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Geothermal Power Plants of Italy:
A Technical Survey of Existing Installations

by

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Abstract

This report describes the dry-steam geothermal power plants in the Boraciferous (Larderello), Monte Amiatà, and Travale regions of Italy. The geology of these areas is described along with the nature of the geothermal steam. Details are given about the drilling techniques and the methods used to complete the wells. Noncondensing and condensing steam turbines are described in detail, including special features aimed at improving the flexibility of the machines to meet a variety of geofluid specifications while, at the same time, maintaining high performance. The report also covers the type of materials used to resist the corrosive and erosive nature of the geothermal fluid. Economic data and operating experience are presented.

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CONTENTS

1. Introduction

Documentation exists which shows that the natural steam fields in Tuscany were recognized as early as the 3rd century and that the commercial potential of these mineral-laden waters led to wars between the Tuscan republics during the Middle Ages [ENEL]. It was not until 1904, however, that the power of natural steam was first harnessed to produce electricity, the accomplishment of this feat being credited to Prince Piero Ginori Conti.

Conti's original system used a reciprocating engine which received steam separated from the geothermal fluid. The engine was of the noncondensing type, exhausted to the atmosphere, and generated about 15 kW of electric power. The output from the DC generator provided lighting for the boric acid factory at Larderello in the boraciferous region of Italy. This primitive engine was replaced by a turbo-alternator of 250 kW capacity in 1913, thus marking the beginning of the production of electricity from geothermal sources on a commercial scale [Conti, 1924].

Since that time endogenous fluid has been tapped at two other sites, Monte Amiata and Travale, and the total installed geothermal electric generating capacity in Italy has grown to 420,000 kW.

In the following sections we will describe some of the geological features of the two main geothermal regions currently under exploitation, Larderello and Monte Amiata, as well as the technical details related to the gathering and distribution of the geothermal fluid, the energy conversion systems and the associated auxiliaries, and the economic and operating experiences of the plants.

2. Boraciferous Region (Larderello)

2.1 Geology and exploration techniques

The Larderello region in general structural terms corresponds to a tectonic high located between the Era graben to the north and northwest and the positive feature of the crystalline basement which is evident in outcroppings to the south and southeast [ENEL].

The presence of a deep magmatic intrusion at about 6-8 km (4-5 mi) is inferred from the huge gravity deficit. The structural outline of the region is caused by the Apennine and plutonian tectonics in conjunction with the magmatic intrusion. The upheaval of Pliocenic coastal deposits to about 600 m (1970 ft) gives evidence of the plutonian tectonic.

The high heat flow in the region is generated by the gross interaction between the African and Eurasian tectonic plates and several smaller plates which are in contact in the area. The Larderello geothermal field is a part of an arc of high heat flow which extends along the west coast of the Italian peninsula from Tuscany to Sicily [Mongelli and Loddo, 1975].

Figure 1 shows a geological map of the Boraciferous Region in both plan and cross-sectional views [ENEL]. The major outcrops may be grouped into three main complexes: (1) The upper complex (denoted by regions "2" in the figures) which comprises shales, limestones, sandstones ("Argille scagliose") and constitutes, for the most part, the impermeable cap rock for the underlying reservoir; (2) The main permeable complex (denoted by "4") which forms the circulation region for the endogenous fluid and which comprises the very pervious Tuscan formations ranging from radiolarities to evaporites; and (3) The basement complex (denoted by "5") consisting of phyllitic-quartzitic formations which is highly impervious where phyllites predominate but which can be highly pervious where there are intercalations of quartzites or crystalline limestones [ENEL]. The outcroppings of the main permeable complex in the southern region contribute importantly to the recharge of the aquifer through the absorption of rainfall.

The methods employed during the exploration phase include geological, geochemical and geophysical methods. Geochemical techniques have proven highly effective. Normal analytical techniques have been used along with those applied to determine the isotopic relationships of certain elements in the geothermal fluid and the rocks including oxygen, hydrogen and carbon. Of the geophysical methods, the Schlumberger quadripole technique has been used extensively because of its relatively low cost and high efficiency. The application of this method is favored since the reservoir is usually located at depths less than 1000 m (3280 ft) and is characterized by a distinct resistivity high (>100 Ω·m) relative to the overlying cap rock (~2-40 Ω·m).

Heat flow, thermal gradients and thermal conductivity measurements have also been employed as prospecting tools. The area is characterized by exceptionally high thermal gradients, being of the order of 30°C/100 m (16°F/100 ft) and in some places, as high as 100°C/100 m (55°F/100 ft). These should be compared with the accepted normal gradient of about 3°C/100 m (1.6°F/100 ft). The geothermal field at Larderello is believed to cover about 25,000 ha (62,000 acres) [Koenig, 1973], although the drilled area extends over only about 18,500 ha (45,700 acres) [Ceron, et al., 1975; Ellis and Mahon, 1977].

2.2 Well programs and gathering system

There are roughly 190 producing wells in the Larderello region out of a total of 511 drilled [Overton and Hanold, 1977]. The average depth of all wells is 656 m (2152 ft); wells drilled since 1969 average 1129 m (3704 ft) in depth [Ceron, et al., 1975].

The techniques used in the drilling, casing and cementing of the wells in the Italian geothermal fields have been reported in detail elsewhere [Cigni, 1970; Cigni, et al., 1975]. Furthermore an extensive discussion dealing with the design and construction of geothermal steam pipelines has been published [Pollastri, 1970]. It is the intent here only to summarize the most important features of these operations as described by these authors.

2.2.1 Drilling

Geothermal drilling operations are in some ways similar to those in oil well drilling. The notable exceptions are that the geothermal wells tend to be larger in diameter, the formations are of higher temperature, and the flow velocities tend to be larger. These factors lead to the conclusions that drill rigs with larger capacities (for a given depth capability) are needed to support the heavier drilling strings, that special drilling muds are required to withstand the high temperatures, and materials are needed which are resistant to erosion.

Since the reservoir at Larderello is at about 1000 m (3280 ft) and taking into account margins of safety and the inherent differences between geothermal and oil well drilling, the appropriate sized rig will be one of 1600-1800 m (5250-5900 ft) capacity. Some of the rigs are capable of reaching 3000 m (9800 ft). The drilling string consists of 127 mm (5 in) and 168 mm (6 5/8 in) drill pipe with 203 mm (8 in) O.D. drill collars for drilling 406 mm (16 in) and 508 mm (20 in) holes, respectively [Cigni, 1970]. Large diameter collars are preferred because of added drill string stability and the improvement in maintaining vertical alignment of the hole.

The power required to conduct the drilling operations varies according to the particular phase involved. The figures below are estimates of the maximum power requirements under three sets of conditions for various machines and field services [Cigni, 1970]:

- Regular drilling (rotary machine and mud pump at full rate):

Rotary machine	75 kW (100 hp)
Mud pump	520 kW (700 hp)
Field services	35 kW (50 hp)
	630 kW (850 hp)

- Round trip for pipe extraction from maximum depth or casing operations:

Draw-works	330 kW (440 hp)
Field services	35 kW (50 hp)
	365 kW (490 hp)

- Emergency hoisting (during fishing operations):

Draw-works	300-330 kW (400-440 hp)
Mud pump (half load)	185-260 kW (250-350 hp)
Field services	35 kW (50 hp)
	520-625 kW (700-840 hp)

The accepted procedure for drilling wells in the geothermal fields of Italy is to use drilling muds while passing through the cap rock [Celati, et al., 1975]. The drilling mud must be carefully selected since the high temperatures encountered stimulate chemical reactions in the mud, altering the fluid viscosity, its free-water content and other properties [ENEL]. The presence of clays, anhydrites and gypsum lenses in the formation makes it difficult to maintain mud properties during drilling. Furthermore the permeable layers which are encountered lead to frequent loss of circulation. The muds which are used are dispersed ferro-chrome-lignosulonate-treated types. These exhibit good dispersion characteristics owing to their protective effect on clay particles. Furthermore, in high concentrations they inhibit exchange reactions [Cigni, et al., 1975]. Drilling operations in the permeable reservoir and in the basement rock are usually carried out with fresh, cold water without a return because of the high loss of circulation.

2.2.2 Casings and cementation

A pair of typical well profiles are shown in Fig. 2; a standard casing program is shown on the left and a casing program for an exploratory or a relatively deep well is shown on the right. The standard well produces natural steam through a 311 mm (12 1/4 in) open hole and a 400 mm (13 3/8 in) casing which is cemented within a 406 mm (16 in hole). The deeper well has a 216 mm (8 1/2 in) open hole throughout the permeable zone with a 244 mm (9 5/8 in) production casing. In this case the 400 mm (13 3/8 in) casing serves as an intermediate casing for safety purposes. The casings are J-55 API heavy wall pipe to withstand the corrosive nature of the geothermal fluid and the severe temperature cycling to which the wells may be subjected.

Cementation of the casings to the formation or to other casings is a critically important operation. A proper cementation job must result in complete and uniform filling of the well-casing annulus in order to withstand the various strains undergone by a casing, guarantee good bonds between the cement and the casing and between the cement and the formation to strengthen and protect the entire casing column, and finally allow for well checks during drilling so as to assure proper production during later stages. The art of casing and cementing geothermal wells requires attention to many factors such as the correct choice of cement and additions, exact centering and placement of the casing, and proper flushing of the annulus prior to cementation to avoid mud contamination [Cigni, et al., 1975].

The cement used for wells in the Boraciferous Region consists of a mixture of Portland 425 cement and a fine-grained silica flour, in 60-40 proportions. In laboratory tests under a pressure of 9.8 MPa (1420 lbf/in^2) and a temperature of 150°C (302°F) this cement showed a compressive strength of 34 MPa (4950 lbf/in^2) after a 28-day curing period [Cigni, et al., 1975].

2.2.3 Wellhead equipment

The design of wellhead equipment for geothermal applications differs considerably from that used in the case of oil wells. The most important unique characteristics of geothermal wells are [Cigni, 1970]:

- high fluid velocities,
- relatively low well closing and operating pressures,
- high mud and steam temperatures,
- strong corrosive nature of fluid, and
- connection to large diameter surface pipelines.

Four wellhead arrangements are shown in Fig. 3; each of these is used during various stages of the drilling operation as described below.

Arrangement I: Used during drilling through the caprock; wellhead mounted on the surface casing with a guiding bore of 311 mm (12 1/4 in). Side valves are 254 mm (10 in); mud filling is accomplished through a side connection.

Arrangement II: Used during widening of the hole in caprock from 311 mm (12 1/4 in) to 406 mm (16 in); wellhead mounted on surface casing; central valve eliminated since blowouts are not expected in this phase.

Arrangement III: Used during drilling in the production zone; wellhead mounted on production casing. Since flow of steam is expected in this phase, all equipment is in place to handle the situation, starting with the 356 mm (14 in) central valve.

Arrangement IV: Used when production casing is in place but only partially cemented; wellhead mounted on surface casing. A device which supports and allows for centering the production casing is provided. Equipment is installed to handle the expected steam flow in case of a blowout.

In all cases a blowout preventer is installed on the wellhead. It is designed to close off the central bore in case of emergencies, even when the drilling string or other pieces of equipment happen to be in the well. This is accomplished by means of a mechanically or hydraulically actuated valve fitted with appropriate jaws to clamp around anything that may be in the well. High-temperature gaskets are required for steam-well drilling [Cigni, 1970].

2.2.4 Steam pipelines

Steam is conveyed from the individual wellheads to the power stations by means of an interconnected network of pipes. The photograph in Fig. 4 shows a typical wellhead connection; it is characterized by the sweep of a large-radius expansion bend from the wellhead to an anchor. The types of supports used include fixed moorings (anchors), sliding supports, turning type, and supporting trestles of the fixed and fixed slotted type [Pollastri, 1970]. A zig-zag layout of the network is designed to accommodate the thermal expansion associated with the operation of the plants. Expansion caused by temperature fluctuations from ambient values to 260°C (500°F) can be absorbed.

The network consists of over 118 km (73 mi) of steam pipes [Ceron, et al, 1975]. The pipes are fabricated from weldable steel and have a wall thickness of 6 - 8 mm (0.24 - 0.31 in) and diameters of 250, 350, 450, 650 and 810 mm (10, 14, 18, 26 and 32 in). Asbestos fiber is used for insulation, in thicknesses of 30, 60, 90 and 120 mm (1.2, 2.4, 3.5 and 4.7 in) [DiMario, 1961]. The pipe and insulation are protected within an aluminum-plate jacket or painted with coating of bituminous material [ENEL].

2.3 Geofluid characteristics

The geothermal fluid produced at the wells in Larderello consists of steam (dry, saturated or slightly superheated) and a mixture of noncondensable gases. The amount of noncondensables is relatively high, ranging from 1 to 20% by weight of the total fluid flow, on average, with some new wells showing even higher percentages. As a rule, the gas content of the steam at Larderello has remained roughly constant during the period of exploitation. This is attributed to the fact that the natural surface thermal manifestations which have existed for centuries have prevented a build-up of large amounts of gas. The reservoir is thus viewed as being in a steady-state as regards the evolution of noncondensable gases. One well, drilled a few kilometers east of Larderello and believed isolated from the main thermal area and thus not having the benefit of the purging action in the main field, produced geofluid that contained 98% gas and only 2% steam. The composition of the gas was essentially identical to that found in the fluid from the wells of the main field [ENEL].

The noncondensable gas consists of carbon dioxide, for the most part, with small amounts of hydrogen sulfide, hydrogen, methane and nitrogen. Recent reports [ENEL] put the CO_2 percentage at about 4.8% (by weight of geofluid), H_2S at 0.5%, and all others at less than 1%. Table 1 lists the composition of the noncondensables, for specific areas within the Boraciferous Region.

The highest reservoir temperature encountered so far has been 300°C (570°F) [Overton and Hanold, 1977]; the maximum pressure is 3.1 MPa (450 lbf/in^2).

Steam is produced at temperatures ranging from 140 - 220°C (285 - 430°F) and at pressures from 200 - 700 kPa (29 - 102 $\mathrm{lbf/in^2}$) [Ellis and Mahon, 1977].

The average fluid flow rate per producing well is about 17 Mg/h (37,500 lbm/h) [Ceron, et al, 1975], although maximum flow rates may range from 50 - 100 Mg/h (110,000 - 220,000 lbm/h) and in some cases may even exceed 300 Mg/h (660,000 lbm/h) [ENEL]. The flow rate varies considerably from well to well and depends strongly on the age of the well, particularly in the early stages of production. Figure 5 shows the production history of two wells in the Larderello field. Each one exhibits an approach to a steady-state flow rate after an initial transient period during which the flow rate decreases by a significant amount. Figure 6 gives well productivity curves as a function of wellhead pressure for three wells, one each from Sasso Pisano, Lagoni Rossi and Gabbro. All three curves exhibit the expected behavior for gas flow and may be represented analytically by an equation of the form:

$$(P/P_o)^n + (\dot{m}/\dot{m}_o)^n = 1 ,$$

where the exponent n lies in the range, $1.5 \leq n \leq 1.85$. The subscript o denotes the maximum value of either the pressure or the flow rate.

2.4 Energy conversion systems

Power is produced at the present time in Larderello by means of two types of energy conversion systems: direct-intake, noncondensing, impulse or impulse-reaction turbines ("Cycle 1"), or direct-intake, condensing, impulse-reaction turbines ("Cycle 3"). Prior to 1968, another type was in operation, namely one which used pure steam generated from geothermal steam in heat exchangers and expanded in impulse or impulse-reaction, condensing turbines ("Cycle 2"). These three schemes are shown schematically in Figs. 7a, 7b, and 7c.

Cycle 1 plants are installed at locations which either have high noncondensable gas content in the geothermal steam or are not sufficiently developed to justify the construction of steam lines to join the field to the main network. Such plants are extremely simple, highly reliable, easily assembled or disassembled, and offer low costs because they may be remote controlled from a nearby power station.

Cycle 2 plants were used when it was desirable and economic to extract chemicals, such as boric acid and ammonia, from the geothermal fluid, while at the same time avoiding materials corrosion problems in the turbine and taking advantage of the improved power output associated with condensing operation. However, considerable difficulty was encountered in the operation of the heat exchanger because the water tubes which formed the boiler section were subject to deposits of iron sulfide or breakage depending on whether iron or aluminum were used for the tube material [Hahn, 1923]. Since chemicals are no longer extracted from the fluids and the problems of corrosion of turbine blades can be avoided, this energy conversion scheme has been eliminated.

Cycle 3 plants form the mainstay of the Italian geothermal plants. The effects of impurities or corrosive substances in the steam can be reduced by scrubbers located upstream of the turbine inlet. Pure water or alkaline solutions may be injected to wash the steam; axial separators then remove the injected liquid prior to admission into the turbine. The large amount of noncondensable gases in the steam requires the use of high-capacity turbocompressors to remove the gases from the condensers. The schematic layout diagram of Fig. 8 shows a typical arrangement for a Cycle 3 power unit. Of particular interest are the three stages of intercooling used with the gas compressor, the first stage of which is integral with the condenser.

A typical flow diagram for a 14.8 MW (gross), 13.4 MW (net) power unit is given in Fig. 9. The inlet steam is at 185°C (365°F) and 443 kPa (64.3 lbf/in^2)

with about 4% (by weight) of noncondensable gases. The geothermal resource utilization efficiency, based on the available work of the geofluid relative to the design wet-bulb temperature of 19.4°C (67°F), is about 52%. However, none of the actual units analyzed and described below had efficiencies as high as this; the highest actual efficiency was 47.4% for the two units located at the Sasso 2 geothermal field.

