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**GEOTHERMAL POWER PLANTS OF JAPAN:
A TECHNICAL SURVEY OF EXISTING AND
PLANNED INSTALLATIONS**

By
Ronald DiPippo

March 1978

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

Brown University
Division of Engineering
Providence, Rhode Island

U. S. DEPARTMENT OF ENERGY
Geothermal Energy

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A Technical Survey of Existing and Planned Installations

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Abstract

This report surveys the technical features of the existing and planned geothermal power plants in Japan. A description is given of the Geothermal Energy Research and Development Co., Ltd. (GERD) which has capabilities in all areas of geothermal power development, from exploratory geological activities through construction and operation of the plants. The survey includes reports on four types of plants: natural, dry steam; separated steam or "single flash"; separated steam/flash or "double flash"; and binary fluid. For each geothermal power plant, the following are included or discussed: exploration and geology of the site; wells and gathering system; turbine-generator; condenser, gas extractor and cooling tower; economic data; environmental effects; and plant operations. Many tables and figures are included, and a summary is given of the geothermal resource utilization efficiency for each operating plant. Promising areas of new development are listed with estimates of potential capacity.

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1. Geothermal Energy Research and Development Co., Ltd. (GERD)

All research and development of geothermal energy resources in Japan is carried out by GERD, a consortium formed in November 1975 of twenty-five firms dealing in geothermal energy technology [GERD, 1975]. The associated companies are listed in Table 1. GERD works closely with the Ministry of International Trade and Industry in formulating and implementing Japan's Project Sunshine, the goal of which is to exploit the natural energy resources of the country, including geothermal energy [Sakakura, 1975].

The technical capabilities of GERD extend over the full spectrum of activities associated with geothermal energy from geological surveys and prospecting to heat utilization and electric power generation. The specific areas covered by the consortium include:

- R&D into new techniques for prospecting and for geothermal fluid production.
- R&D into environment preservation.
- R&D into methods of heat utilization.
- R&D into the manufacture of machinery and equipment for prospecting, drilling, production, utilization and power generation.
- Consulting services in all areas of geothermal energy exploitation.
- Gathering of information on geothermal technology abroad.

A typical geothermal energy development program as conducted by GERD consists in the following specific operations:

- Surface survey of the area.
- Estimation of reserves.
- Estimation of resource.
- Evaluation of the feasibility of geothermal development.
- Evaluation of the justification of test boring.
- Design of test wells.
- Test boring.

- Production of steam.
- Tests of geothermal fluid: physical and chemical tests.
- Refinement of estimate of reserves.
- Determination of production capacity per well.
- Calculation of geothermal development capacity.
- Formulation of the development program.
- Start of development operations.
- Installation of production facilities.
- Drilling of production wells.
- Securing of required amount of steam.
- Production control.
- Transportation of steam for power generation.
- Transportation of hot water for heat utilization.

The success of Japanese technology in geothermal energy can be seen from the fact that Japanese companies, notably Mitsubishi Heavy Industries and Tokyo Shibaura Electric Company (Toshiba), have supplied or have on order thirty-two (32) of a total of thirty-nine (39) geothermal turbine-generator units in the world (excluding the Soviet Union and Italy).

The remaining sections of this report will present the technical highlights and plant specifications for the geothermal power stations in Japan.

2. Matsukawa dry-steam power plant

The Matsukawa geothermal power plant was completed in 1966 by the Japan Metals and Chemicals Co., Ltd. It is located in Iwate Prefecture in the northern part of Houshu island. It is one of the few sites in the world where essentially dry, natural geothermal steam is used for electric power production. This was the first geothermal power plant to be installed in Japan. The turbine-generator is rated at 20 MW and was supplied by the Tokyo Shibaura Electric Co. (Toshiba). The power produced is supplied to the network of the Tohoku Electric Co., Ltd. A site photograph appears in Fig. 1. [GERD, 1975].

2.1. Geology and exploration

The Matsukawa Valley is a Quaternary composite volcano with a caldera. The southern margin of the caldera shows thermal outcrops and steam vents (fumaroles). The volcano sits on the andesite lava of yet another volcano, which in turn rests on a Tertiary basement. The surface manifestations result from fractures in the caldera and a deep-seated magmatic intrusion. The hydrothermal reservoir consists of porous beds in the upper portion of the Tertiary, with the Quaternary andesite lavas forming an overlayer [Saito, 1961].

In 1953 area residents began to drill wells in the hope of discovering a source of hot water to supply a health spa. Instead, many of the wells produced steam at depths from 160 - 300 m (525 - 984 ft) [Saito, 1961]. Since that time, numerous methods have been applied to discern the geological nature of the field including detailed geological mappings, geophysical prospecting by means of seismic and electric resistivity methods, and geophysical well-loggings [Sato, 1970; Nakamura, et al, 1970].

Prior to the construction of the power station, tests were run for 18 months on a 450 kW back-pressure turbine to assess the corrosion effects on various

materials from exposure to the geothermal steam and its condensate. Table 2 lists the characteristics of the geothermal steam and its condensate. Fourteen kinds of materials were tested. Table 3 shows the types of materials used for various components and the observed corrosion rate after about three years of operation [Akiba, 1970; Mori, 1970].

2.2. Gathering system and valves

Five wells supply geothermal steam to the plant. Four of these produce superheated steam at a running pressure of 441.2 kPa (64.0 lbf/in²) and at temperatures of 153, 170, 183 and 190°C (307, 338, 361 and 374°F). Recording instruments at each wellhead keep track of pressure, temperature, flow rate and degree of penetration (because of fine rock dust). One of the original wells was found to have a scale build-up which caused a steady, linear decrease in flow rate. Following a work-over of the well, the flow was increased somewhat but not to the full initial value.

Until 1973 all drilling was carried out with mud. With the failure of the No. 3 well at Matsukawa owing to erosion of the casing, air-drilling was initiated for the new No. 3 well. Mud was used to a depth of 815 m (2673 ft), while air was used from there down to 1170 m (3838 ft). The new well produces 70 Mg/h (0.154×10^6 lbm/h) [Iga and Baba, 1974].

The total length of steam pipe is 2.2 km (7218 ft). The pipelines are inspected periodically with thickness gauges at points of high erosion such as bends. Since air tends to enter the pipe during shutdown, the steam is kept flowing even when the plant is down for inspection or maintenance to prevent oxidation. Any pipes or valves which are exposed to the atmosphere tend to corrode rapidly.

The main problem with valves is that they stick. Gate and butterfly valves are used, but it is difficult to secure proper seating. Even though

spring-loaded valves are used for safety valves, these also tend to stick and require periodic rapping to maintain them in working condition.

2.3. Turbine-generator

A schematic heat balance diagram is shown in Fig. 2 [Akiba, 1970] and the technical specifications of the main mechanical components are given in Table 4.

The 4-stage, impulse turbine uses blades of 12% chrome with a carbon steel casing. Early operation encountered damage caused by mud and dust deposits. After about 50 days of operation, in January 1967 the unit was forced out of service by abnormal vibrations. Upon inspection, it was found that 82 buckets of the fourth stage were damaged, the shroud and bucket tennons of the third stage were worn out and that the entire third and fourth stage blades and nozzles were embedded in mud. The mud was formed by the moisture present in the last two turbine stages coming in contact with an excessive amount of dust that had been expelled from one of the wells. The well was identified and disconnected.

The blade failures were attributed to a change in the natural frequency of vibration which is normally far in excess of the nozzle-passing frequency. The encrustation of mud and scale caused the natural frequency to reach that of the nozzle-passing frequency, leading to vibration fatigue. The fatigue strength of the blades, furthermore, is reduced owing to the corrosive atmosphere.

Scale was observed in a number of locations:

- inside steam receiver at branch point of pipeline
- drain separator
- main parts of main stop valve and control valve.
- steam inlet part of turbine casing
- drain pipe from nozzle diaphragm

- steam path through nozzle
- outside perimeter of diaphragm
- effective part of buckets
- inner surface of shroud
- gland packing and wheel of rotor.

The composition of the scale from parts of the turbine is given in Table 5 [Akiba, 1970]. These elements formed such compounds as SiO_2 , CaSO_4 , NaSO_4 , Al_2O_3 , MgO , FeSO_4 and FeS . The decrease in SO_4 , Na and K is attributed to their solubility in the moisture of the last stages of the turbine. The insoluble SiO_2 is believed to be flushed out mechanically by the condensed steam.

The turbine is coupled to an air-cooled generator with a rating of 23,500 kVA, a 0.85 power factor, 11 kV, 3000 rpm and with a static excitation system.

2.4. Barometric condenser

The condenser is of the direct-contact, barometric type and is designed to condense 194 Mg/h (0.428×10^6 lbm/h) at a vacuum of 12.7 kPa (3.74 in Hg), absolute pressure. The condenser is located outside the power house; it is made of carbon steel plate lined with stainless steel and coated with epoxy paint on the inside surfaces. The shell is 4.7 m (15.4 ft) in diameter and is 10.3 m (33.8 ft) in height.

The tail pipes of the inter- and after-condensers for the gas extraction system are now made of stainless steel to protect them against corrosion. Originally these were of carbon steel, but failed from corrosion and led to loss of vacuum in the condenser.

2.5. Water cooling tower

The water cooling tower is of the natural draft type, the only one of its

kind in use for Japanese geothermal power stations. It has a ground-level diameter of 45 m (147.6 ft), a height of 44.6 m (146.3 ft), and is sheathed with 10 cm (3.94 in) thick vacuum concrete panels set to steel pipe shells. The tower is fitted with 1.6 m (5.25 ft) of plastic packing. Water is distributed by means of steel pipes with plastic spray nozzles.

Make-up water is obtained from the Matsukawa River. Some trouble has been experienced at times when the screens are unable to trap all the dust and sediment. Such contaminants can foul and clog the spray nozzles, thereby lowering the efficiency of the cooling tower. This tends to occur at flood time.

Since the ambient temperature during the winter can be as low as -25 to -5°C (-13 to 23°F), it is necessary to cover the draft ports with covers to control the flow rate of air through the tower to prevent freezing.

2.6. Electrical equipment

The main step-up transformer is rated at 23,500 kVA, 11 kV/155 kV, 3-phase, 50 Hz; the plant auxiliaries are fed from a 2500 kVA transformer, 11 kV/3.5 kV, 3-phase. The electrical power from the plant is fed to the grid of the Tohoku Electric Power Co., Ltd. by means of a 20 km (12.4 mi), 155 kV transmission line.

