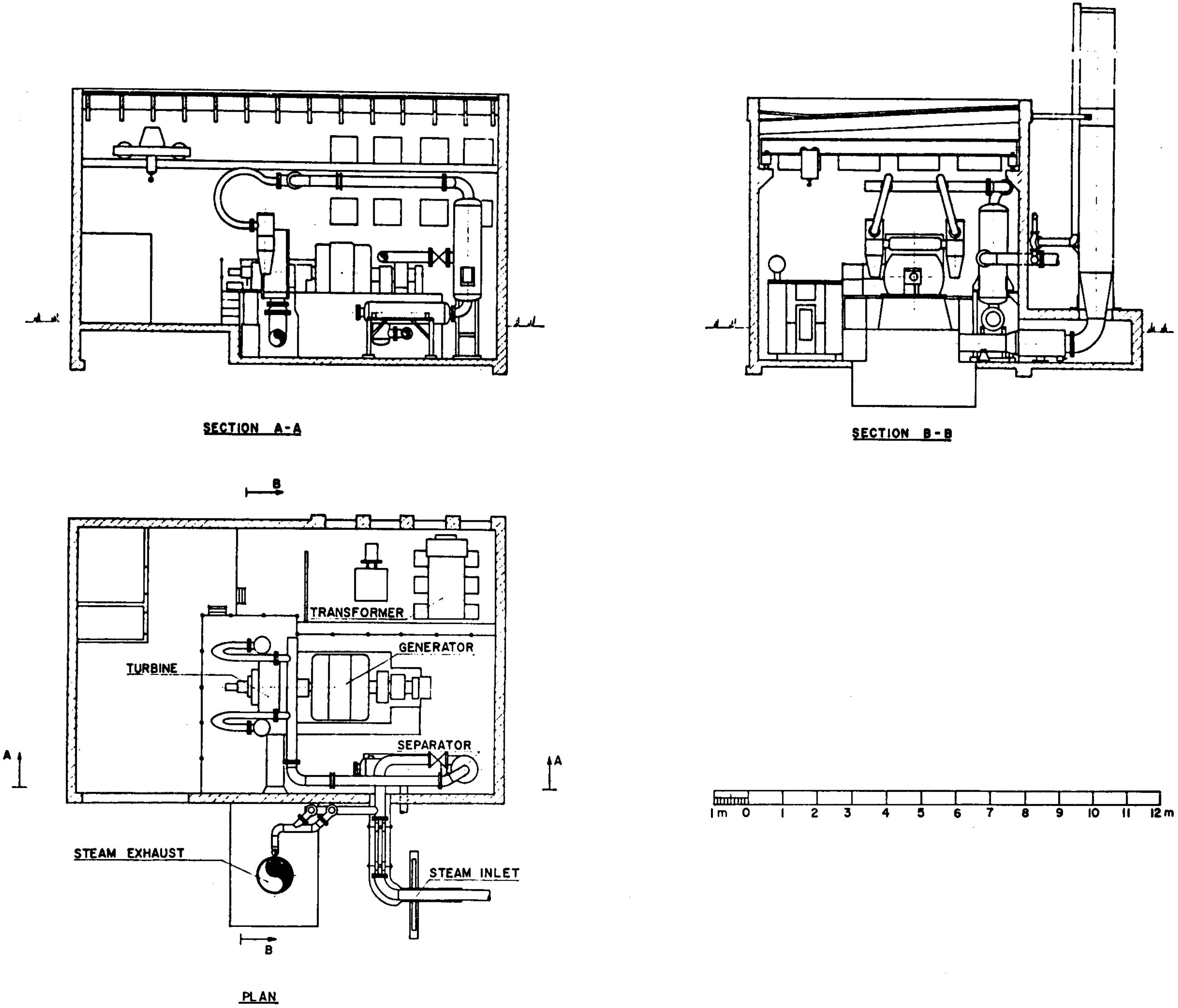
4
5m

Figure 3


SECTION A-A

SECTION B-B

PLAN

Figure 4

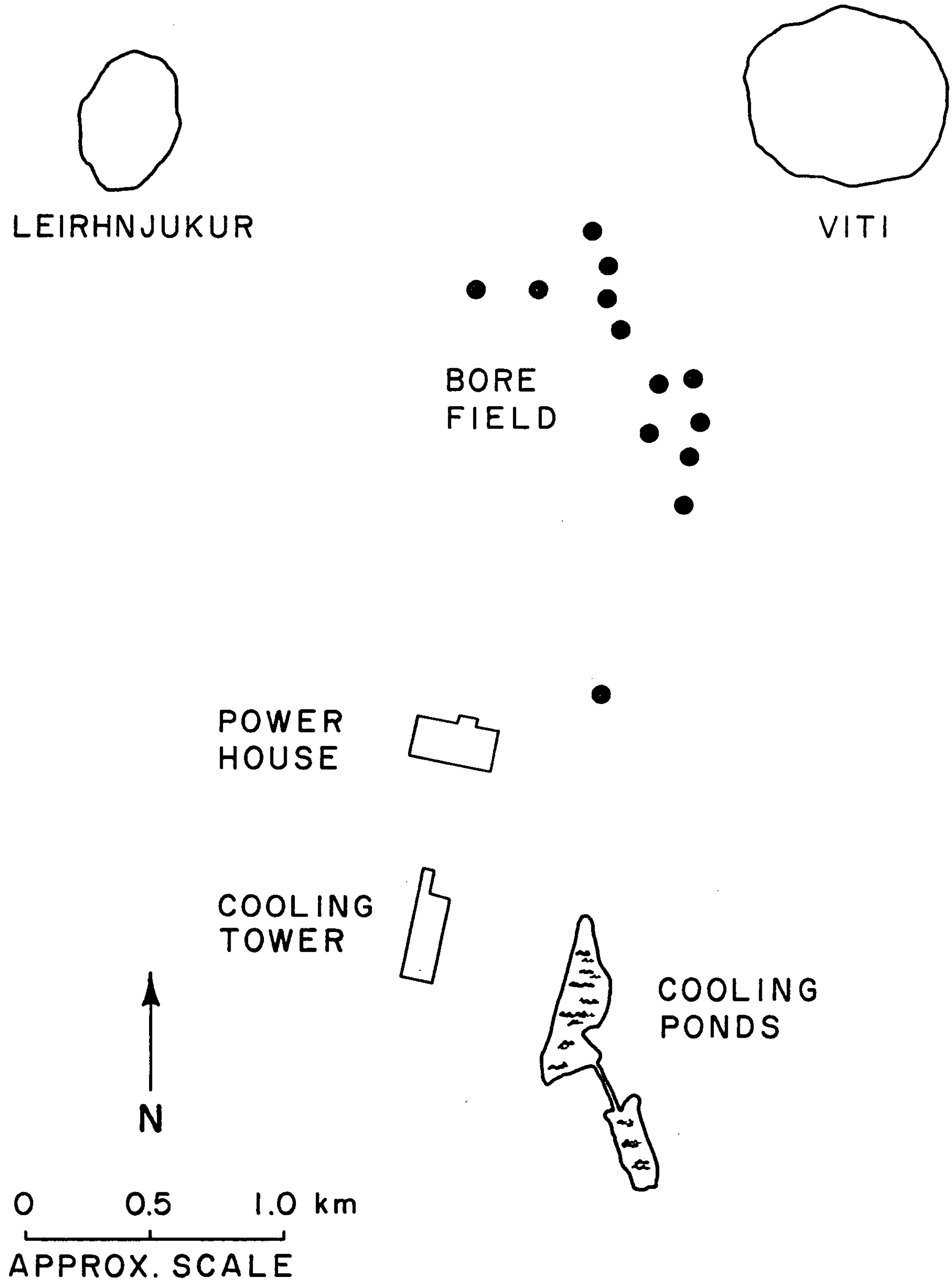

LEIRHNJUKUR
VITI
