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Mechanical Features of a Geothermal Plant

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ABSTRACT

The first geothermal power plant in Japan has been operating 34 months up to the present, since finishing government inspection at Matsukawa area (northern part of Honshu island) and now generating at full load 20,000 kW. Major equipments of this plant are manufactured by Tokyo Shibaura Electric Co. (Toshiba) because of their great experience in provisions for thermal power plants. Fundamental design concepts to equipment are similar to conventional and nuclear use, however special problems for geothermal use exist eg. sticking of scales and corrosions by gas to machine parts. The turbine has several suitable mechanisms which have accumulated from test and experience. As the type of condenser and the capacity of gas ejector are characteristic of a geothermal plant, model tests of them were carried out at the factory and good results were derived from a performance test at the site.

Based on the above actual results, two 37,500 kW sets for Cerro Prieto power station and two 55,000 kW sets for The Geysers power station are being manufactured at the factory. This paper reports on the ideas from study about installations for geothermal plant use, and specification and capacity of machines respectively.

Introduction

The current progress of fossil power plants is remarkable and it has made larger capacity and higher efficiency possible by utilizing supercritical pressure. Nuclear power plant techniques are also being developed yielding larger capacity and safer apparatus in electric power generation. However, geothermal power plants are considered from various standpoints, such as the possibility of low generating cost and the non-consumption of natural minerals. We, the Tokyo Shibaura Electric Co. manufactured and installed the machines of Matsukawa power plant, which was the first commercial geothermal power plant, with 20,000 kW output, in Japan. Nowadays, the two units of 37,500 kW for Cerro Prieto power station of the Commision Federal de Electricidad in Mexico and the two units of 55,000 kW for The Geysers power station of The Pacific Gas and Electric Co. in U.S.A. are being planned and constructed at our works.

This paper reports the mechanical characteristics of the geothermal power plant, especially the steam turbine, condenser and gas ejector, which differ from those used at a fossil and nuclear plant.

Selection of material

The equipment needed in a geothermal plant is quite simple; that is, the design and construction of equipment are easier than for fuel plants, except for the problem of materials. In the case of geothermal steam, the quality of steam is very impure, that is, the machines have to utilize directly or indirectly uncontrolled steam gushing from the earth.

Of course, as the foreign matter which appears as scale in equipment is soluble in steam, geothermal steam blows out with gaseous impurities, including hydrogen sulfide which has a great influence upon corrosion, and sometimes with mud.

So, the accuracy of corrosion tests in selecting material is important as it will affect equipment life and power generating cost.

Before planning the equipment of Matsukawa, a corrosion test was carried out on 14 kinds of material in steam and in condensate water.

Test points were, dimension and weight decrease rate, tension test and microscopic examination. By this test, materials were selected and also allowable stresses and corrosion allowance were decided. Following tests were carried out to decide the exact amount of corrosion and crack sensibility by stress corrosion. Corrosion rate affected by steam velocity, temperature and wetness, corrosion crack sensibility in the vicinity of the limit of stress and corrosion fatigue were examined. These tests showed that the corrosion of materials was caused by the sulfuric compound in the steam, and that the metals containing Ni and Cu were susceptible to this compound, and were affected more. But no corrosion cracking was found. The tests in condensate were made by immersing test pieces into a mixture of condensate from the surface type condenser and cooling water which had same characteristics as water in barometric condenser. The result indicates that no metals had corrosion problems and epoxy resin coating was an excellent anticorrosive.

Typical steam compositions of Matsukawa and Cerro Prieto are shown in Table 1.

In spite of this difference, the natures of the steams are almost similar to the influence of corrosion. It is true that the content of Cl^- which affects corrosion in Cerro Prieto is greater than in Matsukawa but it

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TABLE 1. — *Typical steam compositions of Matsukawa and Cerro Prieto.*

Power Station		Cerro Prieto	Matsukawa
		Vol %	Vol %
Water-gas ratio		99.2 ∼ 99.5 0.5 ∼ 0.8	99.4 ∼ 99.8 0.2 ∼ 0.6
Gas composition	Na	12.5 ∼ 2.8 ppm	280 ppm
	K	3.4 ∼ 2.5	180
	Li	— ∼ 0.01	—
	Ca	4.8 ∼ 0.03	21.2
	Mg	—	8.7
	B	∼ 0.6	—
	SiO_2	∼ 5.0	—
	Cl	21 ∼ 11.5	9.2
	CO_3	—	—
	pH	4.29 ∼ 7.4	4.95

These data are from condensed water after the steam separator.

can be supposed that the fundamental design method need not change. Now corrosion tests are being done at the Cerro Prieto plant, and the result will be published in the near future. As for The Geysers, this client has great experience in the operation of geothermal plants and gives us many recommendations on materials. Those are nearly equal to our consideration of material.