Because of the extremely corrosive atmosphere in the vicinity of the power house, the substation is located about 600 m (0.4 mi) from the plant in an area where the concentration of H_2S is extremely low. Main electrical equipment is sealed in oil-filled containers; terminals are coated with conductive grease; bare wires are made of aluminum; and supporters are coated with anti-rust paint. It is difficult to protect meters and relays from the corrosive action of the atmosphere by anti-rust paint coatings because this tends to cause sticking. Since the trip time for a relay is crucial for the safety of the plant, movement tests of all relays are conducted more frequently than in a conventional

power station. The concentration of H_2S in the turbine room is between 0.06 and 0.40 ppm [Sato, 1970].

2.7. Environmental effects

Water is taken from the Matsukawa River for purposes of cooling water make-up and water tower blow-down. The Akagawa River which is adjacent to the plant receives the excess condensate. There are no controls on the emission of hydrogen sulfide. The main steam contains between 0.03 and 0.11% (by volume) H_2S . The 2-stage steam jet ejectors remove the H_2S and the other noncondensable gases and discharge them to the atmosphere through the 45 m (147.6 ft) high cooling tower. The concentration of H_2S in the atmosphere is described [Sato, 1970] as exerting "no remarkable influence" on the power plant. The specific emissions level of H_2S from the plant ranges from 5050 - 20,800 g/MW·h, a moderate-to-high level of emissions.

2.8. Reliability

In 1973 the Matsukawa plant produced 181,070 MW·h of electricity [Iga and Baba, 1974]. This is equivalent to a capacity factor of 94%, based on 22 MW installed capacity. The average power output was 20.7 MW; the plant has a rated capacity of 20 MW. This type of operation is typical of a highly-reliable, base-load power station.

2.9. Economic data

The construction cost of the Matsukawa geothermal power plant was about 1.5 to 2 times as large as for a thermal power station per kW installed. The higher costs resulted from the added expenses associated with building a plant in a very rugged region and having the geothermal wells separated widely. The figures below show the construction costs in 1968 Yen [Nakamura, S., 1970]:

Geological surveys and exploration.	160 million Yen (1968)
Steam wells	439 million Yen (1968)
Steam gathering system.	193 million Yen (1968)
Buildings	216 million Yen (1968)
Cooling tower	357 million Yen (1968)
Power generation equipment.	407 million Yen (1968)
Substation.	170 million Yen (1968)
Incidental equipment.	49 million Yen (1968)
Interest and other related costs.	66 million Yen (1968)
<hr/>	
Total.	2057 million Yen (1968)
	(~ \$6 million, 1968)

This is about \$285/kW in 1968 dollars.

The cost of electricity for one of the early years of operation turned out to be 2.63 Yen/kW·h (~ 7 mill/kW·h). This was roughly equivalent to the cost of electricity from fossil-fuel power plants at that time. In the light of the fact that fossil-fuel costs have increased by a factor of 3 or 4 since then, it is clear that at present the cost of geothermal electricity from the Matsukawa plant is considerably less than from a fossil plant.

3. Otake separated-steam (single-flash) power plant

The Otake geothermal power plant was the second to be commissioned in Japan, having come on-line in August 1967. It was the first central station to use a liquid-dominated hydrothermal reservoir outside of the Wairakei plant in New Zealand. Otake is rated at 10 MW, with a maximum capacity of 13 MW. The Kyushu Electric Power Co., Inc. owns and operates the plant. Site photographs are shown in Figs. 3 and 4 [MHI, 1976 (A)].

3.1. Geology and exploration

The highly volcanic region near Mt. Aso on the island of Kyushu, Oita Prefecture, is the site of the Otake power station. Mt. Aso is an active volcano of the caldera type.

Exploration began with several test bores in 1949 and 1953. These wells showed that the reservoir was liquid-dominated, yielding a mixture of steam and liquid. The exploitation of such fields, in contrast to dry steam fields, was unknown at that time. Thus, the Otake field lay unused until the experience at Wairakei, New Zealand showed that such fields could be tapped to produce electricity. Renewed investigations began in 1961; five additional wells were sunk from 1963 to 1966. Geological surveys and geophysical exploration were conducted [Hayashida and Ezima, 1970]. These included magnetic, electrical, gravimetric and seismic methods. It was estimated that a power plant of at least 10 MW could be built and supplied with the steam available.

3.2. Steam wells and gathering system

The plant receives steam from five production wells which range in depth from 350 - 600 m (1150 - 1970 ft). Originally three reinjection wells were used for disposal of the geothermal condensate, but recently a program has gotten under way to increase the number of reinjection wells. The location of the production

and reinjection wells is given in Fig. 5; the casing program is given in Fig. 6 for four producing wells and the original three reinjection wells [Kubota and Aosaki, 1975]. Details of the wellhead apparatus are shown in Fig. 7a and a schematic of the steam separator equipment is given in Fig. 7b [MHI, 1976 (B)].

Approximately $3,800 \text{ m}^2$ ($41,000 \text{ ft}^2$) comprises the area of the gathering system with three main steam lines of about 900 m (2950 ft) in total length and having a maximum diameter of 700 mm (27.5 in).

A thorough investigation was conducted of the site and reservoir characteristics for about eighteen months prior to the decision to construct a power plant. The wellflows were traced for one year. The optimum turbine inlet pressure was selected at 245.1 kPa (35.6 lbf/in^2) in order to yield the maximum power output while guarding against power drop-off in the future in the case of scale build-up on the turbine nozzles. Since scaling of nozzles results in higher working pressures, the pressure chosen is somewhat less than the exact value corresponding to the power peak. To produce the desired turbine inlet pressure, the pressure at the outlet of the separator must be 303.9 kPa (44.1 lbf/in^2) [Usui and Aikawa, 1970].

Table 6 gives the characteristics of the geothermal fluid. The amount of noncondensable gases is relatively low (0.2%) and the hydrogen sulfide concentration is also low (~ 25 ppm of steam), with the bulk of the noncondensable gases being carbon dioxide [Kawasaki, 1977].

3.3. Turbine-generator

The schematic for the power plant is given in Fig. 8 [MHI, 1976 (B)]. The technical specifications of the major mechanical components are listed in Table 7.

The turbine was built by Mitsubishi Heavy Industries, Ltd. and is a single-cylinder, single-flow, 4-stage, impulse machine. It is rated at 10 MW (13 MW maximum capacity), turns at 3600 rpm and accepts essentially saturated steam at 127°C (261°F) and 245 kPa (35.6 lbf/in²). The turbine is shown in a cut-away sectional view in Fig. 9 [MHI, 1976 (B)].

To cope with the high moisture content of the steam, the turbine's last stage is fitted with a recessed stellite strip and each stage has a drain catcher. Liquid droplets are induced to travel to the periphery by centrifugal force which is enhanced by a higher-than-normal velocity ratio, i.e., wheel velocity/steam velocity, leading to a higher whirl component for the steam. There was no erosion of turbine blades at the first two-year overhaul after 16,830 hours of operation.

Two main steam stop valves of the swing-check type are located on either side of the turbine thereby allowing a steam-free test under full-load conditions. In series with the main steam stop valves are regulating valves of the butterfly type. Since the valves in geothermal plants are subject to sticking because of the deposition of scale and since base-load operation means full, rated flow nearly always, the regulating valves were designed to move over a large range of angle openings in the vicinity of full steam flow. Thus small departures from full-load operation result in reasonably large angular movement of the regulating valves which tends to keep the valves freely moving. Figure 10 shows the steam flow-regulating valve characteristic curve. It is believed [Usui and Aikawa, 1970] that this is the first steam turbine to be controlled with a butterfly-type regulating valve from zero speed to full load.

The generator was built by the Tokyo Shibaura Electric Co., Ltd. (Toshiba) and was used previously at another power station of the Kyushu Electric Power Co. It is of the horizontal, cylindrical, rotating field type, air-cooled,

rated at 15,000 kVA, 6.6 kV, and a power factor of 0.9.

3.4. Barometric condenser

The condenser is of the direct-contact, barometric type. It is situated outside the power house, about 10 m (33 ft) above the hot well. The pressure is 9.8 kPa (2.90 in Hg), the cooling water enters at 26°C (78.8°F) and leaves at 41.4°C (106.5°F), and the cooling water flow rate is 3900 Mg/h.

A cross-sectional view of the condenser is shown in Fig. 11 [MHI, 1976 (A)]. There are four spray trays, with the top two serving as gas coolers. The basins of the top three trays are made of stainless steel since they are exposed to the most corrosive fluids and cannot be coated with epoxy paint owing to the presence of small spray holes.

The gas extractor is a set of three motor-driven, reciprocating vacuum pumps, each of which is rated at 110 kW. A steam-jet gas extractor was considered and rejected owing to the low pressure of the geothermal steam which would have required about 6 Mg/h (13,000 lbm/h), an amount of steam equivalent to 600 kW of electrical output from the plant. The reciprocating type pump was selected, in spite of the additional maintenance, over other types (e.g., axial blower, radial blower, Nash pump, water ejector, Roots blower and screw pump) because it was the most effective from the standpoints of operating range, efficiency, number required and cost. The limitation in capacity of reciprocating pumps was not a handicap since the amount of noncondensable gases is small (0.2%) in the case of Otake.

3.5. Water cooling tower

The plant uses a 3-cell, cross-flow, mechanically induced draft cooling tower. The relatively low profile of this type was an advantage over the taller natural draft type since the plant is located in a scenic area, the

Aso National Park. The tower receives 4233 Mg/h (9.33×10^6 lbm/h) at 41.4°C (106.5°F) and cools it to 26°C (78.8°F) at a design wet-bulb temperature of 17°C (62.6°F). The wet-bulb temperature at Otake reaches a maximum of 22°C (71.6°F) during the summer; the yearly average is 13°C (55.4°F). A small amount of make-up water (22 Mg/h (48,500 lbm/h)) is taken from the nearby Kusu River for blow-down purposes.

The cells are constructed of ferro-cement and have vinyl chloride elements. Each cell is fitted with a 6-bladed propeller of 5.7 m (18.7 ft) diameter to extract the cooling air. The total air flow is 49,500 m³/min (1.75×10^6 ft³/min); the three fans consume about 200 kW under normal operating conditions.