2.4.1 Condensing units

Condensing units in the Boraciferous Region are in operation at the following sites: Larderello, Gabbro, Castelnuovo, Serrazzano, Lago, Sasso Pisano and Monterotondo. There are 27 such units installed with a combined capacity of 362.7 MW. These range in size from a 2 MW unit at Castelnuovo to 26 MW units, three of which are located at Larderello 3 and one at Castelnuovo.

All plants use natural draft cooling towers which are designed to handle water flow rates of 9, 12, 15 and 18 x 10^3 m^3/h (20, 26, 33 and 40 x 10^6 lbm/h) of water depending on the unit rating. The water is cooled through a range of 41 - 31°C (105.8 - 87.8°F), typically, in an environment at 25°C (77°F) and a relative humidity of 60%, i.e., at a wet-bulb temperature of 19.4°C (67°F). The choice of natural draft towers over forced draft ones was dictated by lower operating costs and the need for reliable, continuous operation. The cooling water is circulated by means of a 2-speed, helico-centrifugal pumps with vertical axes and adjustable blades, and with a maximum flow capacity of 9000 m^3/h (20,000 lbm/h) [DiMario, 1961].

The following sections offer more details on the condensing power units in the Boraciferous Region. A listing of technical particulars may be found in Table 2.

<u>Larderello 2</u> The indirect-steam systems (Cycle 2) which generated clean steam by means of heat exchangers have been abandoned in favor of direct-intake,

condensing plants. Cycle 2 plants had allowed for the recovery of various chemicals from the geothermal fluid (boric acid, ammonia, carbon dioxide, hydrogen sulfide), but were costly both in capital and operating expenses. Furthermore, they required about 14.5 - 16.0 kg of steam per kW·h of electricity produced at the busbar. With the advent of turbine materials that effectively resist corrosion by the geofluid and the decreasing interest in chemical recovery, the simpler and more efficient direct scheme, Cycle 3, has been fully adopted [Cataldi, et al, 1970].

There are five units installed at Larderello 2: four 14.5 MW units and one 11 MW unit. Whereas the total installed capacity is 69 MW, the actual rating is only 37.3 MW owing to insufficient steam supply [Ceron, et al, 1975]. The overall geothermal resource utilization efficiency, based on the actual power output and the available work of the geothermal steam at the plant relative to the design wet-bulb temperature of 19.4°C (67°F), is 43%.

Larderello 3 This complex, the largest of the geothermal units in Italy, is located adjacent to Larderello 2. The power house contains six individual units: three 26 MW units, one 24 MW unit, and two 9 MW units. A view of the turbine hall is shown in Fig. 10. The net capacity of the Larderello 3 plant is only 65.4 MW as compared with the installed capacity of 120 MW. The net geothermal utilization efficiency is 44.3%.

Gabbro The Gabbro plant consists of a single 15 MW (gross), 11.8 MW (net) unit. The turbine is of the tandem-compound design with a single-flow, high-pressure cylinder followed by a separate, double-flow, low-pressure section. The HP-cylinder exhausts at essentially atmospheric pressure and may be uncoupled from the sub-atmospheric section for noncondensing operation during periods of shut-down of the LP-section. Although the unit has been designed to accommodate gas content as high as 8% (by weight) of steam [Corti, et al, 1970], most recent reports show only 6.7% gas concentration [Ceron, et al, 1975]. The unit has a 46% geothermal utilization efficiency. The plant is equipped with a remote and closed-circuit television system for remote-controlled operation from the Larderello 2 power station which is located about 5 km (3 mi) away [ENEL].

Castelnuovo-Val Cecina Originally Castelnuovo V.C. employed three 11 MW, Cycle 2 units and one 2 MW unit for auxiliary services. The geothermal fluid temperature was about 195°C (383°F) and the gas content was 10% by weight. The specific steam consumption was relatively high, 17 kg/kW·h (37.5 lbm/kW·h) [Corti, et al, 1970].

A conversion was carried out which resulted in the installation of four units in 1967 with a total installed capacity of 50 MW; one 26 MW unit, two 11 MW units and one 2 MW unit. All are condensing units of the Cycle 3 mode. The largest unit is supplied with the highest pressure steam available from the field, about 420 kPa (61.1 lbf/in^2); the mid-sized units receive steam at about 186 kPa (27 lbf/in^2); the smallest unit is fed by very low-pressure jets at about 108 kPa (15.6 lbf/in^2). The four units have a combined geothermal utilization efficiency of 36%, and consume, on the average, 14 kg (30.9 lbm) per net kW·h of electricity. The main unit has been designed to handle up to 12% (by weight) of noncondensable gases and to have a specific fluid consumption of less than 10 kg/kW·h (22 lbm/kW·h). Figure 11 shows a photograph of the turbine, generator, and gas compressor arrangement for the 26 MW unit.

Serrazzano There are five condensing units all of the Cycle 3 variety in operation at Serrazzano: one 15 MW unit, and two units each of 12.5 MW and 3.5 MW. The turbocompressors for the two 12.5 MW units are shown in Fig. 12.

Lago 2 The total installed capacity at Lago 2 is 33.5 MW, comprising units of 14.5, 12.5 and 6.5 MW. The three units have a combined geothermal utilization efficiency of 46%, and a specific steam consumption of 10.1 kg/kW·h (22.3 lbm/kW·h). The arrangement of the turbogenerator and gas compressors for the larger units at Lago 2 is shown in the photograph of Fig. 13.

Sasso Pisano (Sasso 2) Although the total installed capacity at Sasso Pisano is 15.7 MW, it was operated at 17.3 MW in 1974 [Ceron, et al, 1975]. There are two units in operation, one of 12.5 MW and one of 3.2 MW. The combined specific steam consumption is one of the best for the Italian geothermal plants: 9.4 kg/kW·h (20.7 lbm/kW·h); the utilization efficiency is 47.4%. The plant is shown in Fig. 14.

Monterotondo One 12.5 MW unit is in operation at Monterotondo. The percentage of noncondensable gases in the steam has fallen steadily from a value of 2.5% (by weight) in 1960 [Cataldi, et al, 1970], to 2.2% in 1969, and to 1.7% in 1974 [Ceron, et al, 1975]. This is the lowest gas content reported for any geothermal plant in Italy. The specific steam consumption is 10 kg/kW·h (22 lbm/kW·h) and the geothermal utilization efficiency is 45%. Figure 15 shows the turbine hall at Monterotondo with the 12.5 MW unit in the right background.

2.4.2 Noncondensing units

Noncondensing units are installed at six sites in the Boraciferous Region: Sant'Ippolito-Vallonsordo, Lagoni Rossi 1 and 2, Sasso 1, Capriola and Molinetto. All operate on Cycle 1 and exhaust to the atmosphere at a pressure of 102.9 kPa (30.4 in Hg), slightly above atmospheric pressure. The noncondensable gas content ranges from 2.7% (by weight) at Sasso 1 to 4.0% at Capriola. The units are relatively small in capacity, with the 900 kW unit at Sant'Ippolito-Vallonsordo being the smallest geothermal unit installed in Italy. The largest unit of this group is at Sasso 1 and has a rated capacity of 7 MW.

All of these small plants are remote-controlled from a larger plant. The control equipment used has been standardized and includes the following capabilities [Corti, et al, 1970]:

From pilot to satellite plant:

- Six controls: opening and closing of generator breaker, increase and decrease of governor setting, excitation increase and reduction;
- One control for emergency plant shut-down.

From satellite to pilot plant:

- Five signals: unit shut-down, unit in operation, switch opened, switch closed, alarm;
- Eight measurements, six of which are contemporary, including: (with breaker open) generator voltage, generator frequency, excitation current, synchronism, line voltage, and line frequency; (with breaker closed) generator voltage, generator frequency, excitation current, generator current, output power, and line voltage.

The remote-control operation of these plants is characterized by extreme simplicity and high reliability.

The following sections describe each of these units in more detail.

Sant'Ippolito-Vallonsordo This unit is designed for continuous operation under a wide range of inlet steam conditions: temperatures from 185 - 250°C (365 - 482°F), pressures from 441 - 686 kPa (64 - 99.5 lbf/in^2), and gas content from 4 - 7% (by weight). The original steam flow contained about 20% noncondensables [Cataldi, et al, 1970], but the most recent reports indicate gas content of only 3.3% [Ceron, et al, 1975]. The unit consumes 26.7 kg of steam per net kW·h (58.9 lbm/kW·h) and has a geothermal resource utilization efficiency of only 15.3%, because a significant fraction of the available work is lost when the steam is exhausted at atmospheric pressure. A photograph of the turbine-generator assembly is shown in Fig. 16, in which the compactness and simplicity of the unit are evident.

Lagoni Rossi 1 and 2 These two units of 3.5 and 3.0 MW, respectively, are characterized by a high degree of flexibility in meeting variable steam conditions. The turbines are capable of performing in an efficient manner with steam conditions ranging in temperature from 230 - 235°C (446 - 455°F), in pressure from 686 - 1079 kPa (99.5 - 156 $\mathrm{lbf/in^2}$), and in gas content from 4 - 20% (by weight). The flexibility in performance is due to three factors: (1) A wide degree of control is available in the first, impulse stage; (2) A significant part of the reaction blading is mounted on removable inner shells; (3) The control valve is equipped with interchangeable internal elements [Saporiti, 1961 (b)]. In this way extreme conditions, say, low pressures and temperatures (and corresponding high steam flow rates) can be accommodated by increasing the effective active nozzles in the impulse stage while reducing the reaction blading and increasing the internal steam passages in the control valve. The other extreme can be handled by reversing the effects. Such design flexibility allows good energy conversion efficiency to be maintained over wide variations in steam conditions with only relatively simple modifications to the apparatus. For example, Lagoni Rossi 1 has a specific steam consumption of 18.2 kg/kW·h (40.1 lbm/kW·h) and a utilization efficiency of 25.2%, which is quite good for a noncondensing unit.

Sasso 1, Capriola and Molinetto These three units have a combined installed capacity of 13.5 MW although the net capacity is only 4.8 MW. The gas content averages 3.3% (by weight); the steam inlet temperature averages 189 ± 3°C (372 ± 5°F). The geothermal utilization efficiency for the three units taken together is 17.7% and the combined specific steam consumption is 25 kg/kW·h (55 lbm/kW·h).

2.5 Materials of construction

Materials used in the fabrication of the steam wells and the transmission pipelines have been described earlier in sections 2.2.2 and 2.2.4, respectively. This section will focus on the materials used for the energy conversion equipment.

In order to reduce corrosion by the geothermal fluid, sodium carbonate is added to the water used for scrubbing the steam and to the condensate. This neutralizes the pH and minimizes corrosion of iron and steel parts [DiMario, 1967].

Erosion of turbine blades can be reduced and their life extended by the use of 13% chrome - 0.1% carbon alloy steel. The jet condenser is made of cast iron covered on the inside by lead-plated sheet. Since direct jet impingement can cause a wearing away of the lead plating, areas subjected to jets are further protected with sheets of AISI 316 stainless steel (0.1% C, 16 - 18% Cr, 10 - 14% Ni, 2 - 3% Mo, 2% Mn) [Ciapica, 1970; Ricci and Viviani, 1970].

The multi-stage, centrifugal compressors together with the associated intercoolers are key elements in the Italian geothermal plants because of the high concentration of noncondensable gases in the neutral steam. In general, austenitic and ferritic stainless steels and lead-clad carbon steel are used for these systems. The body casings for both the high- and low-pressure casings are of meehanite cast iron. The LP-body rotor is of AISI 431 alloy steel (0.2% C, 15 - 17% Cr, 1.25 - 2.50% Ni); there are six impellers of the same material. The HP-unit has a shaft of carbon steel with AISI 431 sleeves and seven impellers in two stages. The journal and thrust bearings are of carbon steel with linings of white metal [Dal Secco, 1970].

The gas coolers are fabricated from carbon steel welded plates and are lined with lead, ebonite or AISI 316 stainless steel on the inside. The dimensions of the coolers are large to keep the fluid velocities as low as possible in order to minimize erosion. The pipes which convey the hot, compressed gases to the coolers are made of AISI 403 alloy steel (0.15% C, 11.5 - 13% Cr); the pipes carrying cool gases are of carbon steel with lead lining [Dal Secco, 1970]. Layers of sandstone rings are suspended in AISI 316 wire hampers downstream of the gas coolers in order to control the humidity to reduce deposits of solid particles, the deposition of which is enhanced by the presence of liquid droplets [Ricci and Viviani, 1970].

Pumps for circulating water are equipped with impellers of 13% chrome - 0.1% carbon alloy steel. Pipes which carry water and are exposed to the air are made of either stainless steel or iron with stainless steel liners. The hyperbolic-shaped, natural draft cooling towers are of reinforced concrete.

2.6 Effluent and emissions handling systems

There are no controls or abatement systems used for the liquid and gaseous effluents from the plants.

In the case of the gaseous emissions, hydrogen sulfide (H_2S) is potentially the most serious because of its corrosive effects and its toxicity. The data in Tables 1-3 may be used to estimate the total H_2S emissions in the Boraciferous Region caused by geothermal power production. The condensing units produce about 3100 kg/h (6800 lbm/h) or roughly 14,000 g/MW·h (31 lbm/MW·h); the noncondensing units emit nearly 190 kg/h (419 lbm/h) or 19,000 g/MW·h. The weighted average for both types of plant in the region is 14,300 g/MW·h (32 lbm/MW·h). This may be compared with the maximum of 200 g/MW·h (0.44 lbm/MW·h) suggested by the Environmental Protection Agency for geothermal plants in the United States.

Liquid discharge from the power stations equipped with condensing units may be estimated using the flow diagram shown in Fig. 9. About 15% of the entering steam flow (by weight) is produced as excess liquid at the cold well of the cooling tower. Assuming that this percentage holds on the average for all plants, the total liquid effluent from the condensing units would amount to about 360,000 kg/h (794,000 lbm/h or 95,000 gal/min). The noncondensing or exhausting-to-atmosphere units discharge all of the steam flow directly to the surroundings; the total amounts to 241,000 kg/h (530,000 lbm/h), as can be seen from the data in Table 3.

2.7 Economic factors

The most recent cost figures for Italian geothermal power plants were reported in 1974 [Leardini]. At that time the actual capital costs to construct a plant consisting of two 26 MW condensing steam turbine units in the Larderello region were 170 U.S. $/kW. The costs for one 15 MW condensing unit in the same area were 226 U.S. $/kW. For noncondensing units, a 15 MW unit cost 95 U.S. $/kW and a 4 MW unit cost 105 U.S. $/kW. The figures for the condensing units are roughly comparable to the costs for fossil power plants at that time. The Italian geothermal plants incurred higher capital costs than dry steam geothermal plants in other countries because of the large gas compressors required to expel the great amount of noncondensable gases. About 20% of the capital cost goes for the gas compressors.

Leardini [1974] also quoted typical operating costs for several types of plant. The largest condensing units (26 MW) had operating costs of 2 U.S. mill/kW·h of net electricity generated. Noncondensing units are simpler to operate and maintain, their operating costs being 1½ U.S. mill/kW·h. Remote-controlled stations are even less expensive to run; condensing units had operating costs of 0.8 mill/kW·h and noncondensing units were reported at 0.6 mill/kW·h.

2.8 Operating experience

In general the operation of the Italian geothermal power plants has been highly successful. One measure of this is the plant availability factor which is consistently above 90% and often exceeds 95% [Cataldi, et al, 1970; Ricci and Viviani, 1970].

Most of the problems which occur are related to the corrosive effects of the natural steam. In plants of the Cycle 1 types (exhausting-to-atmosphere), scale forms on turbine blades leading to clogging of the passageways. The presence of chlorine ions causes the damage, particularly at those locations where the superheated steam becomes saturated or wet steam. Cycle 2 (indirect, pure steam) plants were relatively free of problems except for clogging of boiler tubes. Although plants of this type are now obsolete in Italy, when they were in operation, turbine blades could be counted on lasting 100,000 hours or more. Plants of the Cycle 3 (condensing) variety experienced attacks by corrosion and clogging in all elements of the plant including the turbine, condenser, water circulating pumps, gas compressors and interstage gas coolers. These effects can be mitigated to some extent by the proper choice of materials and through anticipatory design features (see section 2.5). As an example, it has been found that when the turbine blading is treated with a bath of an oil mixture during overhaul, scale build-up is reduced and removal of scale is facilitated. The results shown in Fig. 17 reveal that the oil treatment can reduce the power loss by about 40% after a period of about 2 years of operation [Ricci and Viviani, 1970].

A program of preventive maintenance is employed. A number of key indicators are monitored to detect signs of deterioration or malfunction. These include:

1. Pressure drop across the steam filter.
2. Steam pressure at turbine inlet.
3. Vacuum pressure in the condenser.
4. Temperature of cooling water into the condenser.
5. Suction pressure at gas extraction point.
6. Temperature of cold water into gas coolers.
7. Temperature of hot water out of gas coolers.
8. Temperature of noncondensable gases at exhaust.
9. Temperature of drain water.
10. Temperature of lubricating oil.
11. Pressure of lubricating oil.
12. Composition of lubricating oil.
13. Temperature of bearings.
14. Vibration.

In order to continue operation as smoothly as possible, a large store of spare parts is maintained at each plant. In particular, one spare, bladed rotor shaft is kept on hand for each two units at a given plant. Some sacrifice in machine efficiency is made when a spare rotor is installed because the clearances are generally larger than for a custom-matched rotor. However, repairs on the original shaft are made as soon as possible so as to permit its reinstallation and restoration of the design performance [Ricci and Viviani, 1970].

The maintenance procedures described above apply to all geothermal power stations in Italy, those in the Monte Amiata and Travale regions as well as in the Larderello or Boraciferous region.