Table 2 shows sorts of material used in equipment for the three plants and the final results of the corrosion test at Masukawa.

TABLE 2. — *Material list, and corrosion test data at Matsukawa.*

Location	Material name ( ) in ASTM symbols	Corrosion rate 10^{-3} mm/yr
Turbine casings	Carbon steel plate (A283-6rD)	636
Infringment 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	Al	
Tube sheets	Naval brass sheets and plate (B-111)	4.92 in condensate
Water boxes	Cast iron (48-35)	
Condenser shell and tail pipe	Epoxy coated carbon steel	2.84 in condensate
Condenser tray	Stainless steel (304)	21.2 in condensate
Gas ejector	ditto	

Some experience from the operations in Matsukawa

After a government inspection on October 4, 1966, this plant went into commercial operation and has been operating for more than three years up to the present. The electric power generated to the end of March 1969 totals 220,108 MWh and the turbine-generator is used over 80% of the time. This favorable operating result, though the plant is the first ever installed in Japan and must be operated without the experience of other similar plants, has led us to believe that our idea and attitudes on this planning and manufacturing have been correct. Generally speaking, compared with the conventional thermal plant, the geothermal unit has one disadvantage. That it is obliged to cease production occasionally because of mud and scale contained in the geothermal steam.

We had to jet out the large volume of mud twice. The first time, the mud entered the turbine through the steam receiver and separator, and damaged 82 buckets of the last stage, and in addition, it wore out the shrouds and bucket tennons of the penultimate stage.

This phenomenon was seen to increase the vibration amplitude of turbine-generator bearings. Damages were mostly bending and breakage of shrouds, bending of buckets, separation of stellite shield and so on. All of the bent buckets were straightened and the shrouds were replaced with new ones. After 4 month's operation, one bucket was found broken at the bottom end of the stellite shield and another was found cracked. This time, the broken bucket and the one opposite were removed to maintain the weight balance of the rotating part.

The damaged parts were checked accurately, and it was found out that the buckets were broken by plastic deformation due to breaking force caused by the mixture of mud. After the first accident, several kinds of non-destructive tests were carried out to evaluate the defect, but then the second occurred. The removed buckets were inspected using dye check, magnaflux, radioactive ray, microscopic inspection etc. and it was found by the microscopic inspection that there were micro hair cracks which cannot be detected by ordinary non-destructive tests such as dye check or magnaflux. This fact is very important for planning. That is, the natural vibration of the number of buckets is out of tune far from the nozzle-passing frequency. Buckets coated with mud and scale are imagined to change vibration number and to reach the resonance for the nozzle-passing frequency. And the vibration fatigue strength of a material can supposed to become lower in a corrosive atmosphere.

To counteract these faults, the following items are considered and are being adopted in new machines; natural vibration number far from nozzle passing frequency; large margin of allowable stress to vibration; location of every bucket to avoid stress concentration.

Also, it is important to anticipate the moment of the blow-out of mud in order to protect the machine.

To solve the above problem, the transparency meter combined with a recorder, is installed to measure continuously the transparency ratio of condensed water in the steam line.

Problem of scale: the turbine was overhauled thoroughly after 50 days' operation. We found the adhesion of scale at all points as follows:

a) Inside the steam receiver where there is a branch of the pipe line;
b) Drain separator;
c) Main valve parts of main stop valve and control valve;
d) Steam inlet part of casing and drain pipe from nozzle diaphragm;
e) Steam path part of nozzle and outside perimeter of diaphragm;
f) Effective part of buckets and inner surface of shroud;
g) Grand packing and wheel of rotor etc.

This phenomenon brings about the decrease of turbine performance and capacity, the non-stripping of safety device in an emergency and bucket damage as described above. In order to prevent serious accidents, turbine and other parts through which the steam passes are inspected about once every two months. The duration of inspection which is 50 hours or more, is shortened by preparing the spare rotor.

An analysis of the scales, gathered from each part of the turbine at the inspection after 50 days' operation, is shown in Table 3.