3.6. Materials of construction

Table 8 lists the main elements of the plant that are exposed to the geothermal fluid and their materials of construction. The selection of appropriate materials was made after one year of testing twenty types of material and paint for anti-corrosiveness, stress corrosion and scale deposition.

3.7. Environmental effects

The total area occupied by the Otake power plant is about 8600 m² (2.12 acres), which includes 4800 m² (1.18 acres) for the power station and 3800 m² (0.94 acres) for the steam wells and gathering system. The power house takes up 393 m² (4,230 ft²). The plant was designed in such a way as to blend as well as possible into the scenic surroundings of Aso National Park.

Since the condensate from the geothermal steam is recirculated to provide cooling water for the plant, there is no need for large quantities of external water. There is a need, however, for make-up water to prevent the accumulation

of acid-laden water in the cooling tower basin; 22 Mg/h (48,500 lbm/h) is drawn from the Kusu River.

Wells No. 6 - 10 produce 505 Mg/h (1.11×10^6 lbm/h) of which about 432 Mg/h (0.95×10^6 lbm/h) must be disposed of by means of reinjection. Gravity feed is used out of fear of inducing seismic activity. Originally three wells served for reinjection, but these have not been adequate and a program is now going forward to drill additional wells for this purpose. The importance of careful selection of reinjection wells is recognized, and more exploration techniques are being brought to bear on the problem.

There are no controls on the emissions of hydrogen sulfide, with the full amount being discharged through the reciprocating vacuum pumps to the atmosphere. The specific amount is not large, however, amounting to about 542 g/MW·h, based on a concentration of 48 mg/kg of main steam, 113 Mg/h of turbine steam flow and 10 MW output.

3.8. Reliability

Since August 12, 1967, the date of commissioning, the Otake power plant has averaged an availability factor in excess of 95%.

3.9. Economic data

The capital investment for the Otake plant was \$3.27 million (1968 dollars) or about \$300/kW installed. At a load factor of 90%, the cost of electricity was 7.1 mill/kW·h (1968) [Hayashida and Ezima, 1970].

4. Onuma separated-steam (single-flash) power plant

The power plant at Onuma was the third to be completed in Japan and the second of the liquid-dominated type. The plant was completed and began operations in December 1973. It was built by and is operated by the Mitsubishi Metal Corporation to supply electricity to one of its metal processing mills. The plant is located in the northern part of the main island of Houshu in Akita Prefecture in the Towada-Hachimantai National Park. The turbine is rated at 10 MW. A site photograph is given in Fig. 12 [MHI, 1976 (C)].

4.1. Geology and exploration

The Onuma plant, like its neighbor at Matsukawa, is situated in a Quaternary volcanic region. The area is dotted with surface manifestations of subterranean magmatic activity, such as fumaroles, active volcanos and hot springs. Prospecting and development began in 1965, with construction commencing in 1970.

4.2. Steam wells and gathering system

The geothermal wells are drilled from central platforms with inclination to allow wellhead equipment to be grouped together so as to minimize land usage and to avoid unnecessary replication of equipment. The wells are so inclined that the well-bottoms are located 150 m (492 ft) away from the drilling platform, measured horizontally at ground level [MHI, 1976 (C)].

4.3. Turbine-generator

The steam turbine is similar to that installed at Otake with the following principal exceptions: speed = 3000 rpm, last-stage blade height = 500 mm (19.7 in). The inlet and exhaust conditions are essentially identical to those at Otake. The Onuma turbine is located on the ground floor of the power house with the exhaust duct directed upward and leading outdoors to the barometric condenser.

By placing the turbine at ground level and auxiliaries beneath the floor, it was possible to achieve a very low roof elevation for the power house. It was desirable to maintain a low profile for the power plant buildings since the station is situated in a scenic national park.

The generator is rated at 12,500 kVA, 6.6 kV, 0.8 power factor and is air cooled. The step-up transformer is rated at 12,000 kVA and feeds power to the transmission line at 66 kV. The power is used at the Akita Mills metal processing plant of the Mitsubishi Metal Company.

Figure 13 gives a simplified schematic of the plant [MHI, 1976 (C)]; Table 9 lists the technical specifications of the major mechanical components of the plant.

4.4. Heat rejection system

The condenser, gas extractor and cooling tower are similar to those at the Otake power plant, and do not require additional comment. A reinjection system is in operation to dispose of the hot water produced at the wellhead separators and the excess water from the cooling tower.

During the initial trial operation of the plant, a portion of the hot water liquid was used in a heat exchanger to produce hot water for local use. At that time about 12 - 15 Mg/h ($26 - 33 \times 10^3$ lbm/h) was distributed while the plant was operating at about half-capacity at 5 - 6 MW [Iga and Baba, 1974].

5. Onikobe dry-steam power plant

The 25 MW power plant at Onikobe was the fourth to be built in Japan. In March 1975, the plant was turned over to the Electric Power Development Co., Ltd. by Kawasaki Heavy Industries, Ltd. who constructed all the major plant elements except for wellhead equipment, steam transmission pipelines and the substation. The plant is located in Kurikoma National Park in Miyagi Prefecture on the northern part of Houshu island, about 120 km (75 mi) south of the Matsukawa-Takinoue region. A site photograph is given in Fig. 14 [Kawasaki, 1975].

5.1. Geology and exploration

The Onikobe reservoir is likened to that of Wairakei, New Zealand. Faults in a Miocene and granite basement allow high temperature fluids to reach from depth to the overlying Pliocene beds of porous rocks, which form the hydrothermal convective reservoir containing ground water.

The area is an elliptical basin, 10×8 km (6×5 mi) across the axes. A major part of the subsided area was filled by a lake from the Pliocene to the Pleistocene epoch. Exposed pre-Neogene granite and a thick series of Miocene rocks make up most of the subsided area. The rocks are mostly volcanic and partly sedimentary.

The total thickness of the formation is about 300 m (984 ft) and consists of a lacustine formation in loose deposits of: conglomerate, andesitic tuff-breccia and tuff, pumiceous tuff of dacitic nature and mudstone from the base-upwards [Saito, 1961].

Although the region is a Quaternary volcanic zone, there are no active volcanos present; the usual surface manifestations (e.g., hot springs, fumaroles, solfataras and geysers) are scattered throughout the area. Early exploration

included a topographic survey and a geological mapping in 1955, and the drilling of three test bores to depths of 255, 250 and 192 m (836, 820 and 630 ft) [Nakamura, 1959].

The general environment of the site is quite hostile to power station operation. The altitude of the site is 530 m (1738 ft) above sea level, winter snowfall exceeds 2 m (6.6 ft), ambient temperature ranges from - 15 to + 30°C (5 - 86°F), the natural concentration of hydrogen sulfide in the air is 0.2 ppm, and the neighboring brooks are extremely acidic with pH of 2-3. Thus the effects of corrosion and erosion place severe design constraints on the Onikobe power plant [Kawasaki, 1977].

5.2. Steam wells and gathering system

Although the plant began operation with nine production wells, the number has been increased to twelve. The characteristics of the geothermal fluid are given in Table 10. The hydrogen sulfide concentration is the highest of any geothermal power plant now in operation.

The geofluid is essentially saturated vapor with a small amount of liquid entrained. Separators are used at the wellheads and at the power house to remove the liquid droplets. Steam is collected at the station header where its pressure is controlled by an electro-hydraulic regulating valve. Two main steam lines conduct the working fluid to the turbine.

The production from the wells has been only half of what was expected. Furthermore, the actual well characteristics of pressure versus flow rate have turned out to differ from the designed values. Attempts to correct for these deficiencies are described later (See Sect. 5.5.).

5.3. Turbine-generator

Kawasaki Heavy Industries, Ltd. built the steam turbine which is a 5-stage, impulse-reaction, single-cylinder, single-flow machine rated at 25 MW at 3000 rpm.

The generator was furnished by Fuji Electric Co., Ltd., and is rated at 28,000 kVA, 11 kV, power factor of 0.9 (lagging), horizontally-mounted, revolving field, self-ventilated, enclosed duct circulating type with air cooler [Kawasaki, 1974].

A schematic of the plant is given in Fig. 15; a listing of the technical particulars of the major mechanical elements is given in Table 11; and Figure 16 shows the turbine assembly in cross-section [Kawasaki, 1977].

Owing to the very high levels of hydrogen sulfide in the working fluid, extensive corrosion fatigue tests were conducted on the materials for the turbine rotor and blades. These tests were in addition to the usual static corrosion tests. Fatigue strength decreases markedly in the presence of a corrosive atmosphere. Thus, absolutely no resonance could be allowed in the turbine and all blades for each of the five stages were designed to avoid resonance with any excitation force. In addition, the static steam bending stress was set at a value one-half that allowed in conventional steam turbines.

Stellite plates were silver soldered to the leading edge of the first-stage blades to prevent erosion by dust particles entrained in the steam. Titanium, with its outstanding anti-corrosion characteristics, was used in the rotor shaft glands because of their exposure to geothermal steam and air leakage.

The turbine was forced to shut down in May 1975, only two months after it had begun operation. A new well had been connected to the plant and an excessive amount of scale was carried over and deposited on the nozzles and blades of the first stage. Excessive vibrational stress resulted when the leading edge of the blades came in contact with the deposited scale, leading to the breaking of one blade and the cracking of eleven others. Following an overhaul, there has been no repetition of this problem and indeed no scale build-up has been observed.

5.4. Heat rejection system

The Onikobe plant uses fairly conventional equipment to handle the problem of heat rejection. There is a barometric condenser, a gas extraction apparatus which consists of one set of two steam jet ejectors (in parallel) working to maintain vacuum in the barometric condenser, a motor-driven vacuum pump which removes noncondensable gases from the inter-condenser, and a counter-flow, mechanically induced draft water cooling tower. The plant originally was designed and operated with two sets of steam jet ejectors, but the second set was replaced by the vacuum pump in October 1975.

The inner surface of the condenser is coated with a neoprene lining which had proved to be superior to epoxy paint with regard to anticorrosion and wearability. During the May 1975 overhaul, it was observed that part of the lining had separated from the condenser wall near the bottom. This was attributed to the direct impingement of hot water and a lack of adhesion. Some minor improvements solved this problem.