3. Monte Amiata Region

3.1 Geology

A schematic geological map of the Monte Amiata region is shown in Fig. 18 [ENEL]. The area is located about 70 km (44 mi) southeast of Larderello. Although the geology of the site is similar to that of Larderello, there are some noteworthy differences. The outcroppings consist of essentially three major complexes: (1) The volcanic complex (denoted by regions "2" in the figure) which includes the volcanites of Radioofani and Monte Amiata and constitutes a fairly pervious layer; (2) The upper complex (denoted by "4" and "5") consisting of shales, marls, limestones, calcarenites, sandstones, etc.; and (3) The main pervious complex (denoted by "6") of Tuscan formations from maiolica to evaporites and which constitutes the main geothermal reservoir [ENEL].

As can be seen from Fig. 18, the area is marked by magmatic extrusions, a feature absent at Larderello. The products of this volcanic activity are acid in nature and cover about 10,000 ha (24,700 acres) in the vicinity of M. Amiata. Unlike the case at Larderello, there are relatively few outcroppings of the main aquifer complex. The main source of recharge fluid for the reservoir is the pervious volcanic formation which is linked to the aquifer by fractures, extrusion chimneys, and volcano-tectonic faults.

The two areas of the field at which power plants are located, Bagnore and Piancastagnaio, are characterized by extremely high thermal gradients of about 50°C/100 m (27°F/100 ft), nearly seventeen times the normal gradient. The gradient exceeds 10°C/100 m (5.5°F/100 ft) over a wide area of 40,000 ha (100,000 acres) [ENEL].

3.2 Geofluid characteristics

The wells in this region produce dry, slightly superheated steam as at Larderello, but at generally lower temperatures. The steam temperature in the Bagnore area averages about 138°C (280°F) whereas the temperature at Piancastagnaio is 183°C (361°F). There has been a considerable decline in the shut-in pressure of the wells since the field was first exploited nearly 20 years ago. At that time the closed-in wells showed pressures of 2157 kPa (313 lbf/in^2) and 4118 kPa (597 lbf/in^2) at Bagnore and Piancastagnaio, respectively. Presently these values have fallen to 588 kPa (85 lbf/in^2) and 1961 kPa (284 lbf/in^2), respectively. Wellhead operating pressures at the two sites are about 309 kPa (45 lbf/in^2) and 804 kPa (117 lbf/in^2).

The amount of noncondensable gas in the geothermal steam is significantly more than for the case of the Boraciferous Region. At the time the field was being developed, gas content exceeded 90% (by weight) of the natural vapors. The earliest power plants encountered "steam" that contained between 30 - 80% (by weight) of noncondensables. This percentage has declined during exploitation and now ranges from 7 - 20%. On average, the noncondensable gas contains (by volume) 95% carbon dioxide, 0.4% hydrogen sulfide, 0.4% hydrogen, 3.5% methane, and 0.7% nitrogen [ENEL].

3.3 Energy conversion systems

The only geothermal power stations in the Monta Amiata region are of the noncondensing type or Cycle 1 plants. In the late 1960's there were four units in operation, two at Bagnore and one each at Piancastagnaio and Senna. The last of these was a 3.5 MW unit, very similar to the 3.5 MW unit installed at Lagoni Rossi 1 (see section 2.4.2). It was remote controlled from Piancastagnaio but has since been shut down. The technical particulars for the remaining three units are listed in Table 4.

Bagnore 1 and 2 During the 15-year lifetime of the plants at Bagnore there has been a 40% decline in the operating pressure which has resulted in a significant loss of net electrical capacity, as may be seen from the values shown in Table 5. The thermodynamic performance of these units is rather poor: 31.3 kg of geothermal fluid are required to generate each kW·h of electricity (69 lbm/kW·h). The geothermal utilization efficiency for the two units combined is only 16%.

Piancastagnaio The 15 MW unit at Piancastagnaio began operations in 1969 and is one of the two largest plants of the noncondensing type in existence. It receives steam from a single well, P.C./8, which produced 300 Mg/h (660,000 lbm/h) at a wellhead pressure of 980 kPa (142 $\mathrm{lbf/in^2}$) in 1965. Since that time, the output has fallen by 29%; in 1974 the well produced 219 Mg/h (483,000 lbm/h) at 804 kPa (117 $\mathrm{lbf/in^2}$) [Corti, et al, 1970; Ceron, et al, 1975].

The power house is shown in Fig. 19. The structure is designed to allow for easy disassembly in the event that the steam flow becomes too low to justify the existence of the plant. In such a case the entire plant may be readily relocated at another site.

Figure 20 shows the turbogenerator unit. The turbine is encased in a single cylinder, employs combined impulse-reaction blading, and has an adjustable intake to allow efficient operation over a wide range of steam pressure from 490 - 1079 kPa (71 - 156 $\mathrm{lbf/in^2}$). The turbine is, in fact, identical to the high-pressure turbine installed in the condensing plant at Gabbro which was described earlier in section 2.4.1. A sub-atmospheric turbine may be attached to the existing machine should steam conditions at Piancastagnaio warrant the conversion to a condensing unit. Gas content would have to drop to about 4% to justify such a change.

The turbine incorporates the same features described earlier in section 2.4.2 for the Lagoni Rossi 1 and 2 units. The cut-away view of the turbine in

Fig. 21 reveals that there are three sets of blading each of which has the stationary blades mounted on removable inner shells. The first two sets of blades are essentially impulse-type, while the last set is impulse-reaction. The adjustable inlet nozzle may also be seen in the figure.

The plant operates at a geothermal utilization efficiency of 24% and consumes 17.7 kg/kW·h (39 lbm/kW·h) of net electricity generated.

4. Travale Region

4.1 Geology

The Travale geothermal field is located just on the southwest edge of the Era graben, a northwest-southeast trending feature. The geology of the site is similar to that of the Boraciferous Region which lies 10 - 15 km (6 - 9 mi) to the west-northwest. In fact, the nature of the boundary between the hydrological systems of Larderello and Travale is not well known even though both regions have been the subject of a large number of surveys [Petracco and Squarci, 1975].

The hydrogeological complexes may be described as follows: Surface layer (recent allevial, coastal deposits, travertines, and magmatic rocks); Upper complex (Pliocene and Miocene marine, lagoonal, and lacustrine deposits, flysch-facies formations) which forms the impervious cap rock for the reservoir; and Lower complex (Mesozoic carbonate formations) which is fractured and constitutes the permeable reservoir. When the lower complex outcrops, it provides a reasonably absorptive area which allows for recharge and pressure control in the reservoir [Burgassi, et al, 1975].

4.2 Well programs

The locations of the wells in the Travale area are shown in Fig. 22. Eight wells were drilled prior to 1969 ("old" wells); as of 1975, there had been six additional wells drilled ("new" wells). Information on the new wells is given in Table 6. In the vicinity of well T22, the main permeable zone is believed to trend northeast-southwest, i.e., perpendicular to the direction of the Era graben [Cormy and Musé, 1975]. This seems to account for the lack of production from new wells R1, R2, and R3. Well R4, which lies 0.8 km (2600 ft) northeast of well T22, is a good producer. The wide discrepancy in the geofluid characteristics of wells T22 and R4 is related to the fact that these two wells lie on opposite sides of a step-fault which forms one of the boundaries of the Era graben. As can be seen from Table 6, the production zone is down-shifted by about 680 m (2230 ft) from well T22 to well R4 because of the step-fault feature. Well C1 is a replacement for well R3 which was not completed because of technical difficulties.

4.3 Energy conversion system

There is one power plant in operation at the Travale field. It is a noncondensing unit (Cycle 1) of 15 MW nominal capacity. The plant is essentially identical in design to the one at Piancastagnaio, M. Amiata, described earlier in section 3.3. The unit was installed in 1973 and utilizes the geofluid from well T22. The technical particulars are listed in Table 4. This plant is reported to have the best operating efficiency of any exhausting-to-atmosphere geothermal plant in Italy. The specific steam consumption is 13.5 kg/kW·h (29.8 lbm/kW·h) [Ceron, et al, 1975], and a geothermal energy net utilization efficiency of 29%.

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Table 1

Composition of noncondensable gases found in geofluid produced
in the Boraciferous Region of Italy
[Pollastri, 1970]

	Percentage by volume of total noncondensables				
Area	CO_2	H_2S	H_2	CH_4	N_2
Castelnuovo	95.98	1.75	1.08	0.73	0.46
Lago	89.48	3.02	4.50	1.95	1.05
Lagoni Rossi	88.60	4.00	5.17	1.33	0.90
Larderello	93.82	2.56	1.87	1.10	0.65
Monterotondo	89.30	2.20	3.57	3.74	1.19
Sasso Pisano	91.77	2.77	2.56	2.14	0.76
Serrazzano	91.32	3.03	3.53	1.50	0.67

Table 2

Power system specifications for condensing units in the Boraciferous Region

	(A)	(B)	(C)	(D)	(E)	(F)	(G)	(H)	(I)	(J)	(K)
Year of start-up	1938	1952-54	1969	1967	1967	1967	(NA)	1960	1960	(NA)	(NA)
Turbine data:											
Type	(1)	(1)	(2)	(1)	(1)	(1)	(2)	(3)	(1)	(2)	(1)
Installed capacity, MW	$69^{(4)}$	$120^{(5)}$	15	26	11	2	$47^{(6)}$	6.5	$27^{(7)}$	$15.7^{(8)}$	12.5
Speed, rev/min	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000
Steam inlet pressure, lbf/in^2	59.7	62.6	103.8	61.1	27.0	15.6	69.7	29.9	76.8	71.1	64.0
Steam inlet temperature, °F	385	387	433	370	345	302	385	289	352	365	370
% (wt.) noncondensable gases	7.0	6.8	6.7	14.3	3.8	2.4	3.8	1.8	2.2	3.0	1.7
Exhaust pressure, in Hg	3.0	3.5	3.0	2.6	2.6	2.6	2.9	2.0	2.0	3.0	(NA)
Steam flow rate, 10^3 lbm/h	$899^{(9)}$	$1480^{(9)}$	238	375	127	61.7	$633^{(9)}$	154	$558^{(9)}$	$357^{(9)}$	269
Condenser data:											
Type	All units have low-level, direct-contact, barometric condensers.										
Cooling water temperature, °F	87.8	82.9	87.8	73.4	73.4	73.4	84.2	78.8	78.8	(NA)	(NA)
Outlet water temperature, °F	105.8	106.3	105.8	98.6	98.6	98.6	104.0	95.0	95.0	(NA)	(NA)
Cooling water flow rate, 10^6 lbm/h	(NA)	(NA)	17.8	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
Gas extractor data:											
Type	All units have multistage centrifugal turbocompressors with interstage coolers.										
Gas capacity, 10^3 ft^3/min	$\sim 310^{(9)}$	$\sim 330^{(9)}$	196	182	(NA)	(NA)	$134^{(9)}$	(NA)	$134^{(9)}$	(NA)	(NA)
Power consumption, kW	$\sim 4625^{(9)}$	$\sim 5580^{(9)}$	1625	2270	(NA)	(NA)	$1760^{(9)}$	(NA)	$1760^{(9)}$	(NA)	(NA)
Heat rejection system data:											
Type	All units have natural-draft, water cooling towers.										
No. of towers	3	4	1	1	1	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)
Design wet-bulb temp., °F	67.0	58.4	67.0	63.3	63.3	63.3	58.4	58.4	58.4	(NA)	(NA)
Water pump power, kW	(NA)	855	(NA)	750	(NA)	(NA)	560	(NA)	$365^{(10)}$	(NA)	(NA)

(A) Larderello 2
(B) Larderello 3
(C) Gabbro
(D) Castelnuovo V.C.
(E) Castelnuovo V.C.
(F) Castelnuovo V.C.
(G) Serrazzano
(H) Lago 2
(I) Lago 2
(J) Sasso Pisano
(K) Monterotondo

(1) Single-cylinder, double-flow.
(2) Tandem-compound, single-flow (HP) and double-flow (LP)
(3) Single-cylinder, single-flow.
(4) 4 - 14.5 MW units; 1 - 11 MW unit.
(5) 3 - 26 MW units; 1 - 24 MW unit; 2 - 9 MW units.
(6) 1 - 15 MW unit; 2 - 12.5 MW units; 2 - 3.5 MW units.
(7) 1 - 14.5 MW unit; 1 - 12.5 MW unit.
(8) 1 - 12.5 MW unit; 1 - 3.2 MW unit.
(9) Total for all units.
(10) For the 14.5 MW unit only.

Table 3

Turbine specifications for noncondensing units in the Boraciferous Region

	Sant'Ippolito-Vallonsordo	Lagoni Rossi 1	Lagoni Rossi 2	Sasso 1	Capriola	Molinetto
Year of start-up	1963	1961	1969	1969	1969	(NA)
Turbine type	(1)	(2)	(2)	(2)	(2)	(2)
Installed capacity, MW	0.9	3.5	3.0	7.0	3.0	3.5
Speed, rev/min	3000	3000	3000	3000	3000	3000
Steam inlet pressure, lbf/in^2	109.5	75.4	65.4	71.1	56.9	72.5
Steam inlet temperature, °F	419	313	356	369	379	370
% (wt.) noncondensable gases	3.3	3.2	3.8	2.7	4.0	3.3
Exhaust pressure, in Hg	30.4	30.4	30.4	30.4	30.4	30.4
Steam flow rate, 10^3 lbm/h	52.9	88.2	121	117	112	39.7

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(1) Single-cylinder, single-flow, impulse blading.

(2) Single-cylinder, single-flow, impulse-reaction blading.

Table 4

Turbine specifications for noncondensing units in the Monte Amiata and Travale regions

	Bagnore 1	Bagnore 2	Piancastagnaio	Travale
Year of start-up	1959	1960	1969	1973
Turbine type	(1)	(1)	(1)	(1)
Rated capacity, MW	3.5	3.5	15.0	15.0
Speed, rev/min	3000	3000	3000	3000
Steam inlet pressure, lbf/in^2	42.7	46.9	116.6	159.3
Steam inlet temperature, °F	275	286	361	414
% (wt.) noncondensable gases	8.5	7.2	21.1	10.6
Exhaust pressure, in Hg	30.4	30.4	31.3	31.3
Steam flow rate, 10^3 lbm/h	97.0	110.0	483.0	419.0

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(1) Single-cylinder, single-flow, impulse blading.

Table 5

Production history of the noncondensing units at Bagnore, Monte Amiata

	Bagnore 1	Bagnore 2
Installed capacity, MW	3.5	3.5
1960: [Cataldi, *et al*, 1970]		
Pressure, lbf/in^2	71.1	71.1
Temperature, °F	311	320
Gas content, % (wt.)	30	80
Net capacity, MW	2.70	0.96
1969: [Cataldi, *et al*, 1970]		
Pressure, lbf/in^2	45.5	50.0
Temperature, °F	277	286
Gas content, % (wt.)	8	8
Net capacity, MW	1.50	2.00
1974: [Ceron, *et al*, 1975]		
Pressure, lbf/in^2	42.7	46.9
Temperature, °F	275	286
Gas content, % (wt.)	8.5	7.2
Net capacity, MW	1.20	1.80

Table 6

Information on new wells drilled at Travale

[after Burgassi, *et al*, 1975]

	Well					
	T22(a)	R1	R2	R3	R4(a)	C1
Wellhead elevation, ft(b)	1247	1371	1214	1378	1116	1394
Total well depth, ft	2267	4922	6040	3340	4498	6004
Production casing depth, ft	2087	3763	4856	2359	4429	2290
Casing diameter, in	13 3/8	9 5/8	9 5/8	13 3/8	9 5/8	13 3/8
Reservoir temperature, °F	507	486	516	428(c)	387	>446
Delivery pressure, lbf/in^2	356	—	—	(d)	84	(NA)
Delivery temperature, °F	462	—	—	—	331	(NA)
Total flow rate, 10^3 lbm/h	388	dry(e)	dry	—	201	(NA)
Gas content, % (wt.)	10.3	—	—	—	66	(NA)

(a) Measured during March 1975.

(b) Relative to sea level (s.l. = 0 ft).

(c) Nonequilibrium value; extrapolated value is ∿ 482°F.

(d) Not completed because of technical difficulties.

(e) Originally produced a steam-gas mixture intermittently.

Figure captions

Fig. 1. Geological map and cross-section of the Boraciferous Region, Tuscany, Italy [after ENEL]. Geological formations: 1. Clays, sandstones, conglomerates, etc.; 2. Shales, marls, limestones, etc.; 3. "Macigno", "polychrome shales"; 4. Tuscan formations; 5. Phyllites, quartzites.

Fig. 2. Typical well profiles in Italian geothermal fields: (left) production well and (right) exploratory or deep well [after Cigni, et al, 1975].

Fig. 3. Typical wellheads for various phases of drilling operations at Italian geothermal fields [Cigni, 1970].

Fig. 4. Typical steam pipeline connection at wellhead [Pollastri, 1970].

Fig. 5. Production history of wells (A) 85 and (B) Fabriani at Larderello for wellhead pressures roughly 0.4 MPa (57 lbf/in^2) [after ENEL].

Fig. 6. Flow rate versus wellhead pressure for wells (A) St. Silvestro (Sasso Pisano), (B) Scarzai 3 (Lagoni Rossi) and (C) Gabbro 9 [after Pollastri, 1970].

Fig. 7. Energy conversion schemes at Larderello. (a) Direct-intake, noncondensing, "Cycle 1" plant: a = steam well, b = turbine, c = generator, d = exhaust to atmosphere. (b) Pure-steam, condensing, "Cycle 2" plant: a = steam well, b = heat exchanger, c = turbine, d = generator, e = degassing plant, f = condenser, g = liquid discharge, h = to and from cooling tower. (c) Direct-intake, condensing, "Cycle 3" plant: a = steam well, b = water injection (scrubber), c = axial separator, d = turbine, e = generator, f = condenser, g = gas compressor, h = to and from cooling tower.