TABLE 3. — *Chemical composition of scale.*

Element	Control valve	1st stage bucket	2nd stage bucket	3rd stage bucket
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

The scales were composed of such elements as Si, Ca, Na, Al, Mg and S included in the earth's-crust and these elements formed such compounds as SiO_2, $CaSO_4$, Na_2SO_4, Al_2O_3, MgO, $FeSO_4$ and FeS. Scales decrease

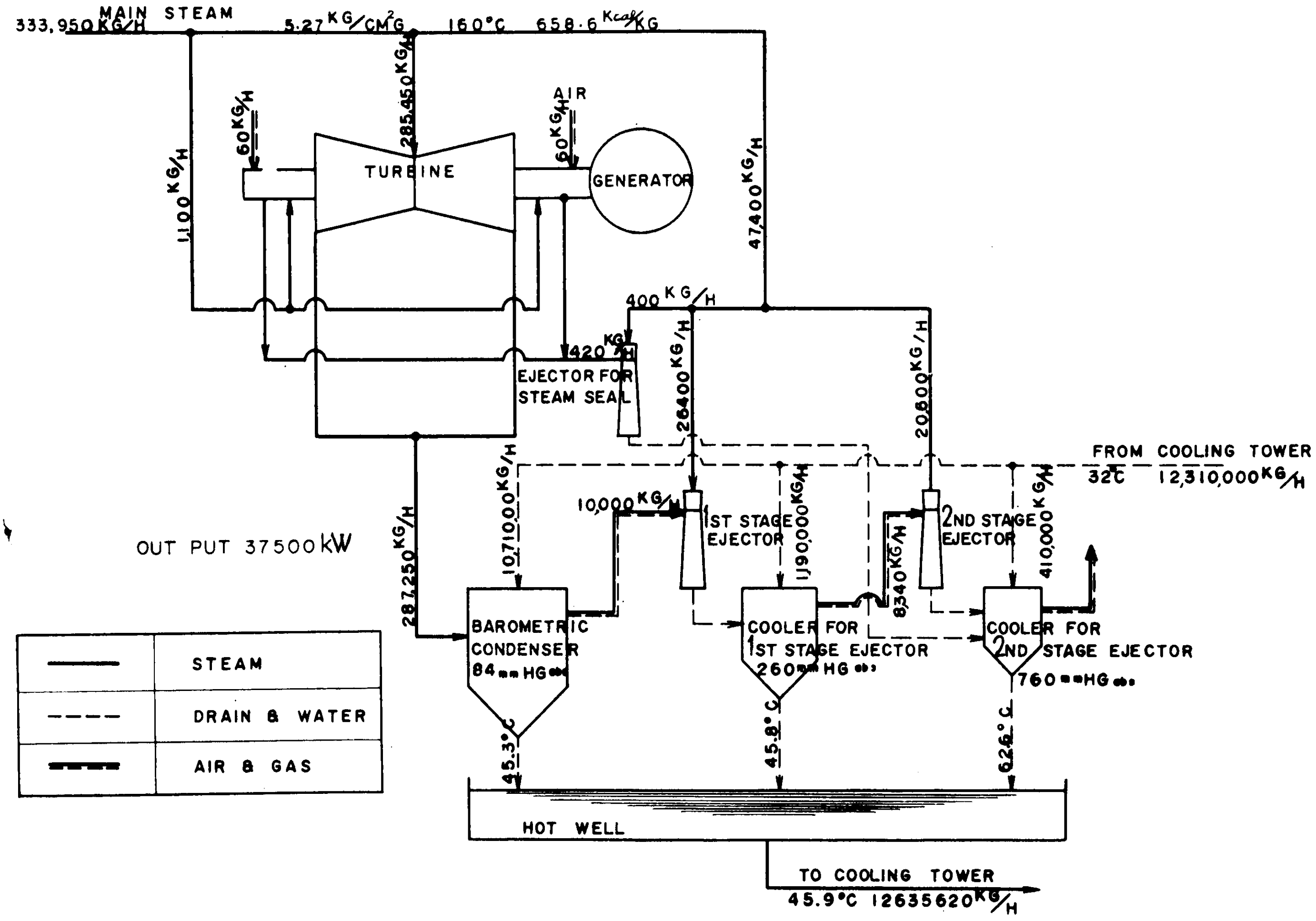

FIG. 1. — *Heat balance diagram of Cerro Prieto.*

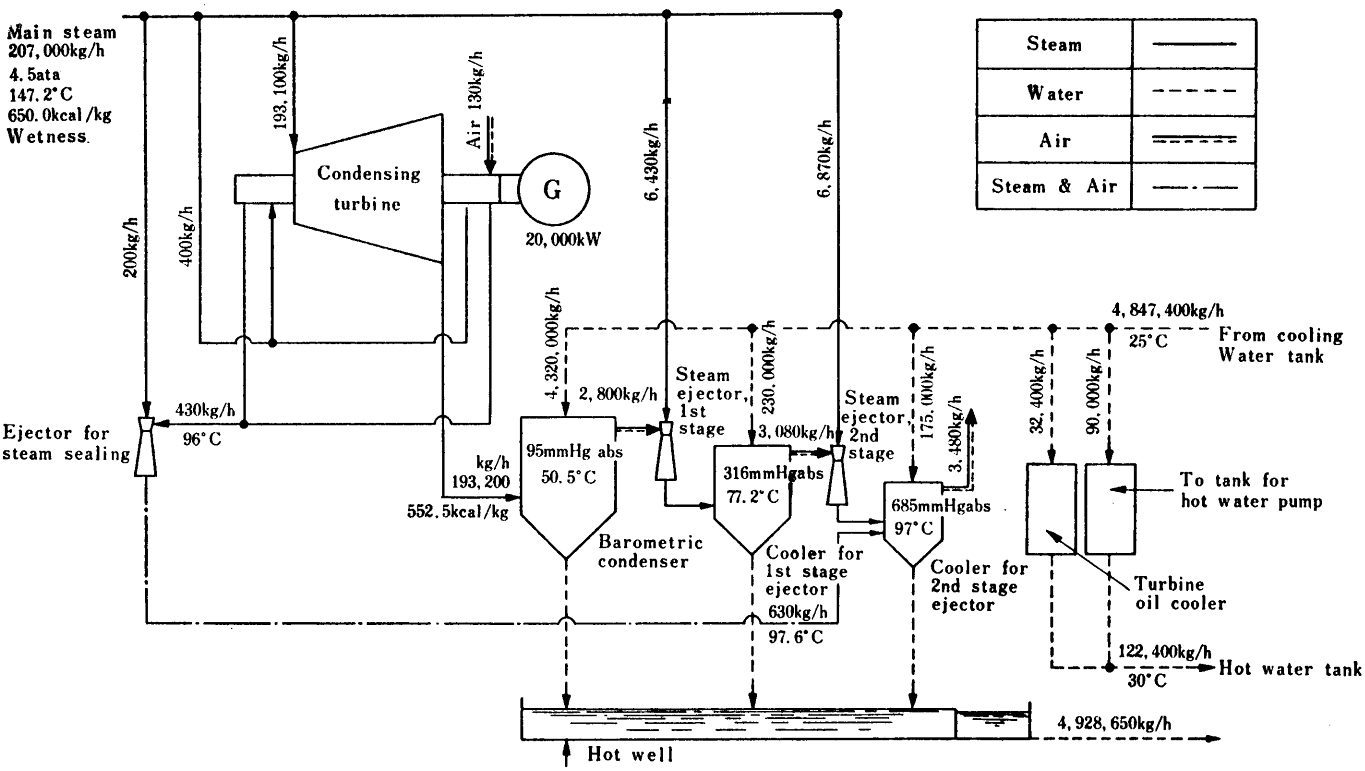

FIG. 2. — *Heat balance diagram of Matsukawa.*

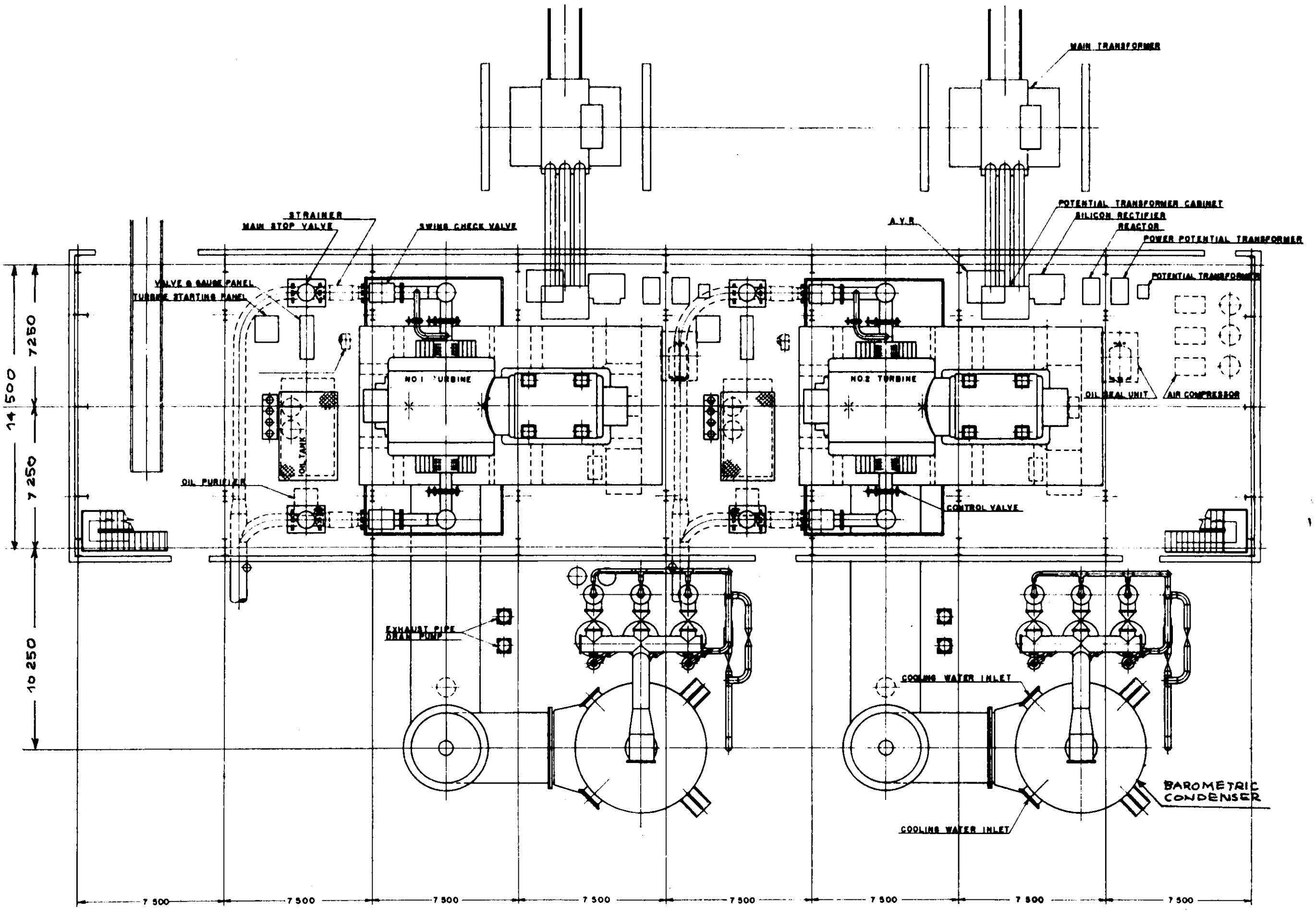

FIG. 3a. — *General arrangement of Cerro Prieto (Plan).*

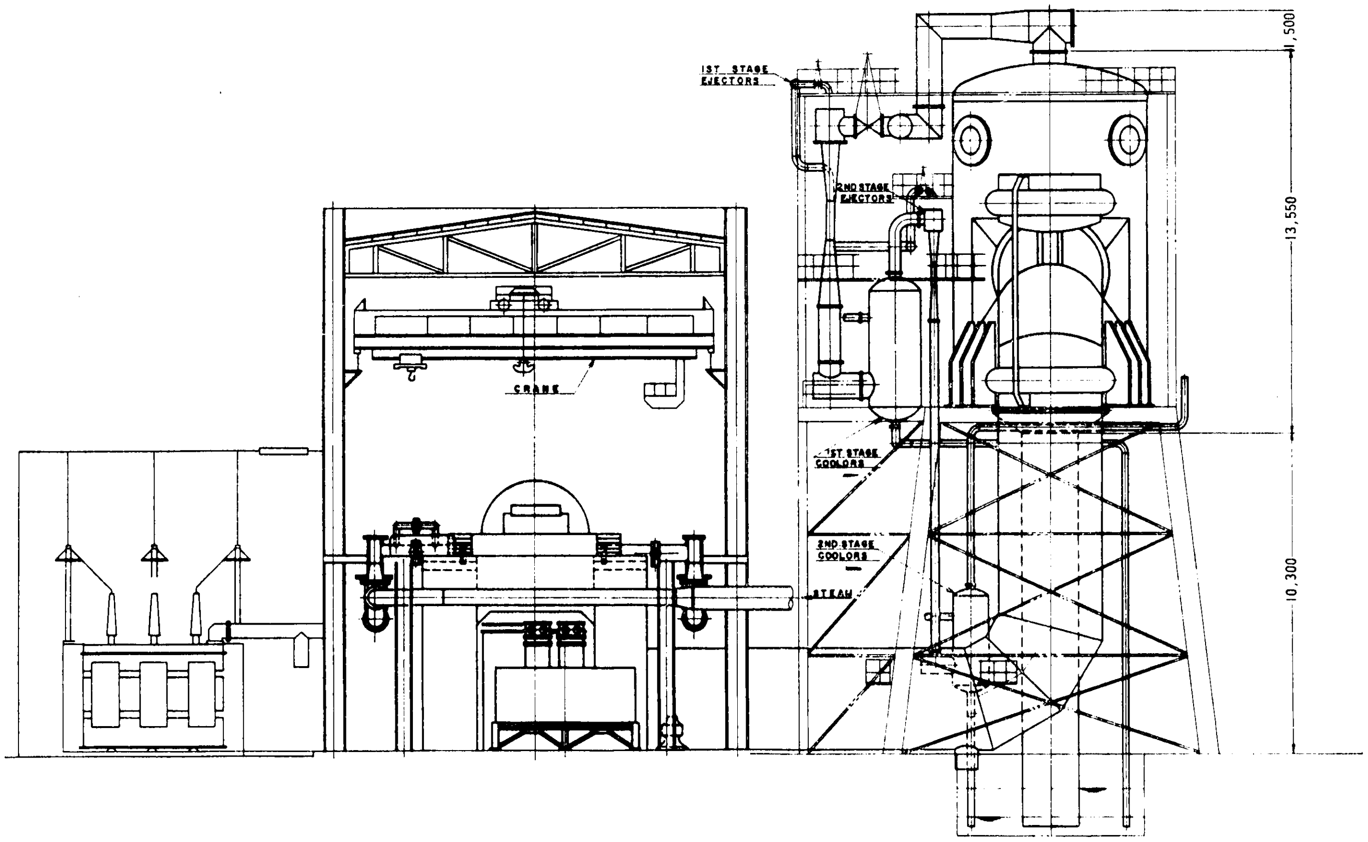

FIG. 3b. — *General arrangement of Cerro Prieto (Section).*

in down stream of the lower part of the steam path. This is because the moisture of steam increases in that area and soluble chloride such as $FeSO_4$ and Na_2SO_4 dissolve and at the same time non-soluble compounds such as SiO_2 flow out mechanically. This estimate is evidenced by the decreasing of soluble elements such as SO_4, Na and K in the lower part of the steam path.