Some of the spray nozzles of the cooling tower had been attacked by corrosion and erosion and had fallen off. Repairs and improvements in the manner of fixing the nozzles to the header solved this problem.

In October 1975, the sleeve on the circulating water pump was replaced; the new one is fabricated from 304 stainless steel whereas the original one (which had heavy pitting) was made of 403 stainless steel.

A summary of the fouling experience of the plant is given in Table 12.

5.5. Operations

The Onikobe plant maintained an average availability of 93.7% for the first seventeen months of its operation. During this period, the plant was shut down twice for improvements, twice for inspection according to the regulations of the Ministry of International Trade and Industry and twice for

periodic inspection.

The output of the plant started at about 9 MW and rose to about 13 MW after seventeen months. Owing to the disappointing production from the steam wells, the plant is operating at about half of its design capacity, albeit very reliably. In October 1975, two improvements were carried out to boost the output. First, the second set of steam jet ejectors was replaced by a motor-driven vacuum pump. Second, the nozzle of the first stage of the turbine was redesigned to correspond more closely with the actual steam conditions. These changes resulted in an increase of about 10% in plant output. However, steam production remains at about 120 Mg/h (0.264×10^6 lbm/h), far below the design value of 219.5 Mg/h (0.484×10^6 lbm/h).

5.6. Environmental effects

All waste liquid (e.g., drains from separators, turbines and other pieces of equipment plus overflow from the cooling water basin) is collected in a drain pond and reinjected into the formation.

Hydrogen sulfide is released to the atmosphere without controls. The concentration of H_2S in the turbine room is 0.40 ppm, in the control room it is 0.050 ppm, and outside the plant it is 0.20 ppm. Since the main steam contains about 3400 mg/kg, the specific emission level is approximately 31,400 g/MW·h, an extremely high value.

Owing to the fact that Onikobe is located within the Kurikoma National Park, special consideration was given to design features to help the plant blend into its scenic surroundings, including colors and low height of buildings and components and restricted sound levels.

6. Hatchobaru separated-steam/flash (double-flash) power plant

The geothermal power plant at Hatchobaru is the most advanced steam plant to be built in Japan. It incorporates the following novel features: (1) two-phase transmission of geothermal fluid; (2) so-called "double-flash" operation (actually one separation followed by a flash process); (3) low-level jet condenser; and (4) so-called "ERR system" gas extractor (steam Ejector followed by two Radial blowers). It is the fifth geothermal station to become commercial in Japan, having gone on-line in June 1977. The power rating is 50 MW; the Kyushu Electric Power Co., Inc. owns the plant. Hatchobaru lies about 2 km (1.2 mi) south of Otake not far from the active volcano Mt. Aso in the Oita Prefecture on the island of Kyushu. Figure 17 is a view of the plant [MHI, 1977 (B)].

6.1. Geology and exploration

The geology of the area is similar to that of the Otake site (See Sect. 3.1.). A good deal of testing of the features which ultimately were incorporated in the Hatchobaru plant was performed at the Otake site as early as 1965 [Aikawa and Soda, 1975].

6.2. Gathering system and two-phase fluid transmission

A plan view of the gathering system is given in Fig. 18, showing seven producing wells and four reinjection wells. At this writing, the drilling program is still in progress and additional wells are being sunk. Eventually eight wells are planned for reinjection purposes.

The seven producing wells are 194 mm (7.625 in) in diameter and range in depth from 920 to 2000 m (3018 to 6560 ft); the eight reinjection wells are of the same diameter and extend from 740 to 2000 m (2427 to 6560 ft). Each well-head is equipped with a simple U-bend separator to allow easy and stable

operation during start-up of the well.

The most unique feature of the Hatchobaru plant is the method of transporting the geothermal fluid to the power house. There are essentially three possible ways to carry out this operation in a double-flash plant:

- (1) Steam-only transmission;
- (2) Separate steam and hot water transmission;
- (3) Two-phase mixture transmission.

In the first case, parallel main and secondary steam pipelines must run from each well to the power house. Although this concept is simple, it has some serious disadvantages:

- (a) Secondary steam pipelines are very large, expensive, and must extend long distances;
- (b) Waste hot water must be piped from each well to the disposal site and such pipes are subject to scaling;
- (c) Separators and flash tanks must be located at each well;
- (d) Maintenance of scattered wellhead equipment is a problem.

In the second case, the main steam is separated at the wellhead and both the steam and the hot liquid are piped separately to the power house where the liquid is flashed to produce the secondary steam. While the number of flash tanks is reduced and the size of the liquid pipeline is smaller than a secondary steam line, there are still disadvantages to this method:

- (a) Waterhammer will occur in the liquid pipeline;
- (b) Static pressure will fall in the liquid leading to flashing and scale deposition;
- (c) Hot water pipes cannot be joined on the way to the power house;
- (d) Pumping of the liquid will be required unless the wellheads are located at a higher elevation than the power house.

In the last case, the entire steam-liquid mixture is transmitted to the station in a single pipeline. This technique does not automatically eliminate the possibility of waterhammer or scale deposition, and there is a danger of large pressure losses. However, this method does offer the following distinct advantages over the previous two methods:

- (a) Only one pipeline is needed between each well and the power house;
- (b) Pipelines may be joined from several wells on the way to the power house;
- (c) Various piping arrangements are possible including upward inclined pipes;
- (d) Separator and flasher are centrally located at the station for ease of maintenance;
- (e) A small number of separators and flashers will serve many wells;
- (f) Only one waste hot water pipeline to disposal is needed.

Extensive field tests were conducted by MHI beginning in 1965 and included tests at Otake (well No. 5, 1966) and Hatchobaru (well No. 1, 1970) which convinced MHI of the superiority of the two-phase transmission system for the Hatchobaru plant [Takahashi, et al, 1970].

Pressure loss was greater for the two-phase pipeline than for the single-phase steam pipeline. However, a portion of the loss can be recovered in the two-phase case since the amount of steam is increased from the separator; pressure loss in the steam-only pipeline means a direct loss in power output.

Severe conditions were imposed to ascertain whether the mixture could be caused to exhibit waterhammer. The data are summarized below:

pipe diameter	300 mm (11.8 in)
pipe length	200 m (656 ft)
pipe inclination.	7°
mixture pressure.	549.1 kPa (79.6 lbf/in ²)

mixture velocity.	58 m/s (190 ft/s)
steam flow rate	42 Mg/h (92.6×10^3 lbm/h)
liquid flow rate.	118 Mg/h (260.0×10^3 lbm/h)

A swing check valve was installed at the end of the pipe to simulate a main steam stop valve. At the instant the valve was slammed shut, the maximum pressure rise was only 117.7 kPa (17.1 lbf/in^2) or about a 21% increase in pressure. No waterhammer was observed along the pipeline.

The pressure-loss tests conducted at Otake showed losses of 0.7 kPa/m ($0.03 \text{ (lbf/in}^2\text{)/ft}$) for a typical pipeline consisting of a bend, a horizontal section, a U-bend, an upward-inclined section and a vertical down-comer. Clearly, care should be taken to reduce such losses in the design of the mixture pipeline.

There are several key factors which will influence the decision on whether or not to install a two-phase transmission pipeline. These are site-specific in nature and include: wellflow characteristics, distance between wells and power house, and geographical characteristics [Aikawa and Soda, 1975].

6.3. Turbine-generator

The turbine is of the mixed-pressure type with main steam admitted to the first two stages, secondary steam entering between the second and third stages, mixing with the main steam and the full flow continuing through the last three stages. The machine is of the single-cylinder, double-flow, impulse-reaction type.

The main steam is produced from two sets of separators located just outside the turbine room. They are of the vertical cyclone variety with bottom steam outlet and yield steam with a quality in excess of 99.9%. They are designed for an operating pressure of 725.5 kPa (105.2 lbf/in^2).

The secondary steam is flashed from the separated hot water from the separators. The flash tank is a horizontal drum, operating at a pressure of 108.8 kPa (15.8 lbf/in²), producing steam with a quality greater than 99.9%.

A simplified plant schematic is shown in Fig. 18. Table 13 lists the specifications of the major mechanical components of the station.

Both the primary and secondary steam inlets are fitted with two main stop valves and two control valves. All stop valves are of the swing check type; the control valves are of the butterfly type. The turbine speed and the flash-tank pressure are both controlled by the butterfly valves on the secondary steam line.

The generator is of the horizontal cylindrical rotating field type, is rated at 55,000 kVA and is equipped with hydrogen cooling.

6.4. Condenser and gas extraction apparatus

For the first time in a Japanese geothermal power plant, a low-level, jet condenser is used. The unit is set below the turbine-generator within the concrete foundation. It is compact and allows the height of the power house to be kept down. The condenser arrangement is shown in Fig. 19a. The right side of the unit is the gas cooler section leading to the gas extraction apparatus. The walls of the concrete condenser are coated with polyester resin to protect the surfaces from the corrosive action of the condensate. It is felt [Aikawa and Soda, 1975] that this new, compact design will remove one of the impediments to larger-sized geothermal power units.

The gas extractor is another innovation of the Hatchobaru station. The system combines steam jet ejectors, which are very efficient for high-vacuum use, with radial blowers, which are better suited for low-vacuum. A schematic of the system is shown in Fig. 19b. The system is called ERR, which stands for steam Ejector-Radial blower-Radial blower. Three steam ejectors in parallel

handle the high-vacuum noncondensable gases, while two radial blowers in series handle the low-vacuum load. The blowers are driven by small steam turbines, the exhaust from which is used to supply the steam jet ejectors. The steam consumption is about one-half what would be required for the usual two-stage steam ejector system. Hatchobaru steam contains about 0.3% of noncondensable gases by weight. About 1520 kg/h (including 260 kg/h of air released from the cooling water) must be removed from the condenser. The ERR system has a capacity of 1970 kg/h.

6.5. Cooling tower

The cooling tower is of the counter-flow, mechanically induced draft type constructed of reinforced concrete and having four cells. There is no need for cooling water pumps owing to the pressure differential between the tower basin (atmospheric pressure) and the condenser (9.8 kPa (2.9 in Hg)).