Fig. 8. Typical arrangement for a Cycle 3 power unit at Larderello [Allegrini and Benvenuti, 1970].

Fig. 9. Typical flow diagram for Cycle 3 power unit with 14.8 MW installed capacity [Dal Secco, 1970].

Fig. 10. Larderello 3 turbine hall. Turbogenerator units in foreground and at left background; gas extractors and turbocompressors at right and in background [ENEL].

Fig. 11. Castelnuovo V.C. 26 MW turbogenerator unit. Gas compressors are at the left end of the shaft, the double-flow turbine and generator are at the right end. The two large vessels in the foreground and the one to the left of the compressors are gas intercoolers [Villa, 1975].

Fig. 12. Serrazzano 12.5 MW units. Turbocompressors for two 12.5 MW units are in the foreground; one turbogenerator unit is at the rear [Dal Secco, 1970].

Fig. 13. Lago 2 turbine hall. Two units are arranged back-to-back; turbocompressors are in the center foreground; one of the turbine-generator sets is at the right rear [Dal Secco, 1970].

Fig. 14. Sasso Pisano (Sasso 2) power station. A total of 15.7 MW is installed in this plant. The turbogenerators are mounted on elevated pedestals in the machine room [Saporiti, 1961 (a)].

Fig. 15. Monterotondo turbine hall. The 12.5 MW unit in the background is the main unit in operation at this site; the unit at the left is rated at 700 kW and provides power for compressor operation [Saporiti, 1961 (a)].

Fig. 16. Sant'Ippolito-Vallonsordo 900 kW unit. Turbine-generator assembly for this noncondensing plant, the smallest of the geothermal power units operating in Italy [ENEL].

Fig. 17. Power loss as a function of time after overhaul for three 26 MW units at Larderello 3. Solid lines-without oil washing; dashed lines - with oil washing. Steam temperatures: 190°C (374°F) for Units No. 1 and 3, 201°C (394°F) for Unit No. 4 [after Ricci and Viviani, 1970].

Fig. 18. Geological map and cross-section of the Monte Amiata Region, Tuscany, Italy [after ENEL]. Geological formations: 1. Travertines; 2. Volcanites; 3. Clays, sands, conglomerates; 4. Shales, marls, limestones, etc.; 5. Calcerenites; 6. Tuscan formations.

Fig. 19. Piancastagnaio power house, Monte Amiata. The steam line from well P.C./8 may be seen at the right. The silencer and exhaust stack is visible on the left side of the building which is designed for ease of portability in the event that the field should become nonproductive [ENEL].

Fig. 20. Piancastagnaio turbogenerator. This exhausting-to-atmosphere unit is rated at 15 MW and designed to accommodate a wide range of inlet steam pressures [Ciapica, 1970].

Fig. 21. Piancastagnaio noncondensing turbine. Removable sections of blading and adjustable inlet nozzles permit high efficiency over wide operating conditions [Ciapica, 1970].

Fig. 22. Well locations at Travale, Italy [after Burgassi, et al, 1975].

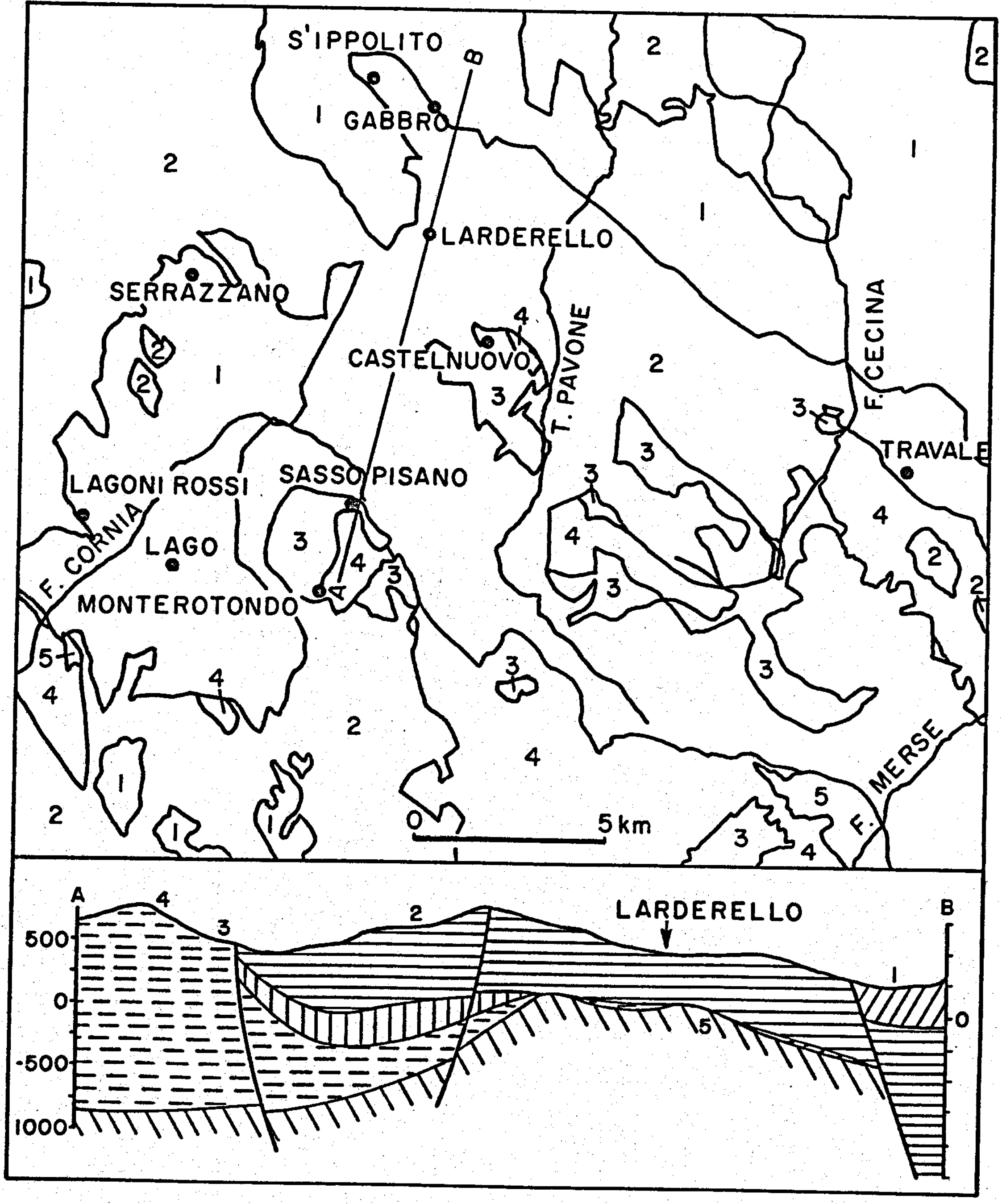

S'IPPOLITO
B
GABBRO
LARDERELLO
SERRAZZANO
CASTELNUOVO
T. PAVONE
F. CECINA
TRAVALE
SASSO PISANO
LAGONI ROSSI
F. CORNIA
LAGO
MONTEROTONDO
A
F. MERSE
0
5 km
1
2
3
4
5
A
B
LARDERELLO
500
0
-500
1000

Figure 1

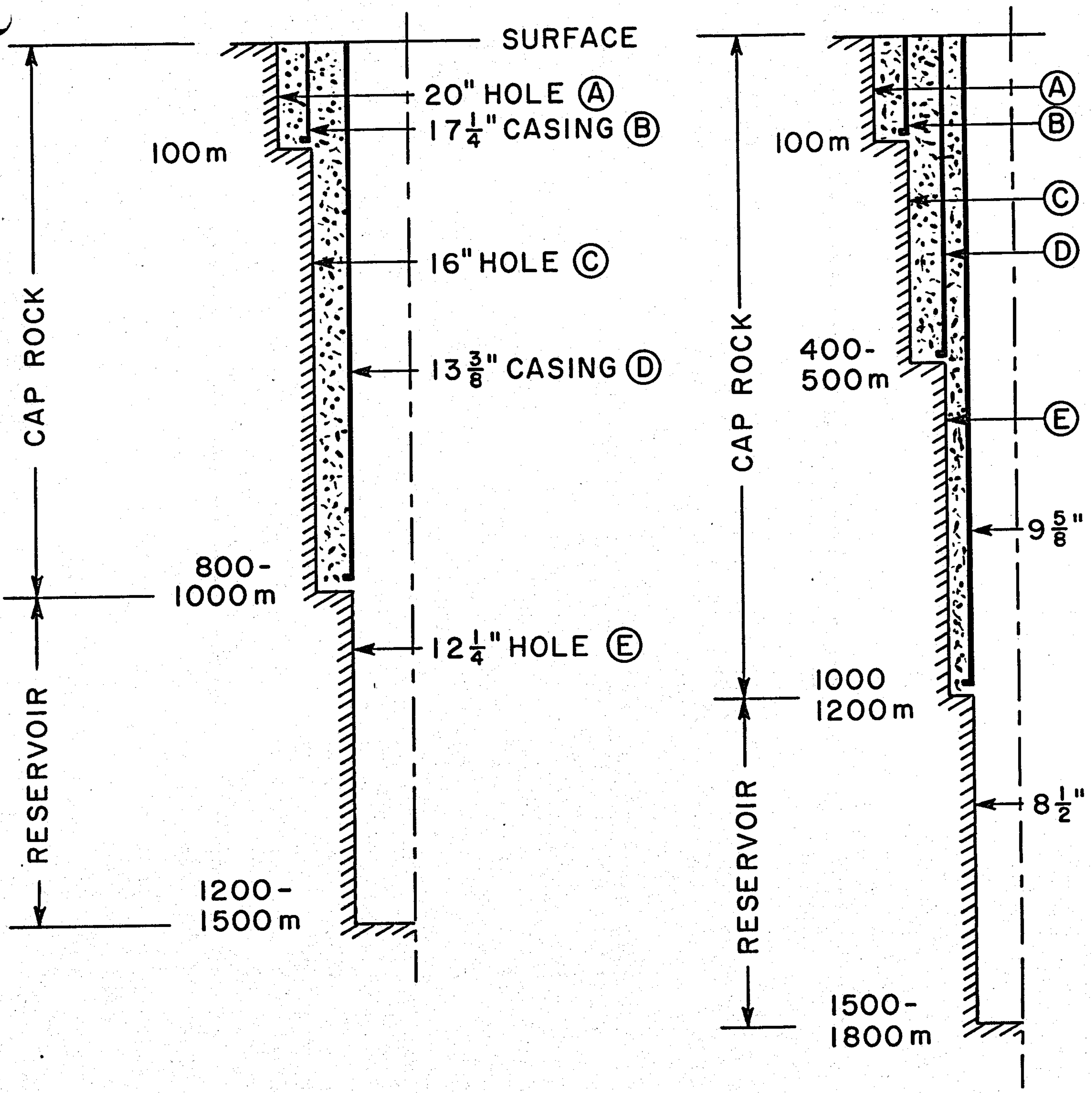
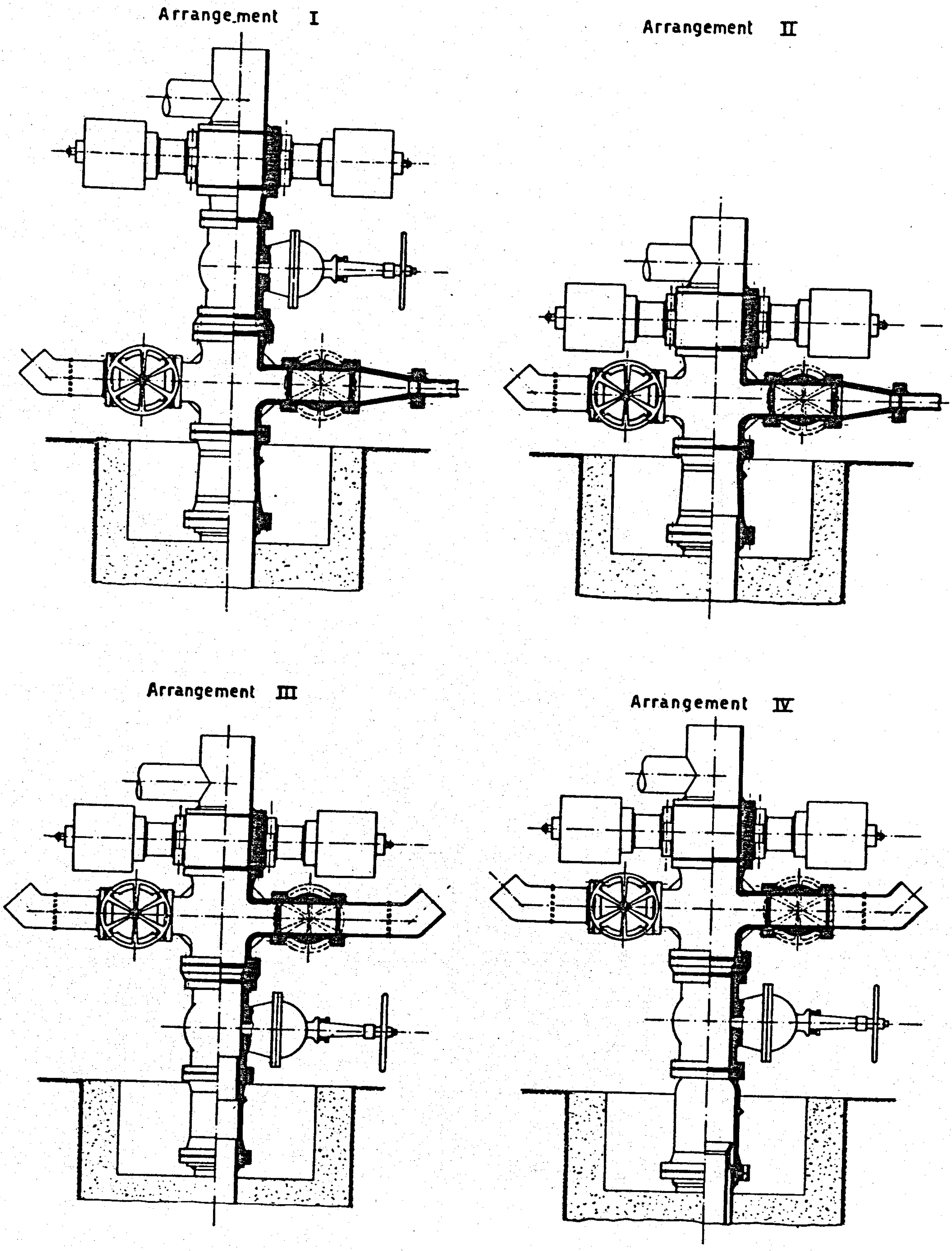

SURFACE
20" HOLE Ⓐ
17¼" CASING Ⓑ
100m
16" HOLE Ⓒ
13⅜" CASING Ⓓ
CAP ROCK
800-
1000m
12¼" HOLE Ⓔ
RESERVOIR
1200-
1500m
Ⓐ
Ⓑ
100m
Ⓒ
Ⓓ
400-
500m
Ⓔ
CAP ROCK
9⅝"
1000
1200m
8½"
RESERVOIR
1500-
1800m