The outline of Cerro Prieto and The Geysers

Whilst planning the Matsukawa plant, every effort was made to use our experience on 12,500 kW turbine which had been delivered to the Japan Energy Research Institute, because the steam condition was near saturation. A turbine stage group was applied to the fossil plant and was used after careful study. In order to decide the size of condenser and large gas ejector, model tests were carried out several times at our factory.

Up to the beginning of the planning of the new plant, the operation records of Matsukawa had already been analysed in detail.

But no way was found of changing the fundamental principle of the design.

Now, the equipment which we are manufacturing for Cerro Prieto and The Geysers is as follows; for the former, a turbine-generator, condenser and gas ejector; for the latter, a turbine generator. The steam condition should be decided by the characteristics of the wells, the quantity of cooling water and the atmosphere. For the steam cycle, normally the straight condensing cycle is chosen, which gains minimum steam rate, not heat rate, in the case of dry or saturated steam. Heat balance diagrams of Matsukawa and Cerro Prieto are shown in Figures 1, 2. Figure 3 (a, b) shows the general arrangement of the Cerro Prieto plant. There are turbine generators indoors and a condensing plant outdoors, and they are connected by a huge exhaust pipe through the wall. Gas ejectors are set along the condenser vertically. This arrangement is similar to the Matsukawa plant and typical in the case of the use of the barometric condenser.

Steam turbines. These turbines are of the double flow condensing type based on low-pressure stage groups which have proved their stable reliability and high efficiency in many fossil units. Principal data of turbine generators are shown here in Table 4.

The turbines are of single cylinder double casing construction (Figure 4). There are two steam inlets on the right and left side of the casing.

The steam inlets are fitted with a bellows expansion joint between the inner casing and outer hood which permits the inner casing to move independent of the outer and prevents air leakage into the hood (Figure 5).

TABLE 4. — *Principal data of turbine-generators.*

	Matsukawa	The Geysers	Cerro Prieto
Rated output (kW) (at generator terminals)	20,000	55,000	37,500
Inlet steam pressure (kg/cm^{2}G) (before main stop valve)	3.5	7	5.27
Inlet steam temperature (% or ^{0}C) (before main stop valve)	1.0% Wet	179	160
Exhaust pressure mmHg abs. (at turbine exhaust hood)	100	101.6	89
Speed (rpm) (directly connected to generator)	3,000	3,600	3,600
Turbine throttle steamflow (kg/h)	193,100	411,580	285,450
No. stages and flows of the turbine	4 × 1	6 × 2	6 × 2
Last stage bucket length (mm)	584.2	584.2	508.0
Last stage bucket tip speed (m/s)	381	424	383
Generator capacity (kVA)	23,500	66,000	44,200
(kV)	11	13.8	13.8
Generator power factor	0.85	0.9	0.85

The casing is attached to the foundation plates at the center of the casing to prevent axial motion and expands from this point.

The standard is free to slide in an axial direction and is guided to prevent transverse motion. To permit good sliding contact between steel standard and foundation plate, cast iron pads with oil impregnated bronze are inserted between the two over a sufficient area to provide a good surface. Atmosphere relief diaphragms and manholes are provided on the casing.