6.6. Environmental effects

Like the Otake plant, the Hatchobaru plant is located in the Aso National Park and due attention was paid to minimizing the impact of the plant on its surroundings. The area of the plant site is $36 \times 10^4 \text{ m}^2$ (89 acres). All waste hot liquid is reinjected into the reservoir under gravity feed to reduce the chance for induced seismic effects. There are no controls on the emission of hydrogen sulfide, and specific levels comparable to that of the Otake plant are likely. The Kyushu Electric Power Co., Inc. intends to plant trees on the plant site in an effort to help the plant conform to the scenic beauty of the area.

6.7. Economic data

The total capital investment to construct the Hatchobaru plant was 11.5 billion Yen (\$47.6 million) in 1977. This reduces to about \$950/kW.

The plant was originally scheduled for completion in 1976 at an estimated cost of 7 billion Yen (\$29 million) or about \$580/kW [KEPCO ., 1976]. It is anticipated that the plant will generate about 350,000 MW·h of electricity per year; this corresponds to an availability factor of 80% for base-load operation.

7. Kakkonda (Takinoue) dry-steam power plant

Since 1972 the Japan Metals and Chemicals Co., Ltd. has been developing the geothermal field at Takinoue which is located 7.5 km (4.7 mi) southwest of the Matsukawa area in Iwate Prefecture [Mori, 1975]. The steam produced is supplied to the power plant at Kakkonda which has been constructed by the Tohoku Electric Power Co., Inc. The unit is rated at 50 MW and came on-line during the latter half of 1977. The turbine-generator was supplied by the Tokyo Shibaura Electric Co., Ltd. (Toshiba). It is expected that an additional 100 MW will soon be installed at this site.

7.1. Geology and exploration

A variety of techniques have been applied to assess the geological nature of the Takinoue area; examples of the results of many of these have been reported [GERD, 1975].

Geological maps have been constructed which show that the area is comprised mainly of tuff, siltstone, sandstone, sandstone and tuff. Chemical surveys and prospecting of the river water, hot springs water and natural steam give indications of the depths, orientation and temperatures of the deep-seated sources of thermal energy. River water in the area shows an average pH of about 5.5 with a low of about 3.8 and high of about 7.1. Hot spring water is somewhat more neutral, having an average pH of about 6.5. Natural steam contains about 0.3% noncondensable gases, of which nearly 17% is hydrogen sulfide and 71% is carbon dioxide, by volume. The other gases present include hydrogen, nitrogen and methane, in small amounts. Electrical soundings have been taken, contour maps of apparent resistivity have been drawn and underground temperature surveys have resulted in the construction of isotherm profiles for various depths. In order to obtain the data for the latter study, 879 shallow (1 m) samplings were taken at 25 m (82 ft) intervals,

109 samplings at depths of 5 - 10 m (16 - 33 ft) were taken and 49 samplings at depths of 30 m (98 ft).

Deep test boring was done to ascertain information about the types of rocks, minerals and structure in the formation, as well as to determine the fluid temperature at depth. Temperature profiles for Well No. 203 at Takinoue [GERD, 1975] show steep gradients ($60^{\circ}\text{C}/100\text{ m}$ ($32^{\circ}\text{F}/100\text{ft}$)) to depths of about 100 m (328 ft). This is about eighteen times as large as the normal gradient ($33^{\circ}\text{C}/\text{km}$ ($1.8^{\circ}\text{F}/100\text{ft}$)). The average gradient over 400 m (1312 ft) is about $30^{\circ}\text{C}/100\text{ m}$ ($16^{\circ}\text{F}/100\text{ ft}$); there is little gradient from 400 - 800 m (1312 - 2624 ft), typical of a hydrothermal convection system.

7.2. Steam wells

All wells are drilled with rotary drilling rigs, by means of the directional drilling method. Once the well reaches depths at which steam is expected, air drilling replaces mud drilling to avoid problems associated with the loss of circulation mud. Air drilling rates of about 4 m/h (13 ft/h) are typical in the Takinoue-Matsukawa regions. The casing programs for test wells, reinjection wells and steam production wells at Takinoue are shown in Fig. 20. It is estimated [Mori, 1975] that each reinjection well should be capable of handling between 350 - 400 Mg/h ($0.77 - 0.88 \times 10^6$ lbm/h) when drilled properly to depths of between 350 - 550 m (1150 - 1800 ft), with 270 mm (10.625 in) diameter open holes, and flowing under gravity feed.

7.3. Turbine-generator

The turbine and generator were supplied by the Tokyo Shibaura Electric Co., Ltd. (Toshiba). The turbine is of the single-cylinder, double-flow type, rated at 50 MW and turning at 3000 rpm. The machine has four impulse stages in each flow. Each half of the turbine is essentially a duplicate of the

single-flow machine used at Matsukawa.

The generator is air-cooled, rated at 55,600 kVA, 11 kV with 0.9 power factor.

Table 14 gives the technical specifications for the primary mechanical components of the plant. The plant layout is similar to that for the Matsukawa plant (See Fig. 2.), although all flow rates will be roughly double the values for Matsukawa owing to the larger output.

7.4. Heat rejection equipment

The condenser, cooling tower, etc. for the Kakkonda plant are essentially the same as for the Matsukawa plant, except for the size factor related to the plant output. (See Sects. 2.4 - 2.6.)

7.5. Economic data

The data quoted below [Mori, 1975] represent rough estimates of the capital investment required to develop a site and install a 50 MW geothermal plant, such as the one at Kakkonda:

Geological surveys and prospecting.	220 million Yen (1975)
Social services, including road construction. .	200 million Yen (1975)
Detailed geologic surveys	180 million Yen (1975)
Exploratory well drilling	240 million Yen (1975)
Production well drilling and wellhead equipment	2200 million Yen (1975)
Reinjection well drilling	300 million Yen (1975)
Power generation equipment.	3140 million Yen (1975)
<hr/>	
Total	6,500 million Yen (1975)
	(\$27 million, 1975)

This is about \$540/kW in 1975 dollars. The time schedule to carry out the above operations stretches over eight years. When approval is needed from

various government agencies, the time schedule will be even longer. In the case of Japan, nearly all of the potential geothermal areas are located in or near national parks, and these parks constitute about 8% of the land area in the country. Even though it is estimated that only 0.1% of the national park area would be needed to support 20,000 MW of geothermal power, there is still the question of how much of this land the government will allow to be used for this purpose [Mori, 1975].

8. Otake pilot binary plant

Mitsubishi Heavy Industries, Ltd. (MHI) is operating a small (1 MW) pilot plant at Otake using the binary principle with isobutane⁽¹⁾ as the working fluid [MHI, 1977 (A)]. The purpose of the plant is to prove out the principle of the binary cycle; economics are of secondary importance at this stage. The plant went into operation at the end of 1977, and is currently under testing. A site photograph is shown in Fig. 22.

8.1. Source of geothermal fluid

The plant makes use of the geofluid from production well no. 10 at the Otake geothermal site. The quality of the fluid at the separator is about 9%, at a temperature of 130°C (266°F). After being used as the heating medium for the secondary working fluid, about 78% of the produced fluid is reinjected into the reservoir through Otake reinjection well no. 2. The geothermal brine (i.e., liquid portion of geofluid) has a pH of 8, contains 4030 ppm of total dissolved solids, which includes mainly chloride (Cl) 1720 ppm, sodium (Na) 1060 ppm and silicon dioxide (SiO₂) 612 ppm.

8.2. Isobutane heater and vaporizer

A multi-stage flash heater provides sensible heating to the liquid isobutane by means of a series of flash-distillation processes. Figure 23 shows a plant schematic. This type of heater has two principal advantages. First, it produces pure, distilled water which is then used in the dry/wet, isobutane condenser during the hot season, and second, the dissolved solids in the geofluid are contained in the liquid or precipitate to the bottom of the heating vessel, leaving the heat exchanger tubes free of scale. Noncondensable

(1) In 1975, the company started the development of binary cycle geothermal power generation systems in cooperation with the Sunshine Project, promoted by the Agency of Industrial Science and Technology, Ministry of International Trade and Industry, Japan.

gases are extracted from the dead end of the heater and pumped out to the atmosphere.

Isobutane vapor is generated in a shell-and-tube heat exchanger which receives geothermal steam and hot liquid from a wellhead separator in the ratio of 1:10, roughly. The geothermal steam makes two passes through the heat exchanger while the liquid makes four passes. The isobutane leaves the vaporizer in a dry, saturated state through a cyclone separator mounted on top of the evaporator.

8.3. Turbine-generator

The turbine, generator, reduction gear and all associated auxiliary equipment for governing, sealing and lubrication are mounted on a common bed for ease of transportation and installation. The turbine is a radial expander with a spiral inlet, axial exhaust and a bleed connection for regenerative heating (not currently in use). The turbine is fitted with variable inlet nozzles which serve as a control mechanism. The turbine speed is 17,000 rpm; the generator speed is 1800 rpm. A planetary gear-box serves as a speed reducer. Turbine shaft sealing is achieved by means of a double-flow, balance-type oil film seal for normal running, a contact seal for shut-down and a buffered gas seal for abnormal operation [MHI, 1977 (A)].

Table 15 lists the technical specifications for the main elements of the plant [MHI; MHI, 1977 (A)].

8.4. Heat rejection system

The plant uses a forced-draft, air-cooled, surface condenser, augmented by a water spray. The water is obtained from the flash-distillation process just described and from a single-cell, counter-flow, mechanically-induced-draft cooling tower. The air-cooled condenser uses six bundles of circular finned tube elements with two top-mounted, induced-draft fans with variable pitch blades.

9. Potential geothermal power plants in Japan

There is an enormous potential for geothermal power in Japan and a large number of areas are under consideration for development or are currently being developed. The following is meant as a brief summary of some of these sites and the expected capacity of the power plants which may be installed [Mori, 1975; GERD, 1975; Iga and Baba, 1974; MITI, 1976].

Kuzuneda	50 MW
Mori	50 MW
Nigorikawa	50 MW
Kita-Yuzawa	50 MW
Matsukawa (extension)	50 MW
Takinoue	100 MW
Ogachi	100 MW
Noji	100 MW
Hakkoda	50 MW
Hakusan	50 MW
Yakedake	50 MW
Takenoyu	50 MW
Aso	50 MW
Kirishima	50 MW

In short, about 2100 MW of installed geothermal power capacity is expected to be on-line by 1985; the ultimate capacity is estimated at 100,000 MW [MITI, 1976].