BORE FIELD
POWER HOUSE
COOLING TOWER
COOLING PONDS
N
0
0.5
1.0 km
APPROX. SCALE

Figure 5

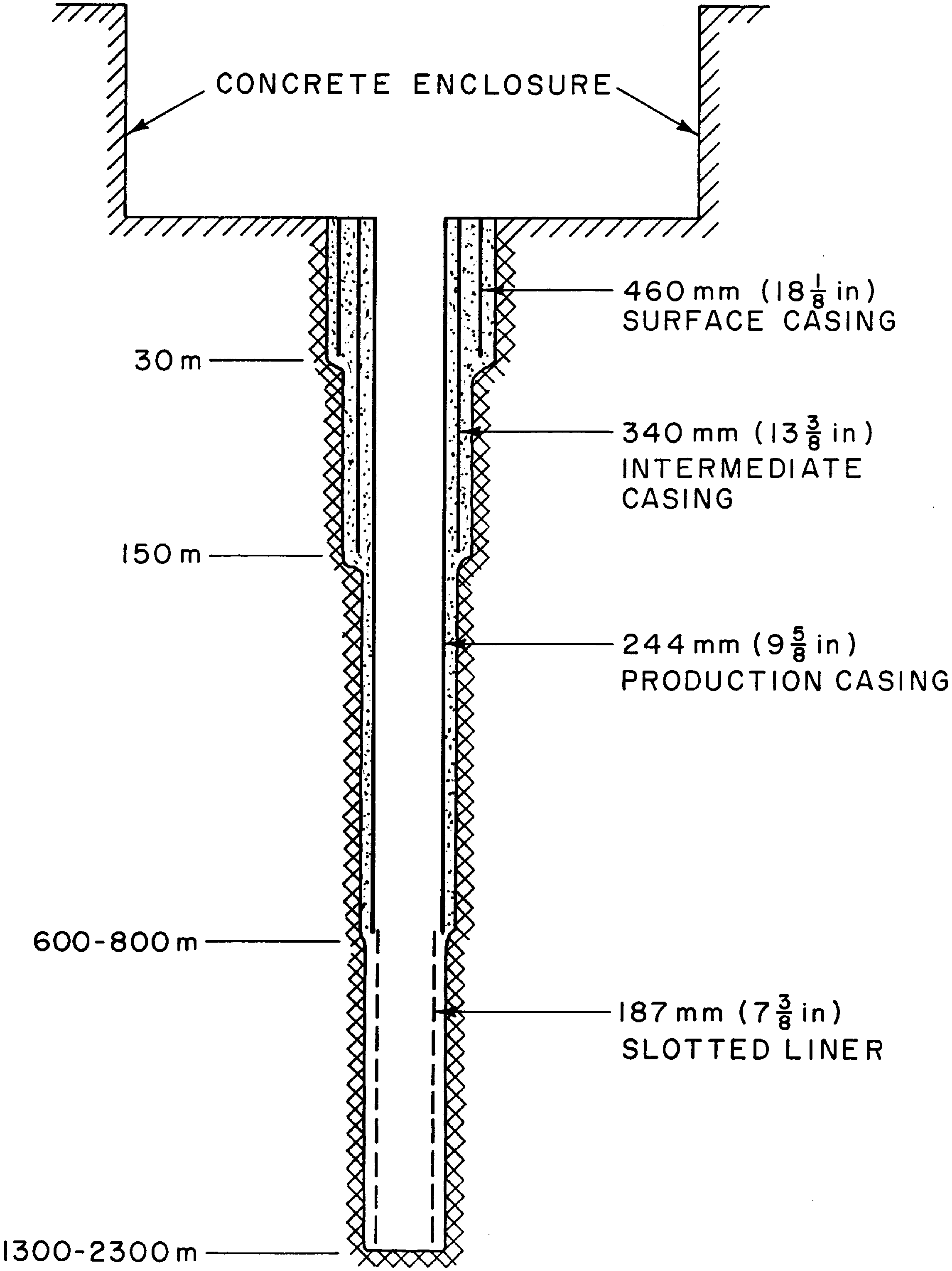

CONCRETE ENCLOSURE
460 mm (18 1/8 in) SURFACE CASING
30 m
340 mm (13 3/8 in) INTERMEDIATE CASING
150 m
244 mm (9 5/8 in) PRODUCTION CASING
600-800 m
187 mm (7 3/8 in) SLOTTED LINER
1300-2300 m