The rotor body is made of Cr-Mo-V alloy steel forgings, which are machined to form a solid rotor com-

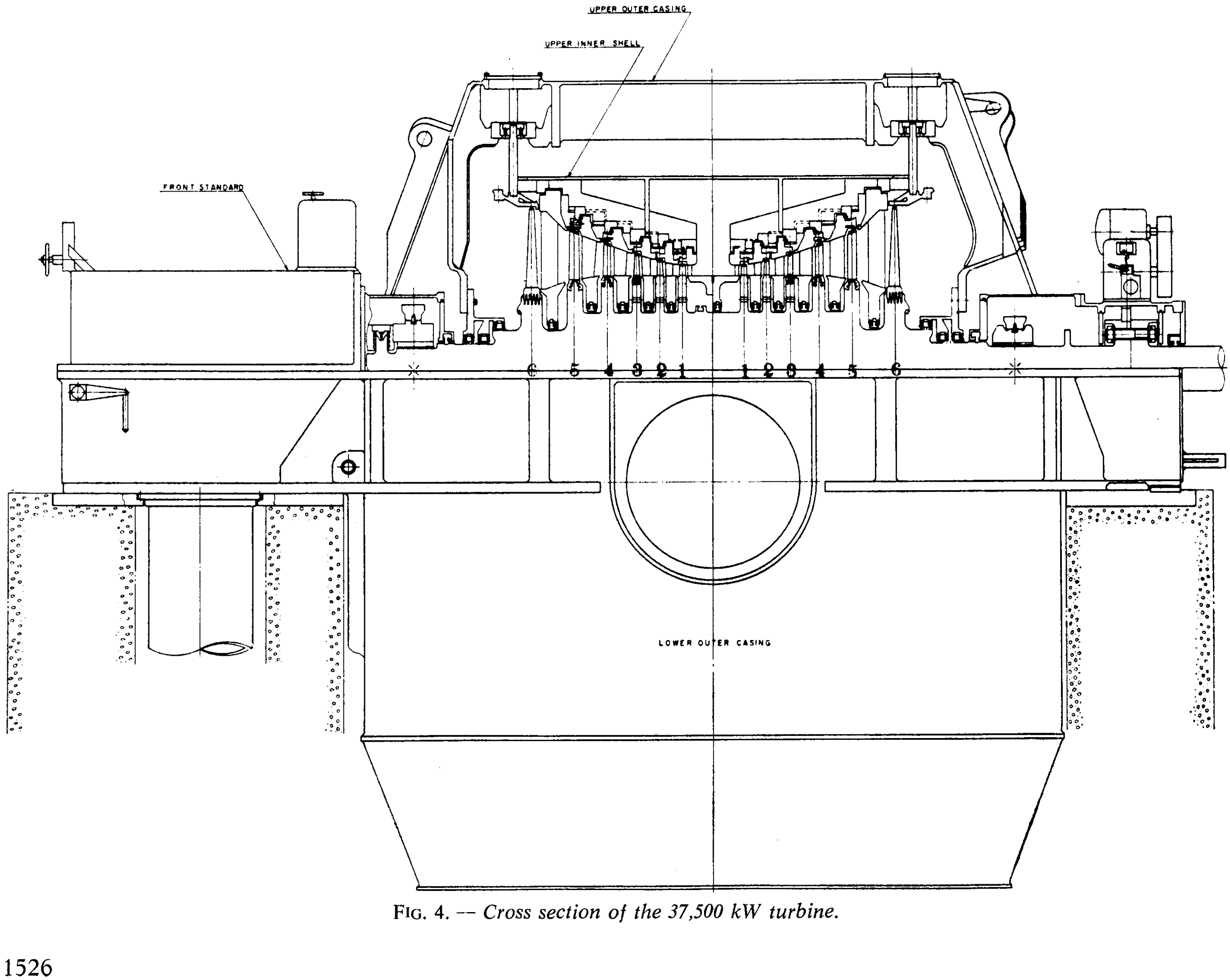

FIG. 4. — *Cross section of the 37,500 kW turbine.*

posed of shafts, wheels, bearing journals and coupling flanges. This Cr-Mo-V steel is the material used for high temperature parts in conventional turbines, but does not contain Ni, which is sensitive to corrosion. A special heating pocket is provided in the rotor considering the influence of cold brittleness.

Buckets are machined from bar stock and are dovetailed into the wheel rims tightly with a rolling machine. Metal shroud bands are used to tie the outer ends of the buckets. The punched shroud bands are fitted in segments over the tennons on the outer tips of the buckets and then tennons are hand riveted to hold the band in place.

The moisture in the steam flow might erode the buckets, shortening their useful life, and might also cause an efficiency decrease.

Moisture extraction buckets are provided for stages where the moisture quantity warrants them. Moisture extraction buckets have demonstrated their ability to take away successfully a significant amount of moisture from the steam path by means of a series of vertical grooves on the bucket at the forward edge of the profile, on the admission side. On last stage buckets where the tip speed is high, « Stellite » erosion shields are welded to the upper portion of each bucket as an additional safeguard against erosion due to moisture, and lashing wire is brazed to last stage buckets to minimize bucket vibration.