10. Utilization efficiency of Japanese geothermal power plants

Since a geothermal power plant does not constitute a heat engine in the sense of a conventional fossil or nuclear power station, the usual measures of efficiency are inappropriate. Thermal efficiency (based on heat input from a reservoir at a constant temperature) cannot be used in the case of a geothermal plant which receives thermal energy from a geothermal fluid undergoing a temperature change.

The resource utilization efficiency, η_u , is the proper measure of the energy conversion process which takes place in a geothermal power plant [Milora and Tester, 1976]. The factor is based on the available work in the geothermal fluid, either as it exists in the formation (or at the well-bottom) or as it is supplied to the boundary of the plant (or at the wellhead). It is calculated from

$$\eta_u = w/w^o \quad , \quad (1)$$

where w is the specific net work output of the plant, in kJ/kg (Btu/lbm), and w^o is the specific available work of the geofluid in the same units; w^o may be found from

$$w^o = h_1 - h_o - T_o (s_1 - s_o) \quad , \quad (2)$$

where subscript 1 is used for the initial state of the geofluid and subscript o represents the ambient sink condition (i.e., saturated liquid water at temperature T_o). In the case where the initial state is chosen at the wellbottom, an additional term, $-gL$, must be included in Eq. (2). This term accounts for the potential energy of the fluid at the bottom of the well a distance L below the surface, and is usually a small term except for very deep wells.

Table 16 contains a summary of the calculations of the resource utilization efficiency for the operating geothermal power plants in Japan, based on wellhead

fluid availability. The values shown for η_u should be reduced by 15 - 20% if the reference is the bottom-hole fluid condition.

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Table 1

Associated Companies of Geothermal Energy Research and
Development Co., Ltd. (GERD)

Chuo Kaihatsu Corporation
Dai-ichi Kangyo Bank, Ltd., The
Furukawa Co., Ltd.
Hokuriku Electric Power Co., Inc., The
Industrial Bank of Japan, Ltd., The
Ishikawajima-Harima Heavy Industries Co., Ltd.
Japan Metals & Chemicals Co., Ltd.
Japan Petroleum Exploration Co., Ltd.
Kyushu Electric Power Co., Inc.
Mitsubishi Heavy Industries, Ltd.
Mitsubishi Metal Corporation
Mitsui Mining & Smelting Co., Ltd.
Niigata Engineering Co., Ltd.
Nippon Electric Co., Ltd.
Nippon Kokan Kabushiki Kaisha
Nippon Mining Company, Ltd.
Nippon Steel Corporation
Nittetsu Mining Co., Ltd.
Sekiyu Sakuseiki Co., Ltd.
Sumitomo Metal Mining Co., Ltd.
Teikoku Oil Co., Ltd.
Tohoku Electric Power Co., Inc., The
Toho Zinc Co., Ltd.
Tokyo Shibaura Electric Co., Ltd.
Tsukamoto Seiki Co., Ltd.

Table 2
Characteristics of geothermal steam and
condensate at Matsukawa [Kawasaki, 1977]

Percentage of noncondensable gases ⁽¹⁾	0.2 - 0.6%
Composition of noncondensable gases (volume percentage):	
carbon dioxide, CO ₂	79.3 - 85.2%
hydrogen sulfide, H ₂ S	12.9 - 17.7%
methane, CH ₄	1.15%
hydrogen, H ₂	0.28%
Composition of condensate (ppm):	
sulfate, SO ₄	1708.1
amorphous silicon dioxide, SiO ₂ ·H ₂ O	795.5
sodium, Na	280
potassium, K	180
hydrogen sulfide, H ₂ S	10 - 42.2
chloride, Cl	9.2
pH of condensate	4.35 - 4.85

(1) Percentage by volume of steam.

Table 3

Materials and corrosion test data: Matsukawa [Akiba, 1970]

<u>Component</u>	<u>Material name (ASTM)</u>	<u>Corrosion rate, $\mu\text{m}/\text{yr}$</u>
turbine casing	carbon steel plate (A283-6rD)	636
infringement shield	stainless steel plate (410)	21.3
rotor	1% Cr, 1.25% Mo, 0.25%V, forged steel	623
buckets	low carbon, 12% Cr steel (410)	21.3
nozzle diaphragms	carbon steel plate (A283-6rD)	636
nozzle partitions	12% Cr Al alloy steel	49.4
labyrinth packing strips	15% Cr, 1.75% Mo steel	—
valve bodies	carbon steel plate	636
valve seats	stellite welding	—
bearing babbits	white metal (D-23-6)	—
oil cooler tubes	aluminum	—
tube sheets	naval brass sheets and plates (B-111)	4.92 ⁽¹⁾
water boxes	cast iron (48-35)	—
condenser shell and tail pipe	epoxy-coated carbon steel	2.84 ⁽¹⁾
condenser tray	stainless steel (304)	21.2 ⁽¹⁾
gas ejector	stainless steel (304)	21.2 ⁽¹⁾

(1) in condensate.

Table 4

Country	Japan
Unit name	Matsukawa
Owner	Japan Metals and Chemicals Co., Ltd.
Year of start-up	1966
Plant type	Natural direct, dry steam

Turbine characteristics

Manufacturer	Tokyo Shibaura Electric Co., Ltd. (Toshiba)	
Type	Single-cylinder, single-flow, 4-stage impulse	
Rated capacity	20.0 MW	
Maximum capacity	22.0 MW	
Speed	3000 rev/min	
Steam inlet pressure	441.2 kPa	64.0 lbf/in ²
Steam inlet temperature	147.5 °C	297.5 °F
Noncondensable gas content	< 1.0 % by weight of inlet steam	
Exhaust pressure	13.5 kPa	4.0 in Hg
Turbine steam flow rate	207.0 Mg/h	0.456×10^6 lbm/h
Maximum allowable pressure	(NA) kPa	(NA) lbf/in ²
Last stage blade height	584.2 mm	23.0 in

Condenser characteristics

Type	Spray jet, barometric	
Pressure	12.7 kPa	3.74 in Hg
Cooling water temperature	25.0 °C	77.0 °F
Outlet water temperature	47.0 °C	116.6 °F
Cooling water flow rate	4,320.0 Mg/h	9.52×10^6 lbm/h

Gas extractor characteristics

Type	Steam jet ejector	
Number of stages or sets	2	
Suction pressure	12.7 kPa	3.74 in Hg
Capacity	~ 18,000 m ³ /h	~ 10,600 ft ³ /min
Steam consumption	(NA)	

Heat rejection system characteristics

Type	Natural draft cooling tower	
Number of towers	1	
Water inlet temperature	47.0 °C	116.6 °F
Water outlet temperature	25.0 °C	77.0 °F
Design wet-bulb temperature	(NA) °C	(NA) °F
Water flow rate	5.00 Gg/h	11.0 × 10 ⁶ lbm/h
Water pump power	(NA) kW	

Table 5

Chemical composition of scale after 50 days' operation
at Matsukawa [Akiba, 1970]

<u>Element</u>	<u>Control valve</u>	<u>1st-Stage buckets</u>	<u>2nd-Stage buckets</u>	<u>3rd-Stage buckets</u>
SiO ₂	37%	24%	11%	4%
SO ₄	44	50	24	18
Fe	1.3	10	51	56
Al	0.9	0.5	0.2	0.2
Ca	1.0	0.8	0.3	0.04
Mg	0.3	0.2	0.1	trace
S	trace	0.4	2.3	4.3
Na	11.5	9.3	2.3	0.6
K	4.3	2.8	0.6	trace

Table 6
Characteristics of geothermal steam and condensate
at Otake [Kawasaki, 1977]

Percentage of noncondensable gases ⁽¹⁾	0.2%
Composition of noncondensable gases (volume percentage):	
carbon dioxide, CO ₂	95.6%
hydrogen sulfide, H ₂ S	1.27%
other gases	3.13%
Composition of condensate (ppm):	
chloride, Cl	1493
sodium, Na	874
amorphous silicon dioxide, SiO ₂ ·H ₂ O	525
sulfate, SO ₄	113
potassium, K	101
pH of condensate	8.0

(1) Percentage by volume of steam.

Table 7

Country	Japan
Unit name	Otake
Owner	Kyushu Electric Company
Year of start-up	1967
Plant type	Separated steam ("single flash")

Turbine characteristics

Manufacturer	Mitsubishi Heavy Industries, Ltd.	
Type	Single-cylinder, single-flow, 4-stage impulse	
Rated capacity	10.0 MW	
Maximum capacity	13.0 MW	
Speed	3600 rev/min	
Steam inlet pressure	245.1 kPa	35.6 lbf/in ²
Steam inlet temperature	127.0 °C	261.0 °F
Noncondensable gas content	0.8 % by weight of inlet steam	
Exhaust pressure	10.8 kPa	3.2 in Hg
Turbine steam flow rate	113.0 Mg/h	0.249×10^6 lbm/h
Maximum allowable pressure	572.0 kPa	83.0 lbf/in ²
Last stage blade height	420.0 mm	16.5 in

Condenser characteristics

Type	Spray jet, barometric, tray-type	
Pressure	9.8 kPa	2.9 in Hg
Cooling water temperature	26.0 °C	78.8 °F
Outlet water temperature	41.4 °C	106.5 °F
Cooling water flow rate	3,900.0 m ³ /h	8.6×10^6 lbm/h

Gas extractor characteristics

Type	Motor-driven, reciprocating vacuum pump	
Number of stages or sets	3 sets	
Suction pressure	9.02 kPa	2.66 in Hg
Capacity	4,620.0 m ³ /h	2,719.0 ft ³ /min
Power consumption	105 kW (starting); 53 kW (steady)	

Heat rejection system characteristics

Type	Cross-flow, mechanical-draft cooling tower	
Number of cells	3	
Water inlet temperature	41.4 °C	106.5 °F
Water outlet temperature	26.0 °C	78.8 °F
Design wet-bulb temperature	17.0 °C	62.6 °F
Water flow rate	4.2 Gg/h	9.26 × 10 ⁶ lbm/h
Water pump power	(NA) kW	
Draft fan type	Vertical, axial	
Air flow rate/fan	275.0 m ³ /s	0.583 × 10 ⁵ ft ³ /min
Fan motor power	66.0 kW	

Table 8

Materials of construction for Otake power plant

[Usui and Aikawa, 1970]

<u>Material</u>		<u>Component</u>
<u>Type</u>	<u>ASTM Spec.</u>	
Rolled steel for general structures	A6-68a	Silencers; steam pipes (> 400 mm (> 15.75 in) dia); receiver; turbine exhaust casing; exhaust duct*; condenser* (exc. spray basins); mist separators for gas extractors*; cooling tower spray basins*
Rolled steel for welded structures	A242-68	Shell of steam separators; shell of ball check valves; tanks for separated hot water; drain tank
Grey iron castings	A48-64, No. 30B or 35B	Turbine inlet casing; turbine diaphragms; gas extractors (without feather valves); warm and cold water pump casings; main water pipes
Carbon steel castings	A27-65 N-2	Sluice valves and safety valves for steam line (with stainless steel parts)
Carbon steel pipes	A120-68a	Steam pipes (<400 mm (<15.75 in) dia.); hot water pipes
Carbon steel pipes	A53-68 Gr. A	Gas extractor and discharge pipes*; barometric pipe for jet condenser*
Low Cr Mo steel		Turbine rotor
Stainless steel	403 or 304	Turbine nozzles, blades, gland packing fins; strainer for main steam; balls of ball check valves; expansion joints; elements of steam separators and steam receiver; feather (plate) valves of gas extractor; condenser spray basins; shafts of warm water pumps and cooling water pumps; cooling water pipes for auxiliary
Stainless steel castings	A296-68, CA40	Impellers of warm water pumps and cooling water pumps
Anti-corrosion aluminum alloy	B211, alloy 5052	Fan impellers of cooling tower

* Painted with protective epoxy coating.