Figure 6

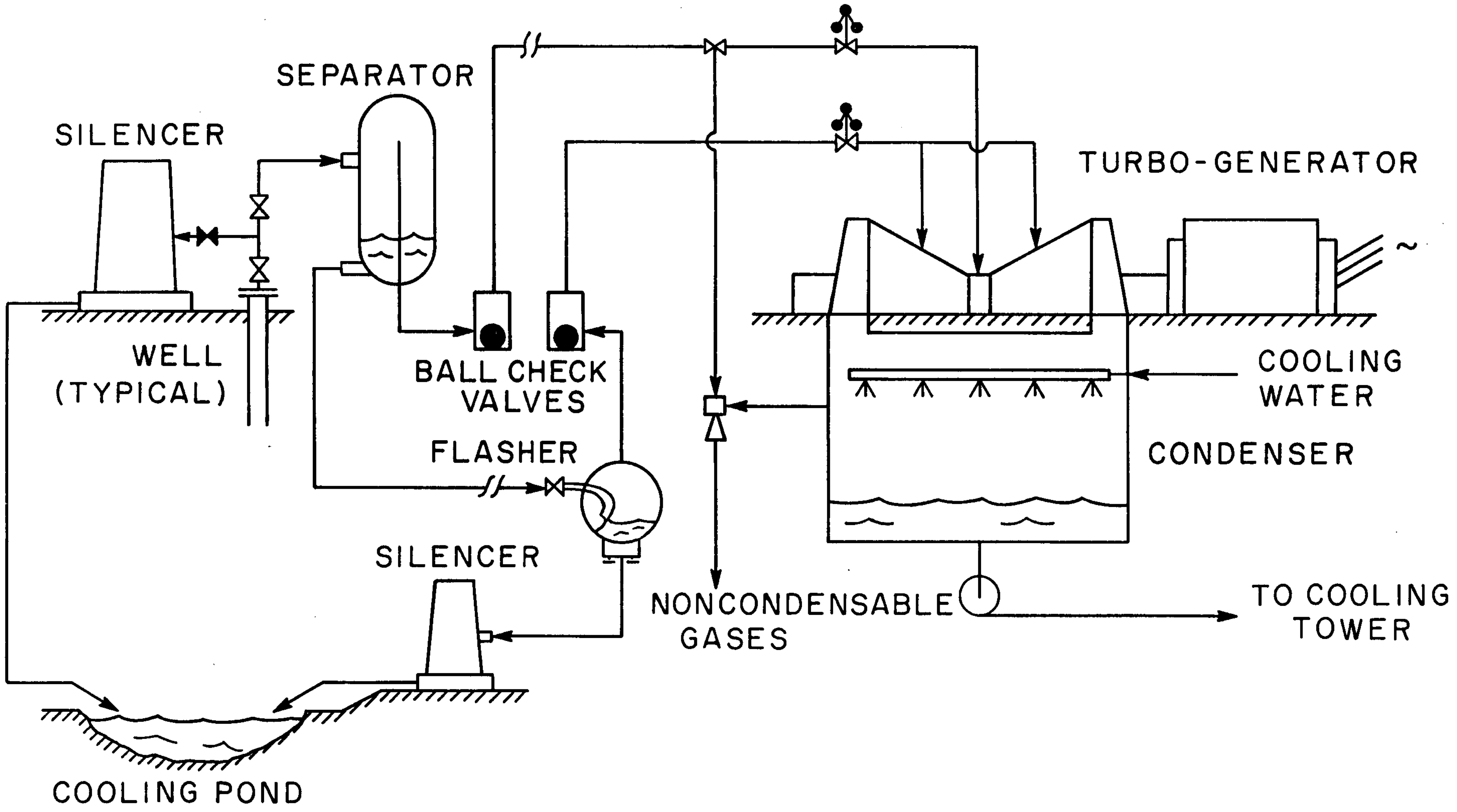

SEPARATOR
SILENCER
TURBO-GENERATOR
~
WELL
(TYPICAL)
BALL CHECK
VALVES
COOLING
WATER
CONDENSER
FLASHER
SILENCER
NONCONDENSABLE
GASES
TO COOLING
TOWER
COOLING POND

Figure 7