Figure 2



Arrangement I

Arrangement II

Arrangement III

Arrangement IV

Figure 3

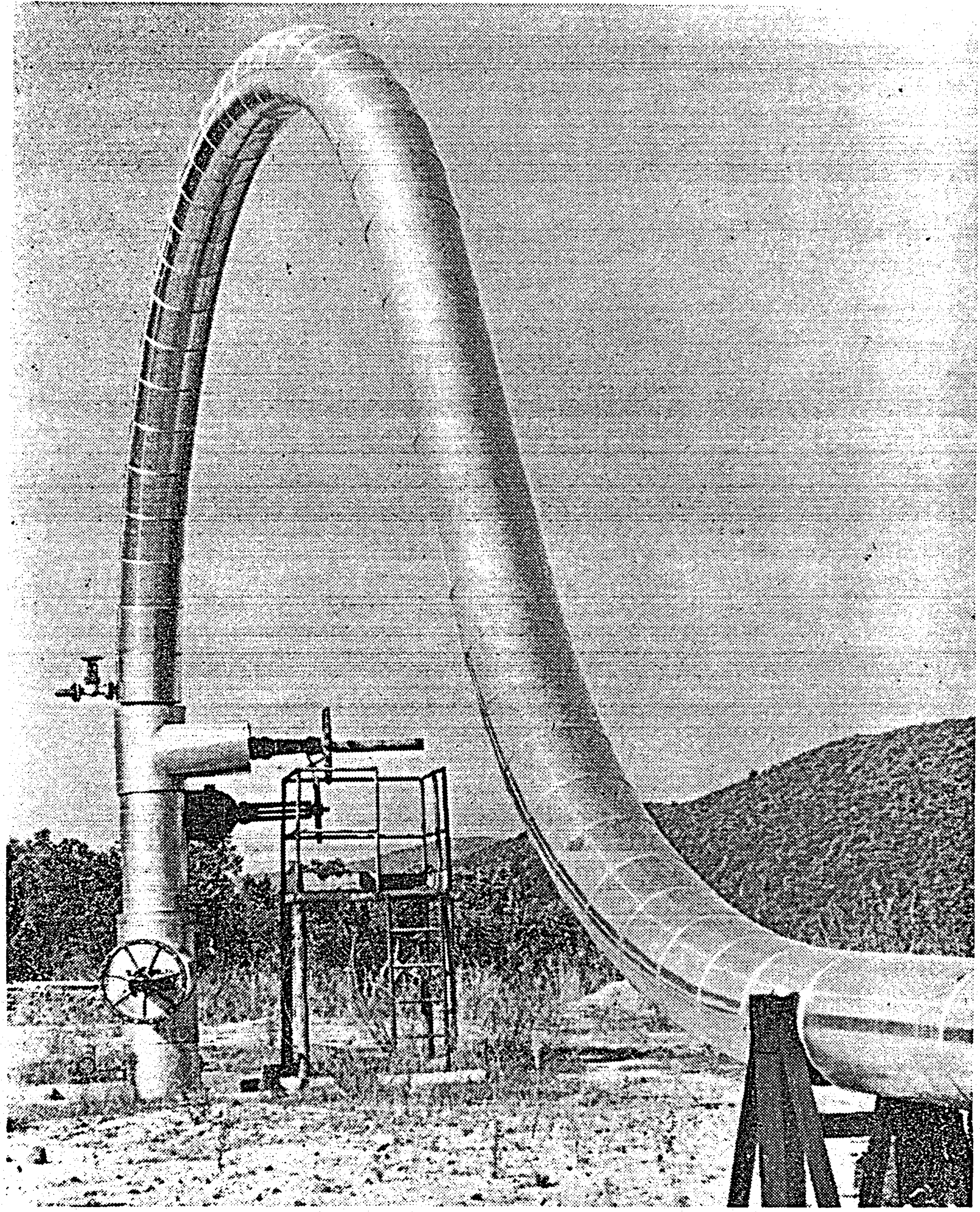


Figure 4

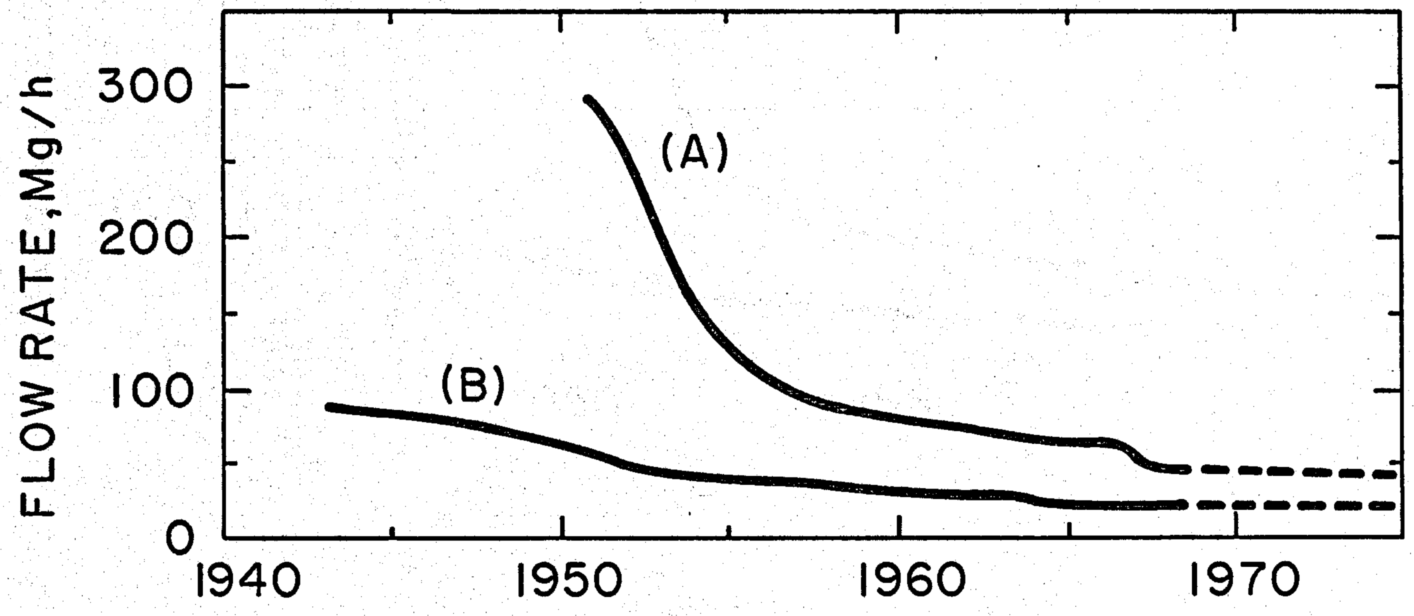


Figure 5

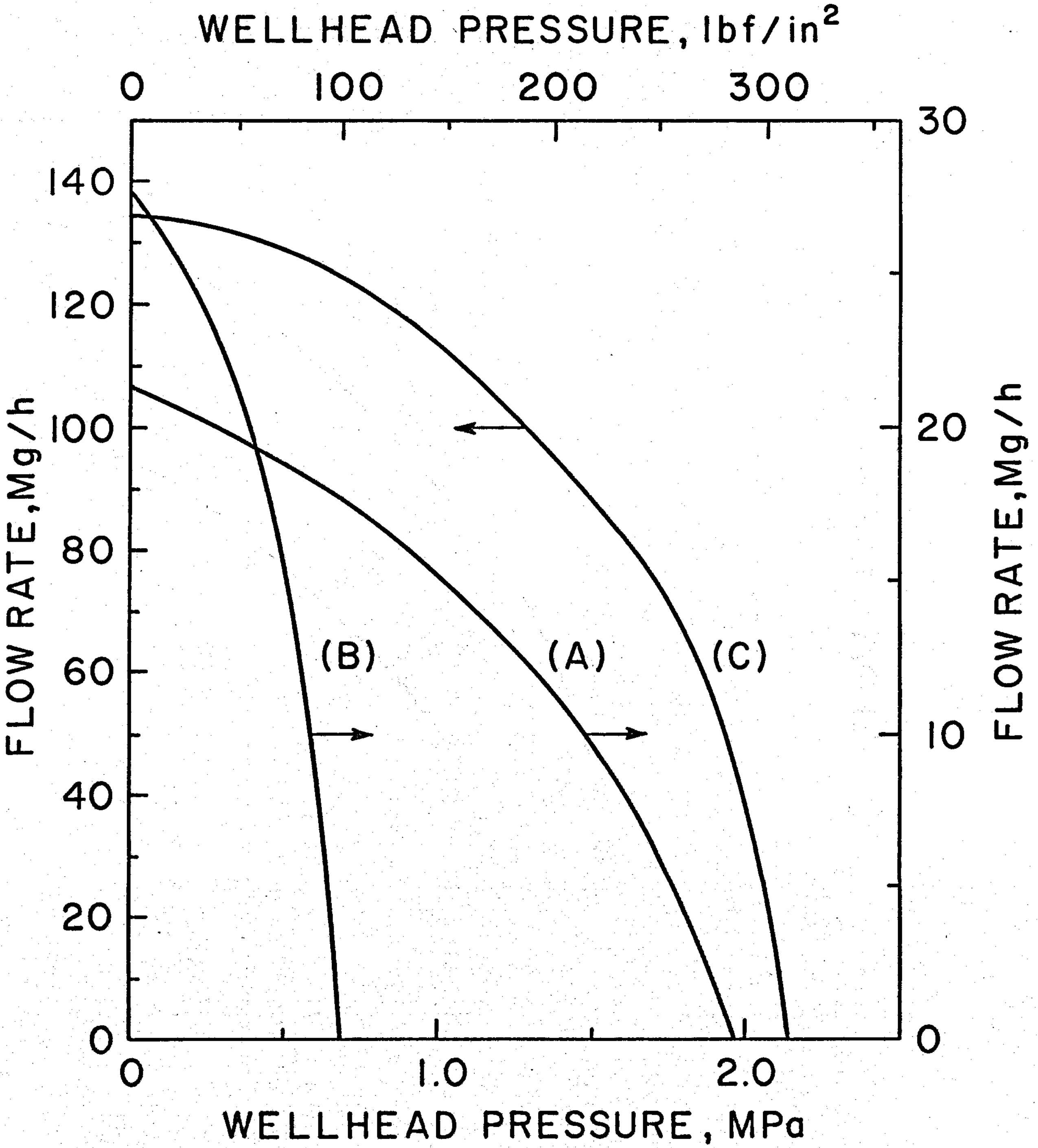

WELLHEAD PRESSURE, lbf/in²
0
100
200
300
140
120
100
80
60
40
20
0
30
20
10
0
FLOW RATE, Mg/h
FLOW RATE, Mg/h
(B)
(A)
(C)
0
1.0
2.0
WELLHEAD PRESSURE, MPa

Figure 6

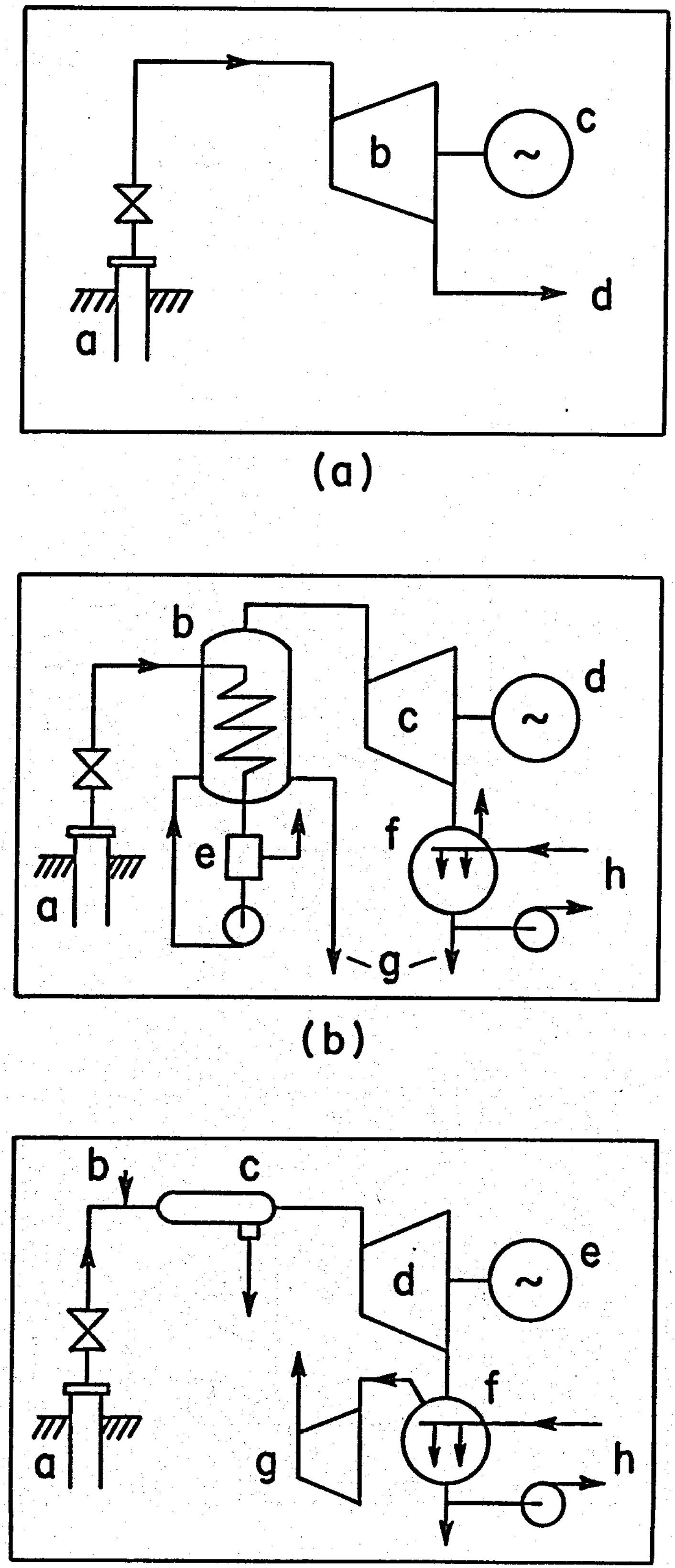


Figure 7

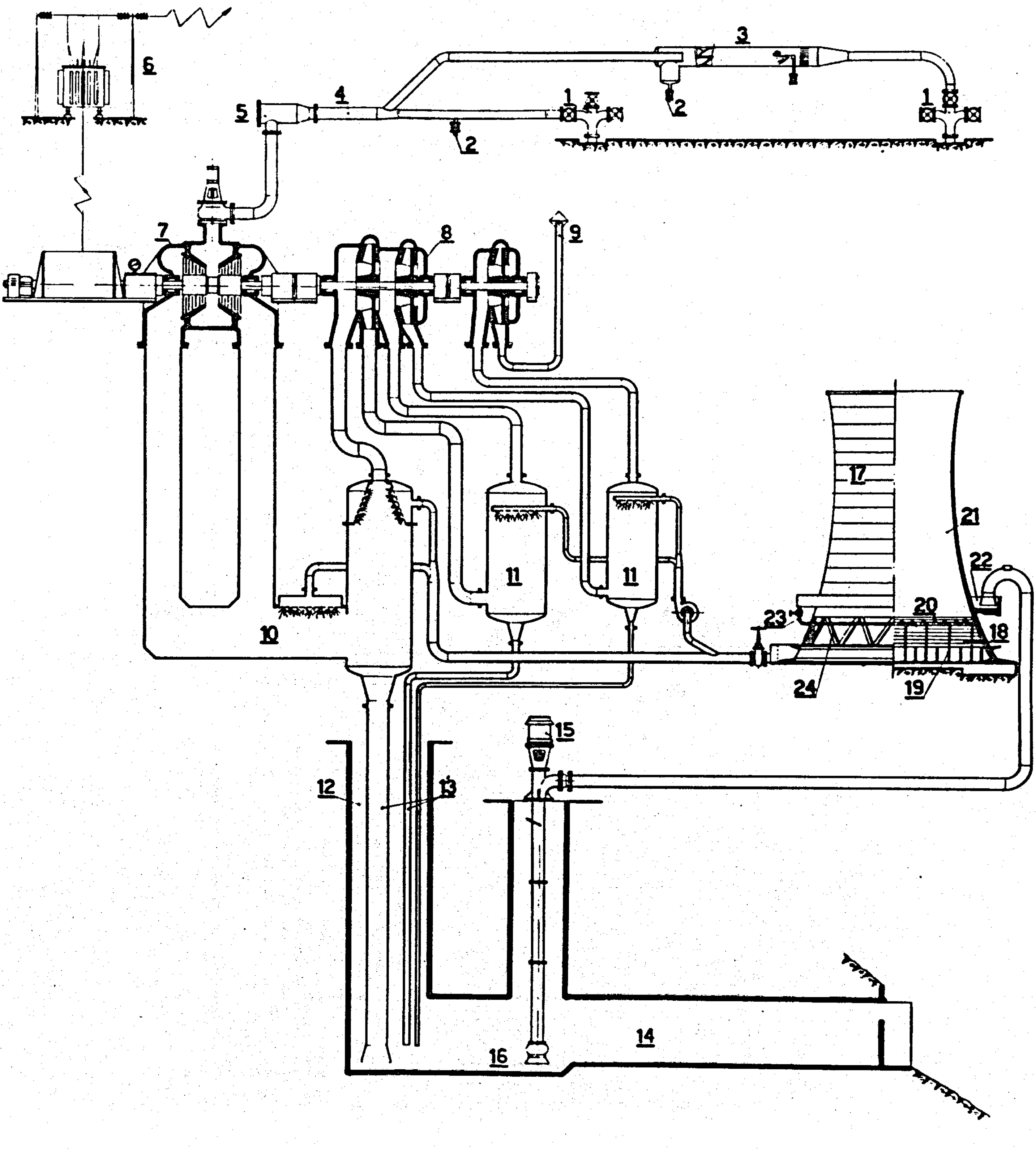


Figure 8

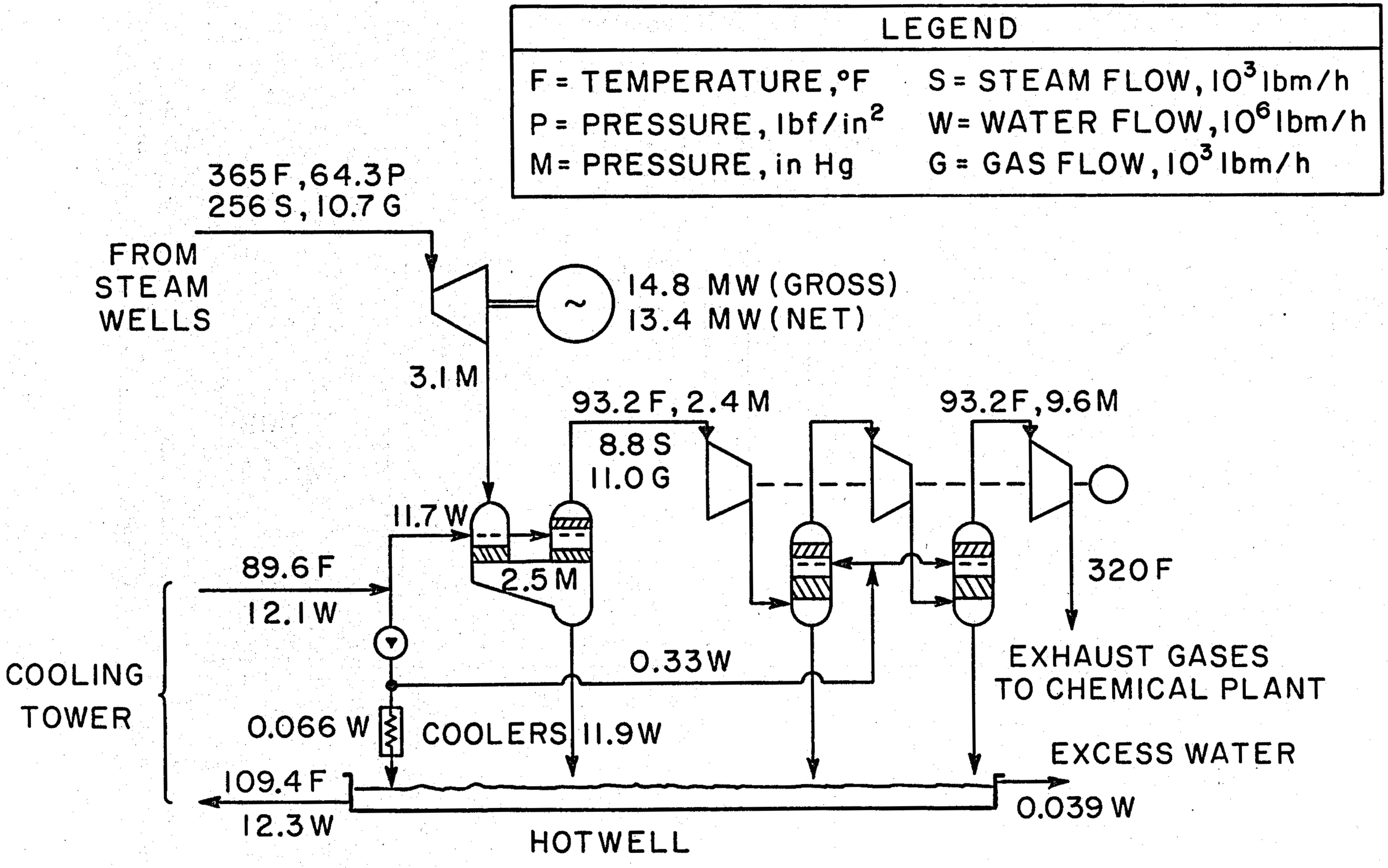

LEGEND
F = TEMPERATURE, °F
P = PRESSURE, lbf/in²
M = PRESSURE, in Hg
S = STEAM FLOW, 10³ lbm/h
W = WATER FLOW, 10⁶ lbm/h
G = GAS FLOW, 10³ lbm/h
365 F, 64.3 P
256 S, 10.7 G
FROM STEAM WELLS
14.8 MW (GROSS)
13.4 MW (NET)
3.1 M
93.2 F, 2.4 M
8.8 S
11.0 G
93.2 F, 9.6 M
11.7 W
2.5 M
89.6 F
12.1 W
320 F
EXHAUST GASES TO CHEMICAL PLANT
0.33 W
COOLING TOWER
0.066 W
COOLERS
11.9 W
EXCESS WATER
0.039 W
109.4 F
12.3 W
HOTWELL