Table 9

Country	Japan
Unit name	Onuma
Owner	Mitsubishi Metal Corporation
Year of start-up	1973
Plant type	Separated steam ("single flash")

Turbine characteristics

Manufacturer	Mitsubishi Heavy Industries, Ltd.	
Type	Single-cylinder, single-flow, 4-stage impulse	
Rated capacity	10.0	MW
Maximum capacity	12.5	MW
Speed	3000	rev/min
Steam inlet pressure	245.1 kPa	35.6 lbf/in ²
Steam inlet temperature	127.0 °C	261.0 °F
Noncondensable gas content	0.1 % by weight of inlet steam	
Exhaust pressure	10.8 kPa	3.2 in Hg
Turbine steam flow rate	107.0 Mg/h	0.236×10^6 lbm/h
Maximum allowable pressure	572.0 kPa	83.0 lbf/in ²
Last stage blade height	500.0 mm	19.7 in

Condenser characteristics

Type	Spray jet, barometric, tray type	
Pressure	9.8 kPa	2.9 in Hg
Cooling water temperature	23.0 °C	73.4 °F
Outlet water temperature	43.4 °C	110.1 °F
Cooling water flow rate	2,850.0 Mg/h	6.28×10^6 lbm/h

Gas extractor characteristics

Type	Motor-driven, reciprocating vacuum pump	
Number of stages or sets	2 stages	
Suction pressure	9.02 kPa	2.66 in Hg
Capacity	1,050.0 m ³ /h	618.0 ft ³ /min
Power consumption	30 kW (starting)	

Heat rejection system characteristics

Type	Cross-flow, mechanical-draft cooling tower	
Number of cells	3	
Water inlet temperature	43.4 °C	110.1 °F
Water outlet temperature	23.0 °C	73.4 °F
Design wet-bulb temperature	14.0 °C	57.2 °F
Water flow rate	3.1 Gg/h	6.38 × 10 ⁶ lbm/h
Water pump power	(NA) kW	
Draft fan type	Vertical, axial	
Air flow rate/fan	285.0 m ³ /s	60.4 × 10 ⁶ ft ³ /min
Fan motor power	86.0 kW	

Table 10

Characteristics of geothermal steam and condensate

at Onikobe [Kawasaki, 1977]

Percentage of noncondensable gases ⁽¹⁾	0.5%
Composition of noncondensable gases (volume percentage):	
carbon dioxide, CO ₂	58.4%
hydrogen sulfide, H ₂ S	36.0%
others (hydrogen, methane, ammonia)	5.6%
Composition of condensate (ppm):	
chloride, Cl	7590
calcium, Ca	930
amorphous silicon dioxide, SiO ₂ ·H ₂ O	550
magnesium, Mg	340
hydrogen sulfide, H ₂ S	107
sulfate, SO ₄	24
pH of condensate.	3.0

(1) Percentage by volume of steam.

Table 11.

Country	Japan
Unit name	Onikobe
Owner	Electric Power Development Corporation
Year of start-up	1975
Plant type	Natural, direct, dry steam

Turbine characteristics

Manufacturer	Kawasaki Heavy Industries, Ltd.	
Type	Single-cylinder, single-flow, 5-stage, impulse reaction	
Rated capacity	25.0	MW
Maximum capacity	25.0	MW
Speed	3000	rev/min
Steam inlet pressure	441.2 kPa	64.0 lbf/in ²
Steam inlet temperature	147.2 °C	297.0 °F
Noncondensable gas content	0.5 % by weight of inlet steam	
Exhaust pressure	10.7 kPa	3.1 in Hg
Turbine steam flow rate	228.0 Mg/h	0.503×10^6 lbm/h
Maximum allowable pressure	(NA) kPa	(NA) lbf/in ²
Last stage blade height	~ 626.5 mm	~ 24.7 in

Condenser characteristics

Type	Spray jet, barometric	
Pressure	10.0 kPa	3.0 in Hg
Cooling water temperature	26.0 °C	78.8 °F
Outlet water temperature	42.1 °C	107.8 °F
Cooling water flow rate	7,062.0 Mg/h	15.6×10^6 lbm/h

Gas extractor characteristics

Type	Steam jet ejector ⁽¹⁾		
Number of stages or sets	2		
Suction pressure	10.0 kPa	3.0	in Hg
Capacity	(NA) m ³ /h	(NA)	ft ³ /min
Steam consumption	15.0 Mg/h	0.033 × 10 ⁶	lbm/h

Heat rejection system characteristics

Type	Counter-flow, mechanical-draft cooling tower		
Number of cells	5		
Water inlet temperature	42.1 °C	107.8	°F
Water outlet temperature	26.0 °C	78.8	°F
Design wet-bulb temperature	17.0 °C	62.6	°F
Water flow rate	6.75 Gg/h	14.88 × 10 ⁶	lbm/h
Water pump power	400 kW		
Draft fan type	Vertical, axial		
Air flow rate/fan	(NA) m ³ /s	(NA)	10 ⁶ ft ³ /min
Fan motor power	(NA) kW		

(1) Improved design (Oct. 1975) replaced second-stage ejector with motor-driven vacuum pump.

Table 12

Fouling experience at Onikobe. [Kawasaki, 1977].

<u>Problem</u>	<u>Component</u>
Scale accumulation	Nozzles and blades of 1st and 2nd stages; turbine gland; nozzle of gland ejector; main steam strainer
Corrosion	Gland packing ring; cooling pipe of heat exchanger; pressure gauge; spray nozzle of cooling tower
Erosion	Valve stem used in condensate line; circulating water pump sleeve
Separation	Neoprene lining at condenser bottom; epoxy coating of exhaust pipe

Table 13

Country	Japan
Unit name	Hatchobaru
Owner	Kyushu Electric Company
Year of start-up	1977
Plant type	Separated steam/Flash ("double flash")

Turbine characteristics

Manufacturer	Mitsubishi Heavy Industries, Ltd.	
Type	Single-cylinder, double-flow, pass-in, 5 × 2	
Rated capacity	50.0 MW	
Maximum capacity	55.0 MW	
Speed	3600 rev/min	
Main steam inlet pressure	637.3 kPa	92.4 lbf/in ²
Main steam inlet temperature	164.2 °C	327.6 °F
Secondary steam pressure	147.1 kPa	21.3 lbf/in ²
Secondary steam temperature	102.0 °C	215.6 °F
Noncondensable gas content	0.3 % by weight of main steam	
Exhaust pressure	9.8 kPa	2.9 in Hg
Main steam flow rate	384.0 Mg/h	0.847 × 10 ⁶ lbm/h
Secondary steam flow rate	116.0 Mg/h	0.256 × 10 ⁶ lbm/h
Maximum allowable pressure	1,070.0 kPa	155.5 lbf/in ²
Last stage blade height	635.0 mm	25.0 in

Condenser characteristics

Type	Spray jet, integral with turbine support	
Pressure	9.8 kPa	2.9 in Hg
Cooling water temperature	26.0 °C	78.8 °F
Outlet water temperature	43.5 °C	110.3 °F
Cooling water flow rate	12,300 Mg/h	27.1 × 10 ⁶ lbm/h

Gas extractor characteristics

Type	Steam jet ejector and two radial blowers, in series	
Number of stages or sets	1 set	
Suction pressure	9.3 kPa	2.75 in Hg
Capacity	16,300 m ³ /h	9,594 ft ³ /min
Steam consumption	5.2 Mg/h	1.15 × 10 ⁴ lbm/h

Heat rejection system characteristics

Type	Counter-flow, mechanical-draft cooling tower	
Number of cells	4	
Water inlet temperature	43.5 °C	110.3 °F
Water outlet temperature	26.0 °C	78.8 °F
Design wet-bulb temperature	17.0 °C	62.6 °F
Water flow rate	12.72 Gg/h	28.0 × 10 ⁶ lbm/h
Water pump power	(NA) kW	
Draft fan type	Vertical, axial	
Air flow rate/fan	710.0 m ³ /s	1.50 × 10 ⁶ ft ³ /min
Fan motor power	213.0 kW	

Table 14

Country	Japan
Unit name	Kakkonda (Takinoue)
Owner	Tohoku Electric Power Company, Inc.
Year of start-up	1977
Plant type	Natural, dry steam

Turbine characteristics

Manufacturer	Tokyo Shibaura Electric Co., Ltd. (Toshiba)	
Type	Single-cylinder, double-flow, 4 × 2	
Rated capacity	50.0 MW	
Maximum capacity	50.0 MW	
Speed	3000 rev/min	
Steam inlet pressure	441.2 kPa	64.0 lbf/in ²
Steam inlet temperature	147.5 °C	297.5 °F
Noncondensable gas content	(NA) % by weight of inlet steam	
Exhaust pressure	13.5 kPa	4.0 in Hg
Turbine steam flow rate	398.0 Mg/h	0.877 × 10 ⁶ lbm/h
Maximum allowable pressure	(NA) kPa	(NA) lbf/in ²
Last stage blade height	584.2 mm	23.0 in

Condenser characteristics

Type	Spray jet, barometric	
Pressure	13.5 kPa	4.0 in Hg
Cooling water temperature	(NA) °C	(NA) °F
Outlet water temperature	(NA) °C	(NA) °F
Cooling water flow rate	(NA) Mg/h	(NA) lbm/h

Gas extractor characteristics

Type	Steam jet ejector	
Number of stages or sets	(NA)	
Suction pressure	13.5 kPa	4.0 in Hg
Capacity	(NA) m ³ /h	(NA) ft ³ /min
Steam consumption	(NA)	

Heat rejection system characteristics

Type	(NA)	
Number of cells	(NA)	
Water inlet temperature	(NA) °C	(NA) °F
Water outlet temperature	(NA) °C	(NA) °F
Design wet-bulb temperature	(NA) °C	(NA) °F
Water flow rate	(NA) g/h	(NA) lbm/h
Water pump power	(NA) kW	
Draft fan type	(NA)	
Air flow rate/fan	(NA) m ³ /s	(NA) ft ³ /min
Fan motor power	(NA) kW	

Table 15

Country	Japan
Unit name	Binary Pilot Plant
Owner	Japanese Government
Year of start-up	1977
Plant type	Binary cycle

Turbine characteristics

Manufacturer	Mitsubishi Heavy Industries, Ltd.		
Type	Single-cylinder, geared, 1-stage radial		
Rated capacity	1.0	MW	
Maximum capacity	1.0	MW	
Speed, turbine/generator	17000/1800	rev/min	
Secondary working fluid	iso-butane ($i\text{-C}_4\text{H}_{10}$)		
S.w.f. inlet pressure	2,843.0	kPa	412.4 lbf/in ²
S.w.f. inlet temperature	120.0	°C	248.0 °F
S.w.f. exhaust pressure	490.0	kPa	71.1 lbf/in ²
S.w.f. exhaust temperature	52.0	°C	125.6 °F
S.w.f. mass flow rate	70.0	Mg/h	0.154×10^6 lbm/h

Geothermal fluid characteristics

Inlet pressure	269.6	kPa	39.1 lbf/in ²
Inlet temperature	130.0	°C	266.0 °F
Outlet pressure	(NA)	kPa	(NA) lbf/in ²
Outlet temperature	50.0	°C	122.0 °F
Mass flow rate	52.8	Mg/h ⁽¹⁾	0.1164×10^6 lbm/h

(1) Vapor flow rate = 4.7 Mg/h (1.036×10^4 lbm/h);

Liquid flow rate = 48.1 Mg/h (1.06×10^5 lbm/h).

Condenser characteristics

Type	Forced-draft, air-cooled with spray surface condenser	
Pressure (isobutane)	490.0 kPa	71.1 in Hg
Cooling water temperature (3)	26.0 °C	78.8 °F
Outlet water temperature (3)	(NA) °C	(NA) °F
Cooling water flow rate (3)	11.5 Mg/h	0.0254×10^6 lbm/h

Gas extractor characteristics

Type	Water-seal rotary pump	
Number of stages or sets	1	
Suction pressure	12.26 kPa	3.62 in Hg
Capacity	600.0 m ³ /h	353.1 ft ³ /min
Power consumption	37.0 kW	

Heat rejection system characteristics

Type	Counter-flow, mechanical-draft cooling tower	
Number of cells	1	
Water inlet temperature	50.0 °C	122.0 °F
Water outlet temperature	26.0 °C	78.8 °F
Design wet-bulb temperature	15.0 °C	59.0 °F
Water flow rate	0.0550 Mg/h	0.121×10^6 lbm/h
Water pump power	(NA) kW	
Draft fan type	Vertical, axial	
Air flow rate/fan	13.3 m ³ /s	0.0282×10^6 ft ³ /min
Fan motor power	30.0 kW	

(3) water spray used only during hot season.

Table 16

Resource utilization efficiency for Japanese geothermal power plants

<u>Name</u>	<u>Type</u> ⁽¹⁾	<u>Year</u> ⁽²⁾	<u>w</u> kJ/kg	<u>T_o</u> °K	<u>$\bar{x}$</u> ⁽³⁾	<u>T₁</u> °C	<u>w^o</u> kJ/kg	<u>η_u</u> ⁽⁴⁾
Matsukawa	DS	1966	348.1	298	1.00	147.5	702.4	0.50
Otake	1F	1967	65.3	299	0.24	127.0	188.9	0.35
Onuma	1F	1973	68.9	296	0.19	127.0	170.5	0.41
Onikobe	DS	1975	394.4	299	1.00	147.2	693.4	0.57
Hatchobaru	2F	1977	163.5	299	0.31	164.2	312.8	0.52
Kakkonda	DS	1977	452.5	298	1.00	147.5	702.4	0.64
Binary	IB	1977	68.2	299	0.089	130.0	112.1	0.61

(1) DS = dry steam; 1F = single flash; 2F = double flash; IB = isobutane binary.

(2) YEAR = year of plant start-up.

(3) $\bar{x}$ = average quality (dryness fraction) of wellhead geofluid.

(4) η_u is based on available work of wellhead fluid.

Figure captions

- Fig. 1. Matsukawa geothermal power plant. [GERD, 1975]. The 45m-high, natural-draft cooling tower dominates the scene at the Matsukawa plant. The power house is in the left background; the barometric condenser is at the far left; two steam pipelines are in the left foreground; and the 11 kV bus line to the substation is visible in the right background.
- Fig. 2. Heat balance diagram of Matsukawa geothermal power plant [Akiba, 1970].
- Fig. 3. Otake geothermal power plant. [MHI, 1976 (A)]. Situated on filled land, the Otake power station is located in rugged terrain near the active volcano Mt. Aso. The plant produces 10 MW for the Kyushu Electric Power Co., Ltd.
- Fig. 4. Gathering system for Otake plant [MHI, 1976 (A)]. Wellhead equipment can be seen at the far left and at the center and right at the rear of the plant. The vapor billows emanate from the liquid flashers/silencers at each wellhead. A reinjection well is in the lower left foreground.
- Fig. 5. Location of production wells and reinjection wells at Otake. [Kubota and Aosaki, 1975].
- Fig. 6. Casing program of four production wells and three reinjection wells at Otake [Kubota and Aosaki, 1975].
- Fig. 7a. Typical wellhead apparatus at Otake [MHI, 1976 (B)].
- Fig. 7b. Schematic of typical steam separator equipment at Otake [MHI, 1976 (B)].
- Fig. 8. Schematic diagram of Otake power plant. [MHI, 1976 (B)].

Fig. 9. Sectional view of Otake 4-stage, impulse turbine [MHI, 1976 (B)].

Fig. 10. Butterfly regulating valve flow characteristic at Otake [Usui and Aikawa, 1970].

Fig. 11. Barometric jet condenser at Otake [MHI, 1976 (A)].

Fig. 12. Onuma geothermal power plant [MHI, 1976 (C)]. The centralized well-head equipment is in the right foreground; the power house, barometric condenser and cooling tower are at the left; the steam lines lead from the wells to the receiver outside the power house.

Fig. 13. Schematic diagram of Onuma power plant [MHI, 1976 (C)].

Fig. 14. Onikobe geothermal power plant [Kawasaki, 1977]. Steam rises from silencers which receive hot liquid from drain separators. The power house is at the left, barometric condenser with steam jet ejectors in the center and cooling tower at the right.

Fig. 15. Schematic and heat balance diagram for Onikobe power plant [Kawasaki, 1977].

Fig. 16. Cross-sectional view of Onikobe turbine assembly [Kawasaki, 1977].

Fig. 17. Hatchobaru geothermal power plant [MHI, 1977]. The No. 4 wellhead is at the left; the transmission pipeline from the No. 6 well is at the lower right; the twin separators and the flasher are located between the cooling tower and the power house.

Fig. 18. Gathering and reinjection system for Hatchobaru [MHI, 1977].

Fig. 19. Schematic diagram for Hatchobaru power plant [Aikawa and Soda, 1975; MHI, 1977].

Fig. 20a. Low-level concrete jet condenser at Hatchobaru [Aikawa and Soda, 1975].

Fig. 20b. Schematic diagram of ERR gas extraction system at Hatchobaru [MHI, 1977].

Fig. 21. Well casing programs for wells in Takinoue (Kakkonda) area [GERD, 1975].

Fig. 22. Pilot binary power plant [MHI, 1977 (A)]. This is how the plant appeared during tests in February 1977. The isobutane heater and evaporator are at the right side, the air-cooled condenser is at the rear of the pilot plant, and the Otake power plant is in the background.

Fig. 23. Schematic diagram for pilot binary plant at Otake.

Fig. 1. Matsukawa geothermal power plant. [GERD, 1975]. The 45m-high, natural-draft cooling tower dominates the scene at the Matsukawa plant. The power house is in the left background; the barometric condenser is at the far left; two steam pipelines are in the left foreground; and the 11 kV bus line to the substation is visible in the right background.

Fig. 2. Heat balance diagram of Matsukawa geothermal power plant [Akiba, 1970].

Fig. 3. Otake geothermal power plant. [MHI, 1976 (A)]. Situated on filled land, the Otake power station is located in rugged terrain near the active volcano Mt. Aso. The plant produces 10 MW for the Kyushu Electric Power Co., Ltd.

Fig. 4. Gathering system for Otake plant [MHI, 1976 (A)]. Wellhead equipment can be seen at the far left and at the center and right at the rear of the plant. The vapor billows emanate from the liquid flashers/silencers at each wellhead. A reinjection well is in the lower left foreground.

Fig. 5. Location of production wells and reinjection wells at Otake.
[Kubota and Aosaki, 1975].

Fig. 6. Casing program of four production wells and three reinjection wells at Otake [Kubota and Aosaki, 1975].

Fig. 7a. Typical wellhead apparatus at Otake [MHI, 1976 (B)].

Fig. 7b. Schematic of typical steam separator equipment at Otake [MHI, 1976 (B)].

Fig. 9. Sectional view of Otake 4-stage, impulse turbine [MHI, 1976 (B)].

Fig. 10. Butterfly regulating valve flow characteristic at Otake [Usui and Aikawa, 1970].

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