Figure 9

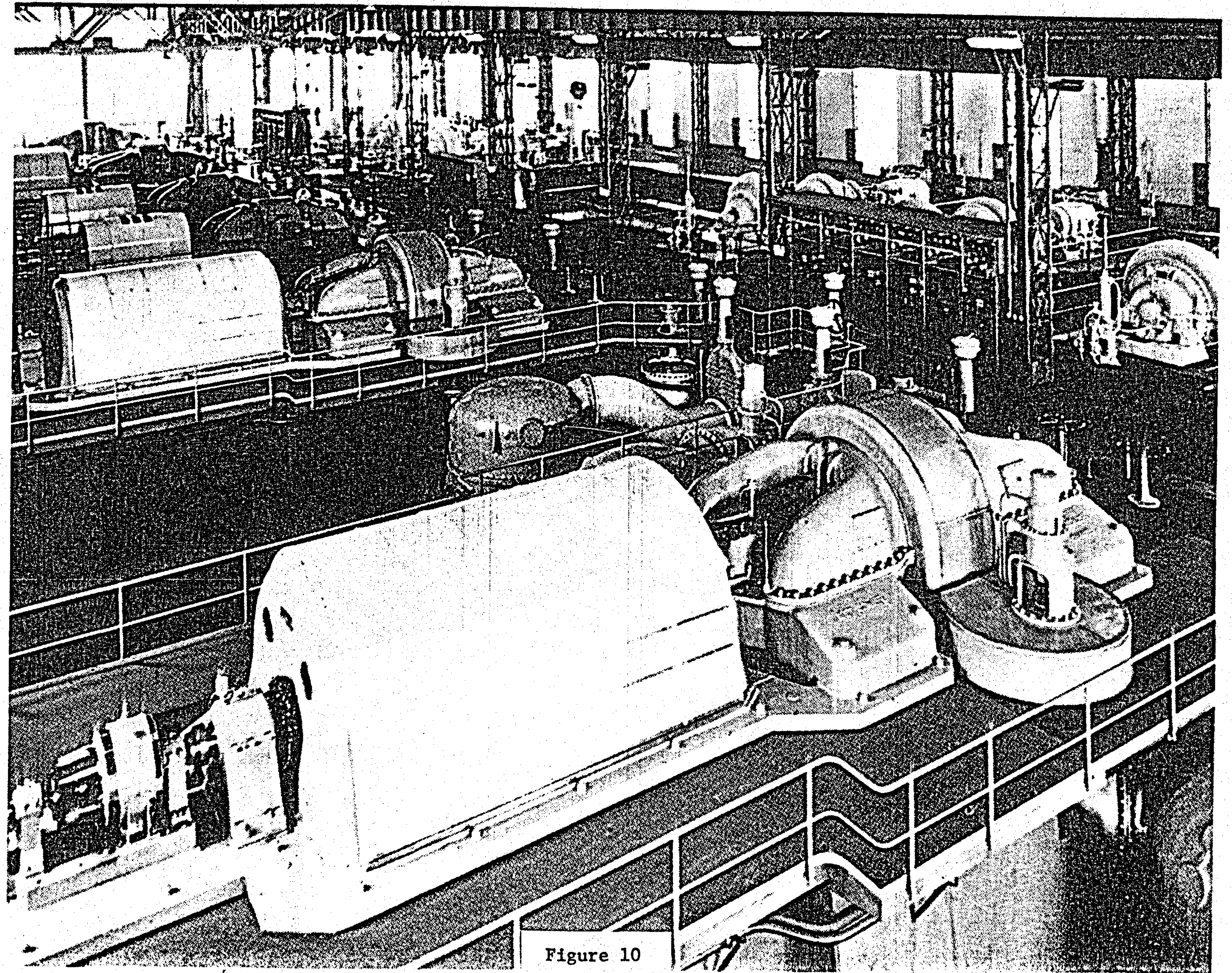


Figure 10

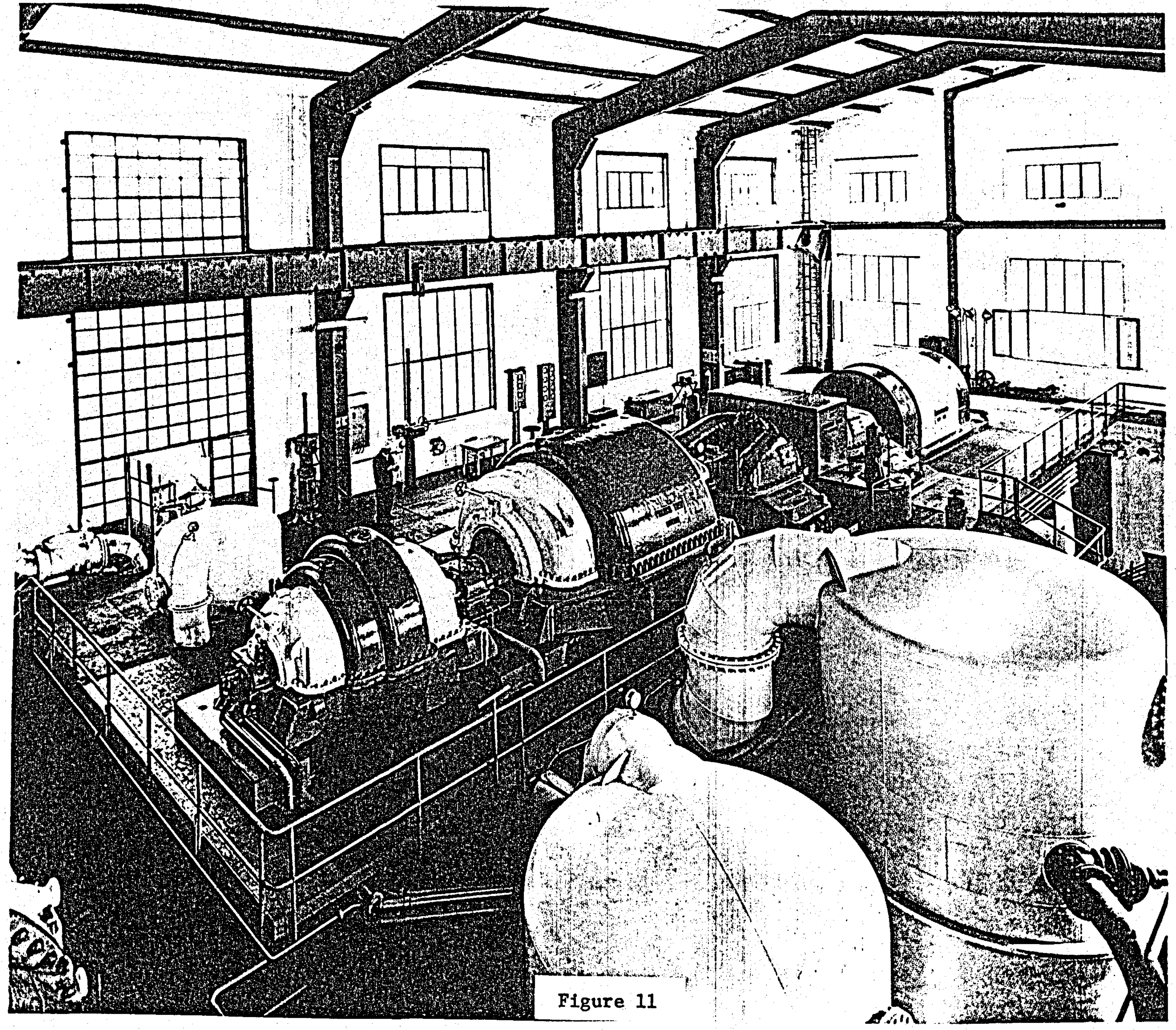


Figure 11

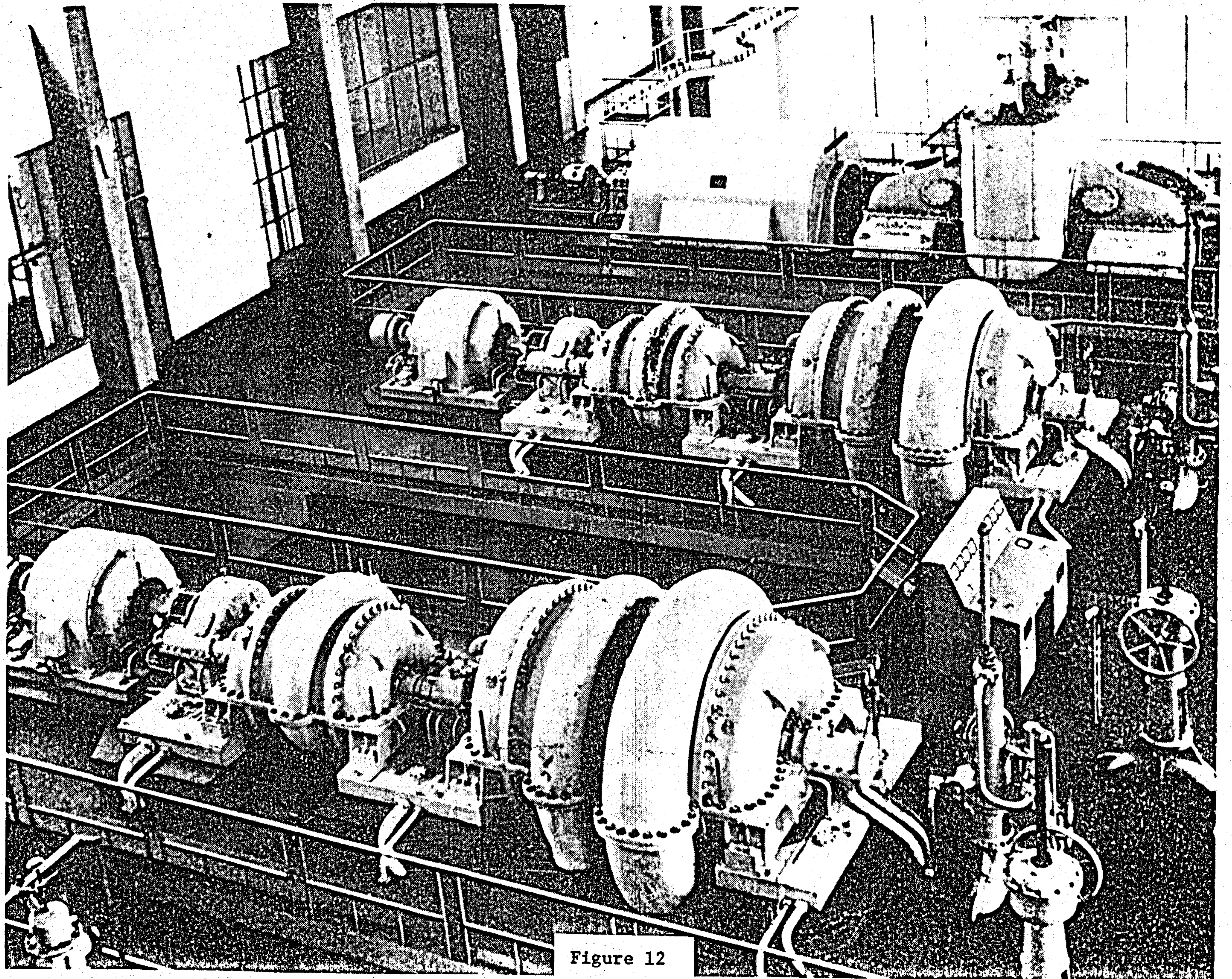


Figure 12

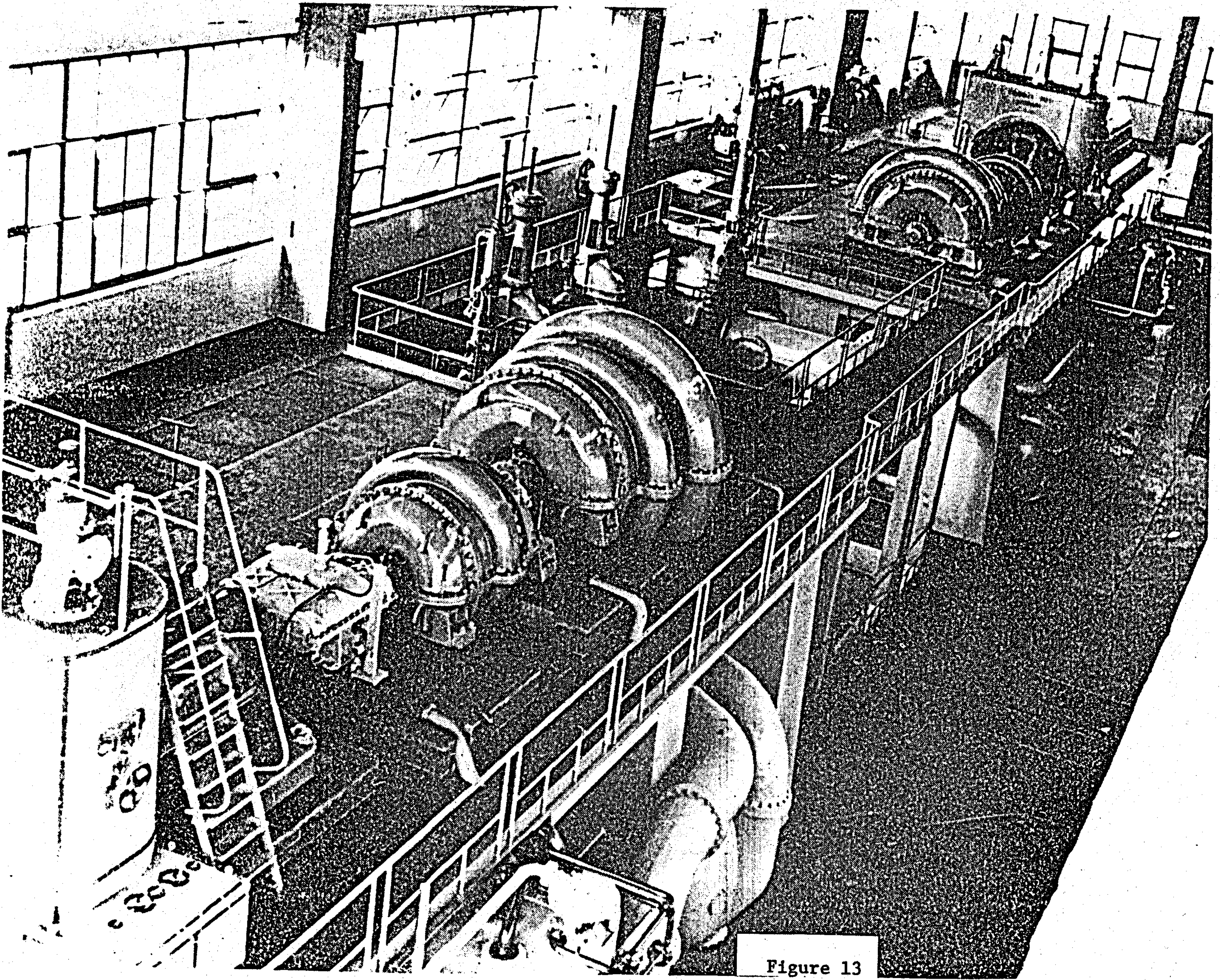


Figure 13

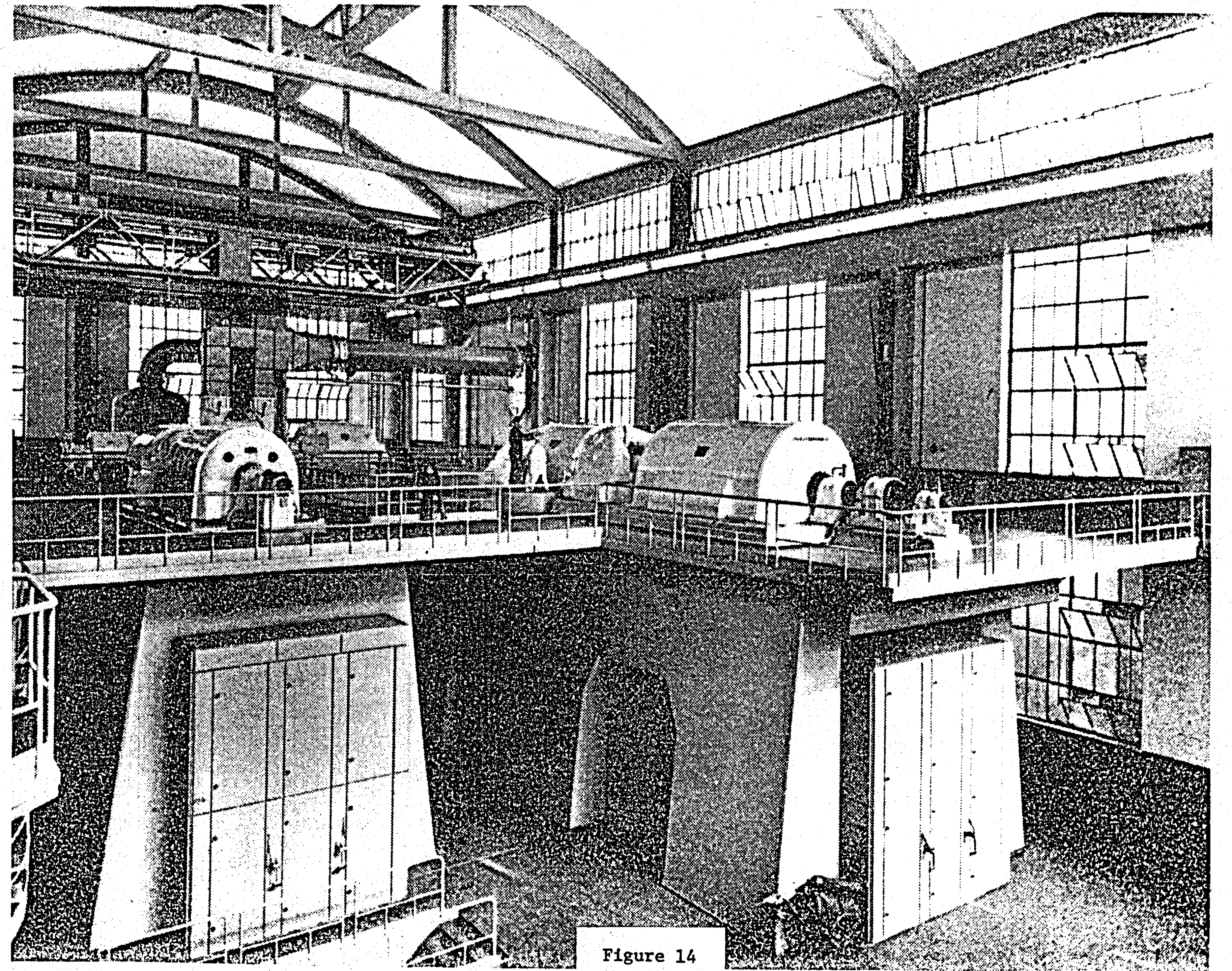


Figure 14

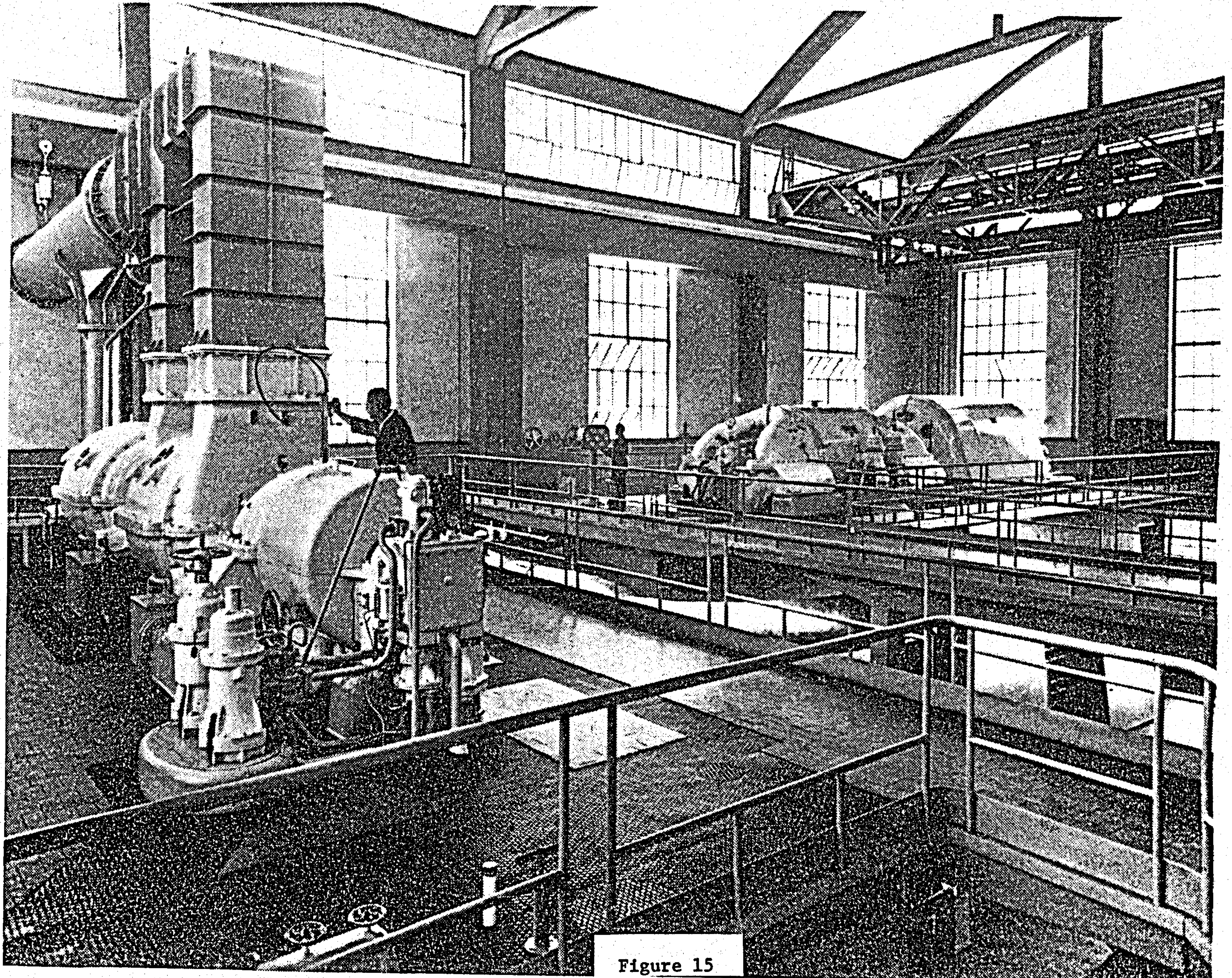


Figure 15

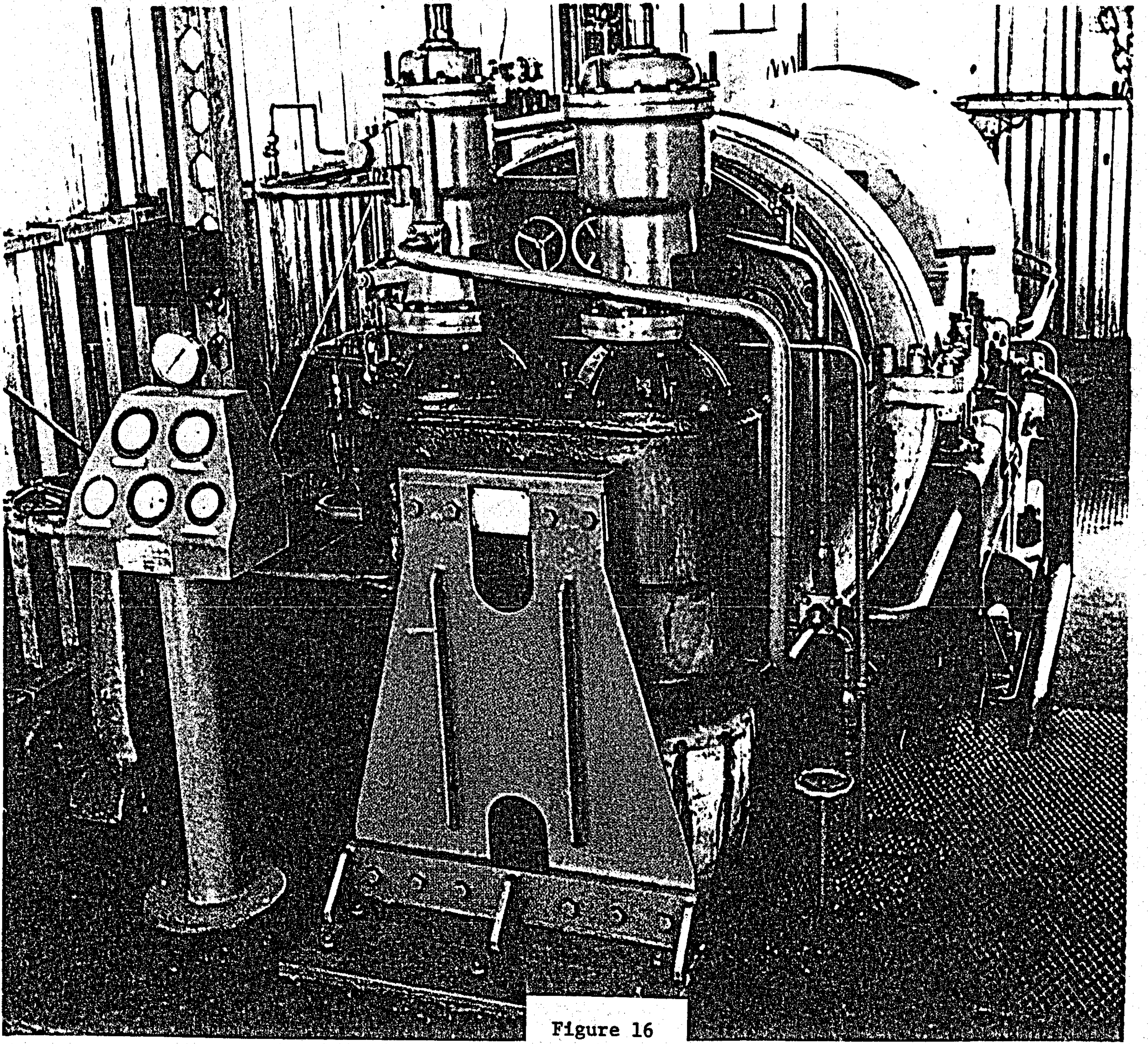


Figure 16

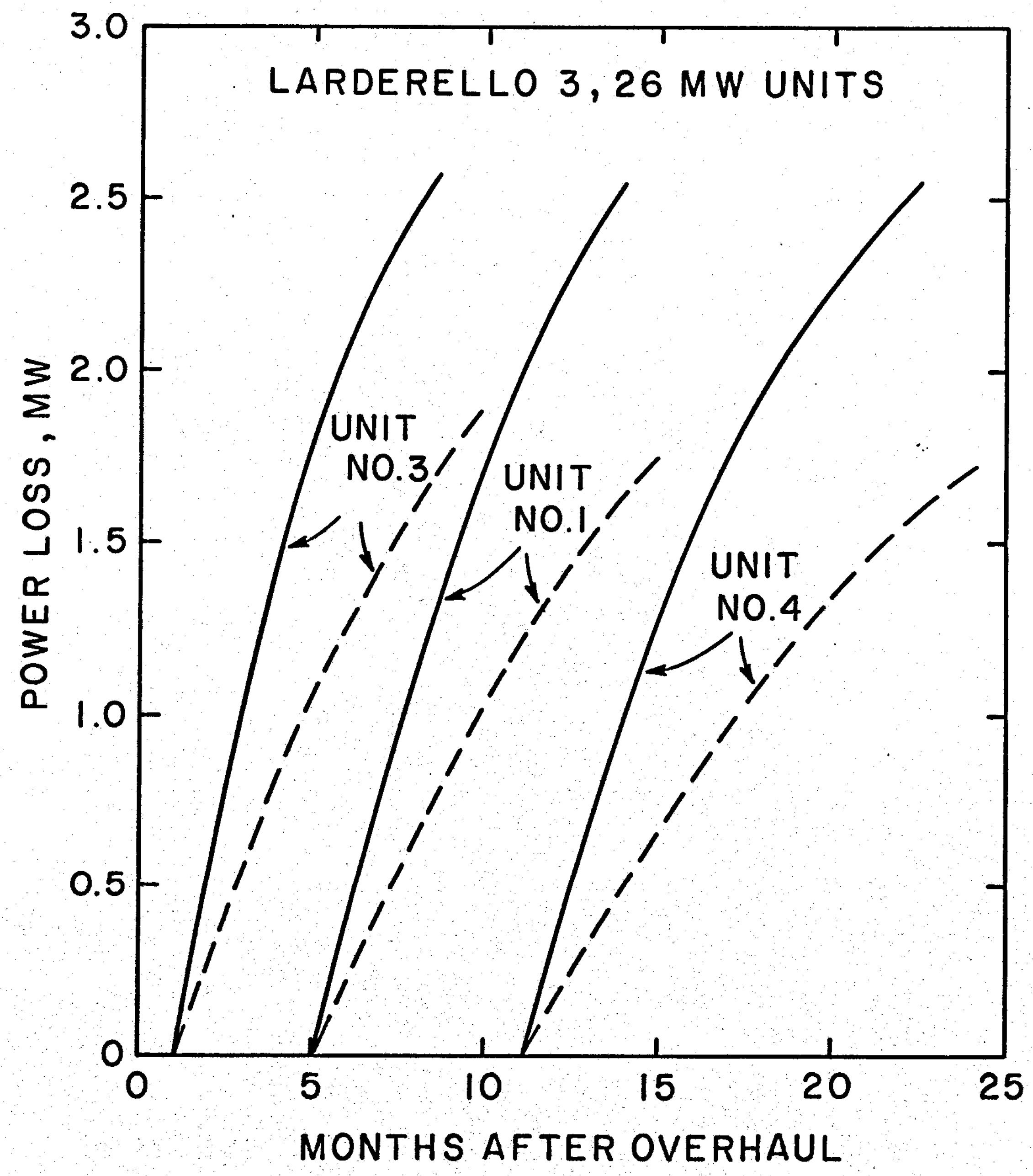
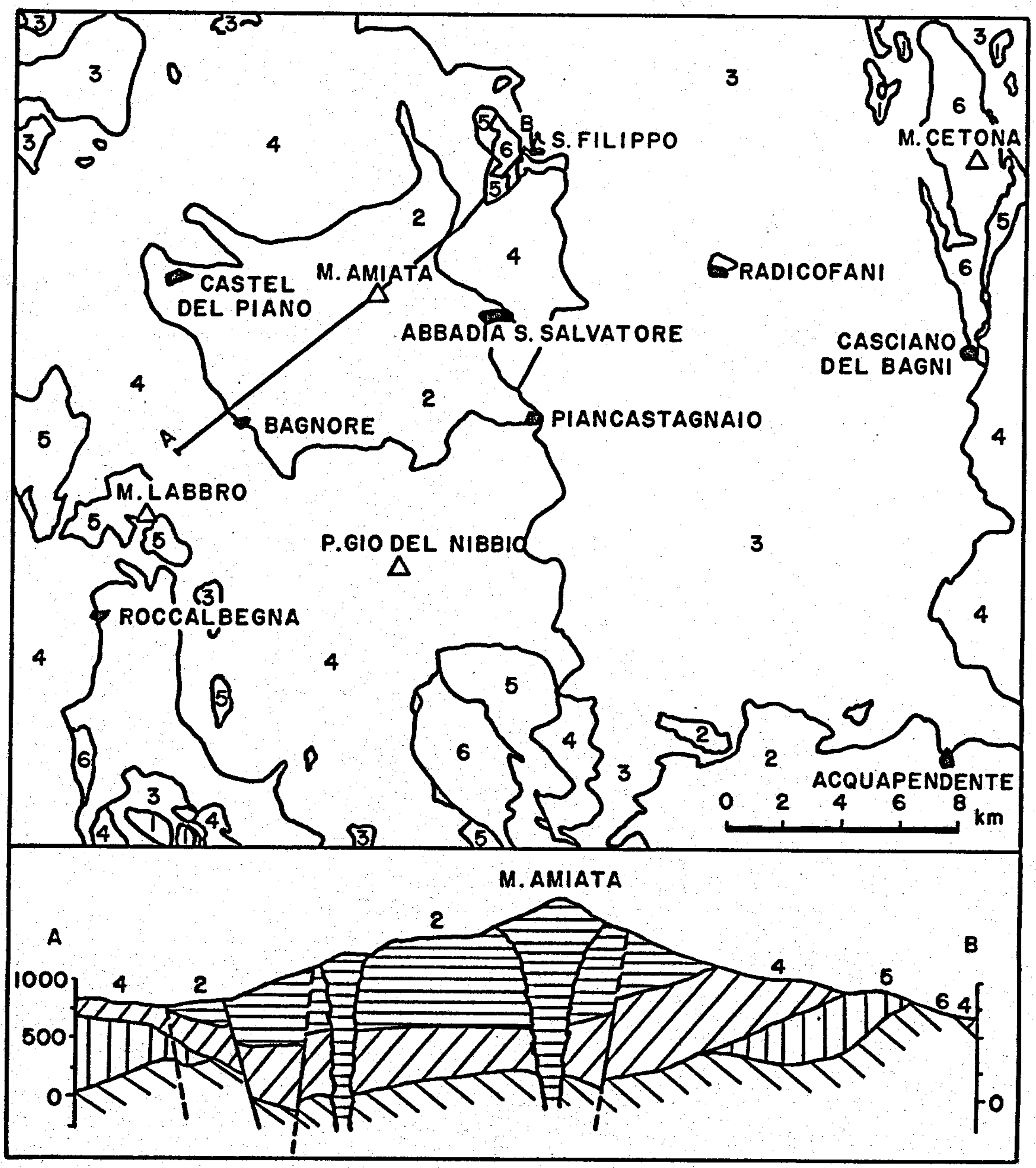

LARDERELLO 3, 26 MW UNITS
POWER LOSS, MW
MONTHS AFTER OVERHAUL
0
0.5
1.0
1.5
2.0
2.5
3.0
0
5
10
15
20
25
UNIT NO.3
UNIT NO.1
UNIT NO.4

Figure 17



S. FILIPPO
M. CETONA
CASTEL DEL PIANO
M. AMIATA
RADICOFANI
ABBADIA S. SALVATORE
CASCIANO DEL BAGNI
BAGNORE
PIANCASTAGNAIO
M. LABBRO
P. GIO DEL NIBBIO
ROCCALBEGNA
ACQUAPENDENTE
A
B
0 2 4 6 8 km
1
2
3
4
5
6
M. AMIATA
1000
500
0

Figure 18

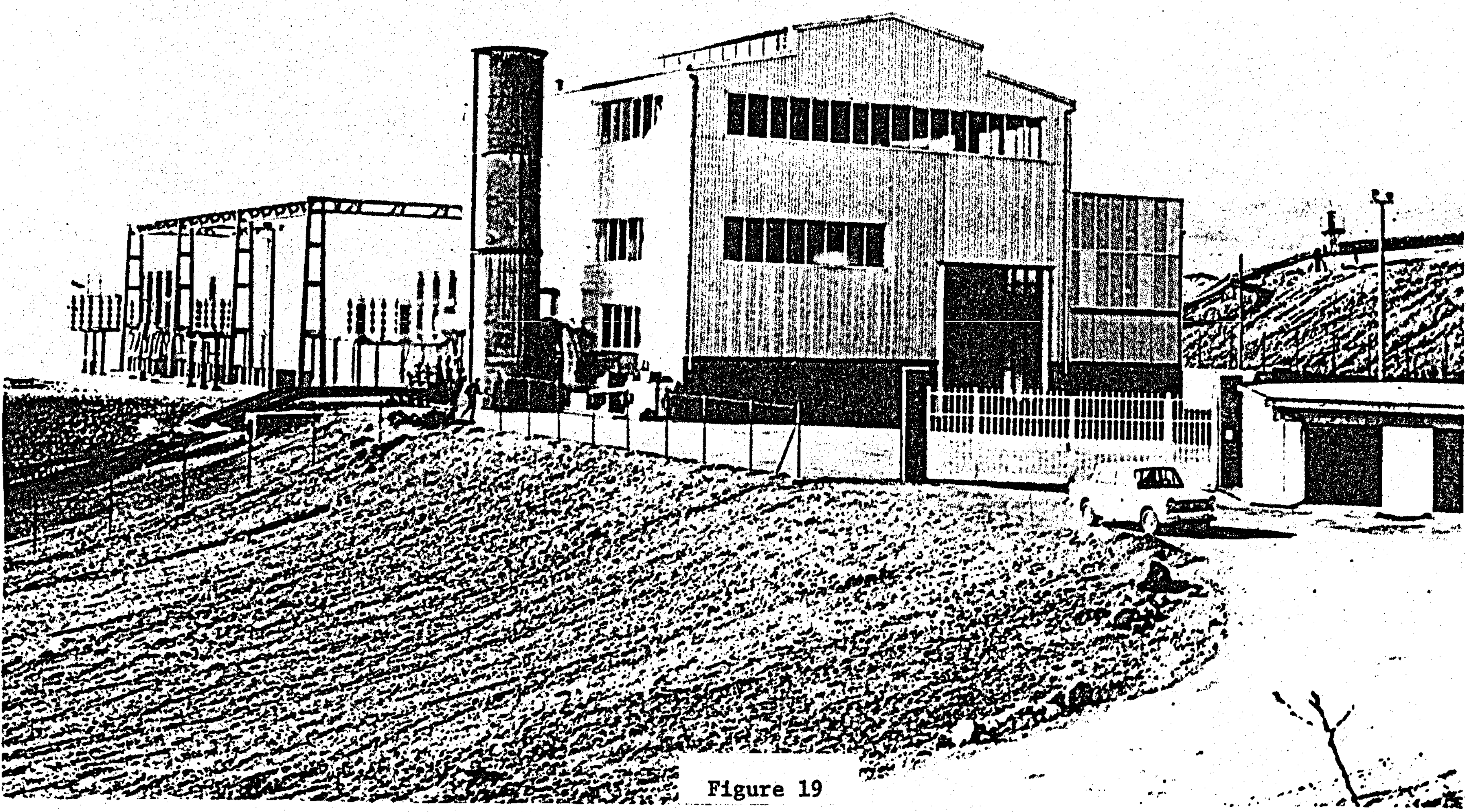


Figure 19

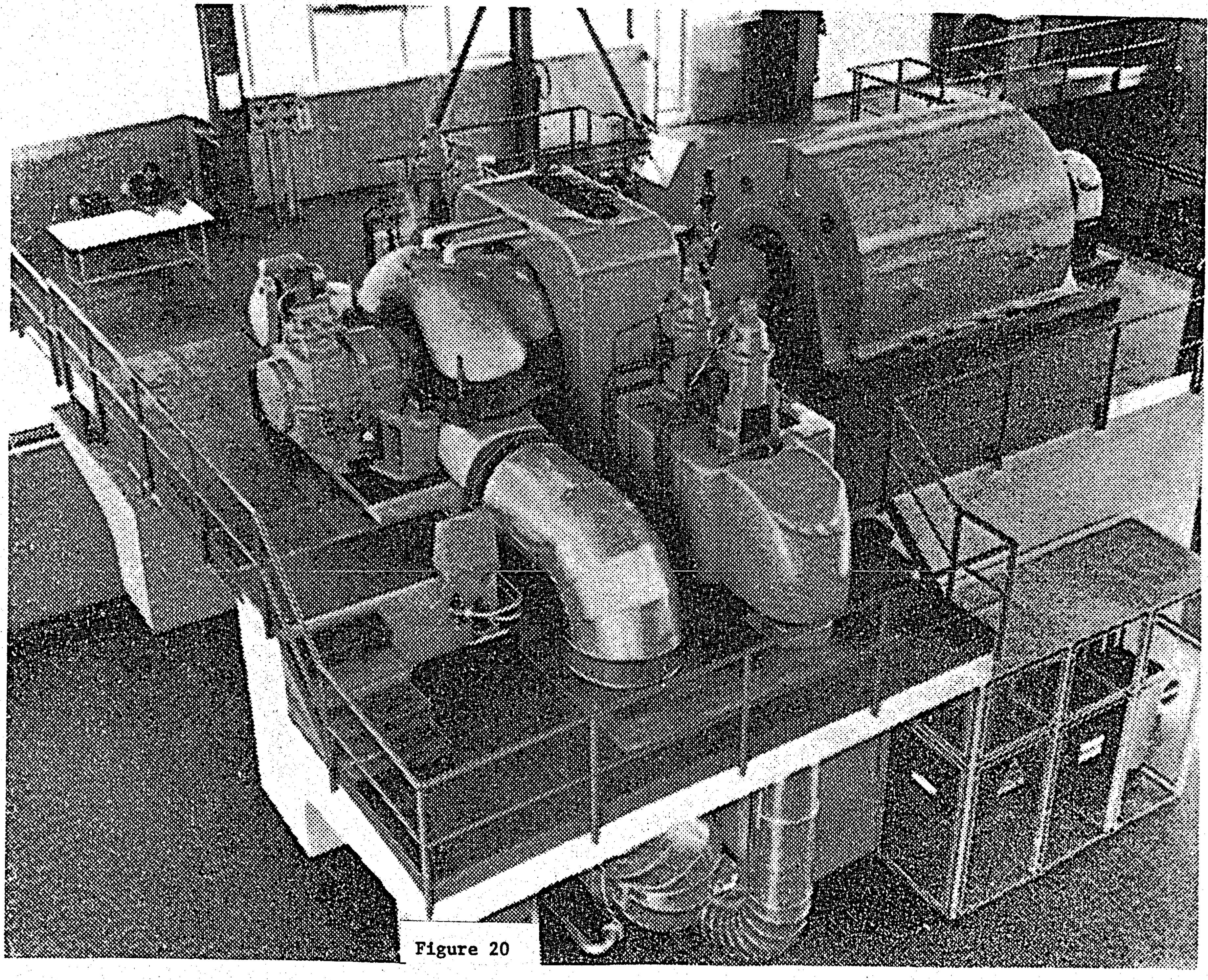


Figure 20

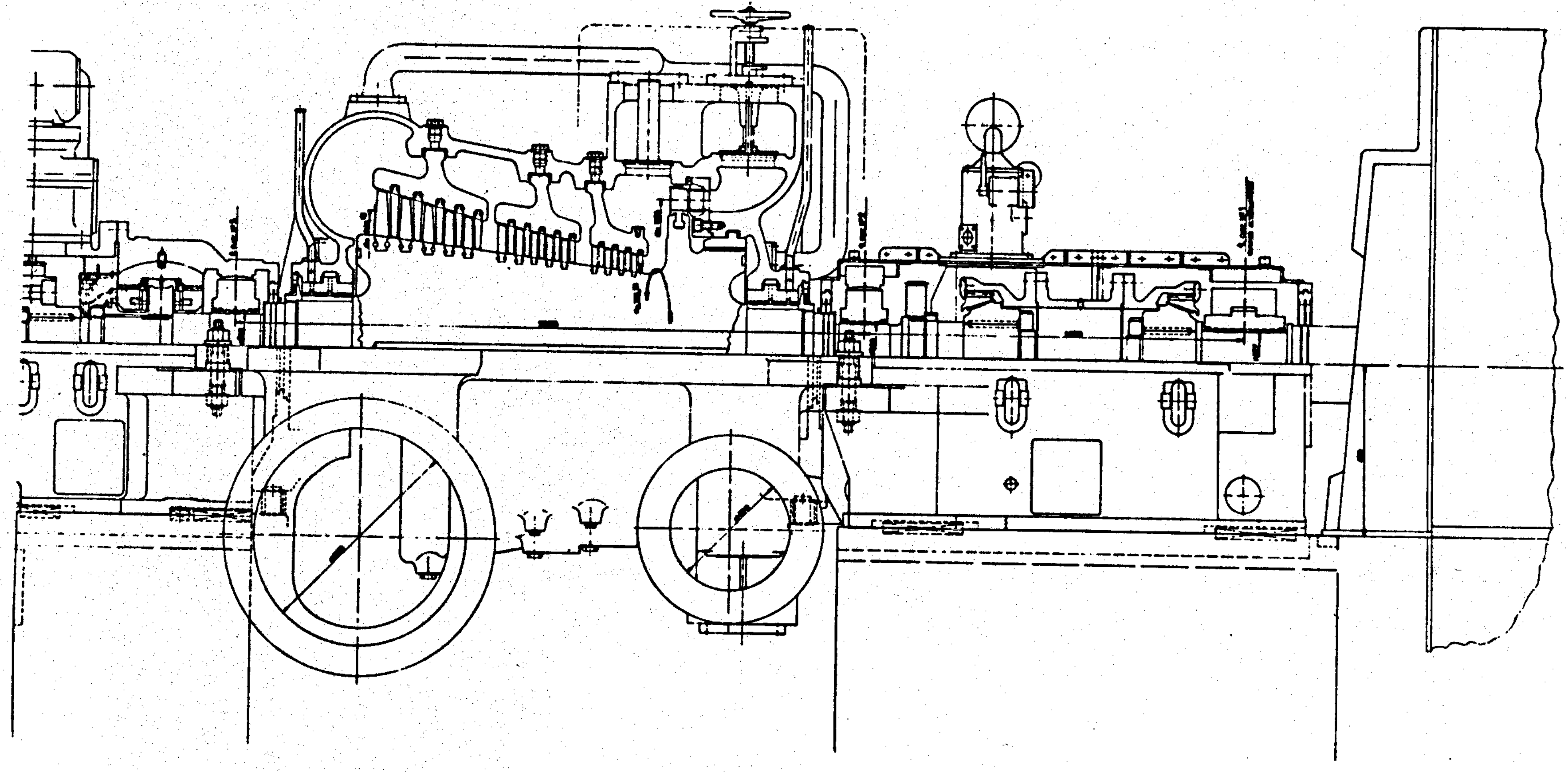


Figure 21

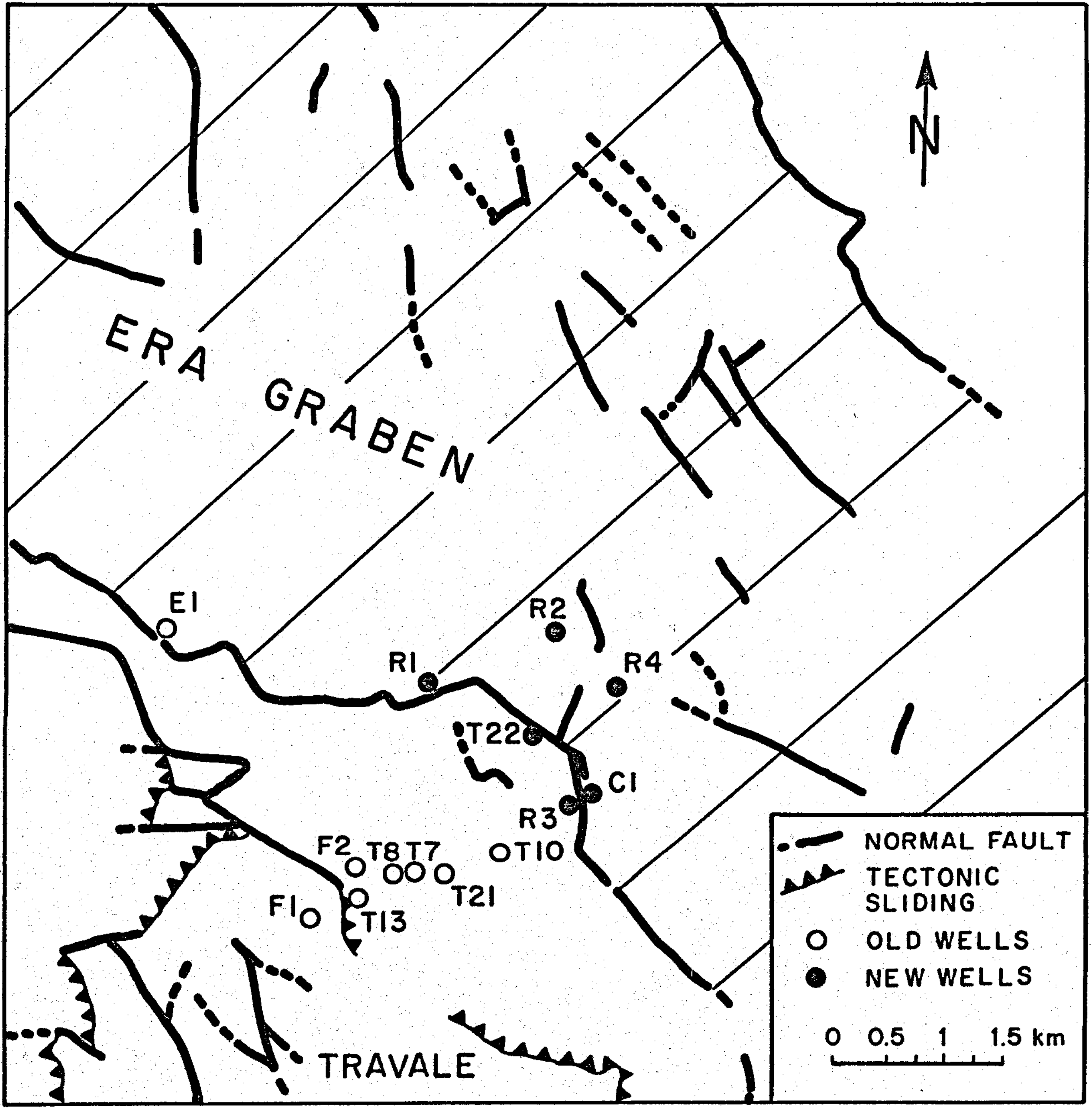

ERA GRABEN
N
E1
R2
R1
R4
T22
C1
R3
F2
T8
T7
T10
T21
F1
T13
TRAVALE
NORMAL FAULT
TECTONIC SLIDING
OLD WELLS
NEW WELLS
0 0.5 1 1.5 km

Figure 22