With reference to moisture, nozzle diaphragms have pockets to gather drain scattered from buckets; in addition, grooves on the outer ring of each nozzle leads accumulating drain to the periphery of the part through which the steam passes, thus preventing inflow into the buckets.

Condensing plant. In the geothermal plant, a condensing plant is adopted using a direct contact type condenser for the following reasons; it is not necessary to recover condensate water; the cooling water ratio is less than the surface cooling type; corrosion protection is easy because of simple construction without cooling tubes. The condensate pump can be eliminated to ensure a height of over 10 m.

The condenser of Cerro Prieto will be the world's

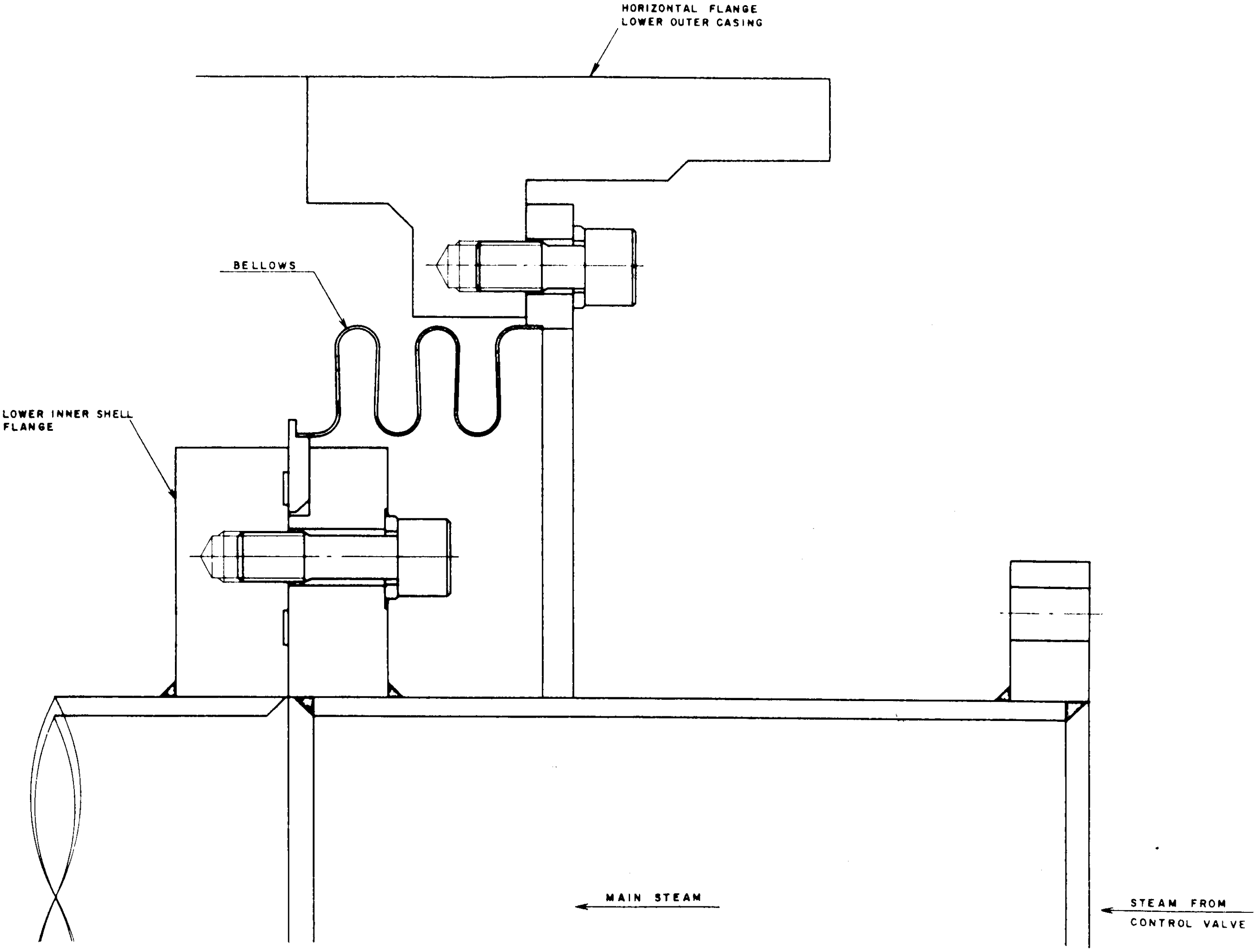

FIG. 5. — *Drawing of steam inlet to casing*

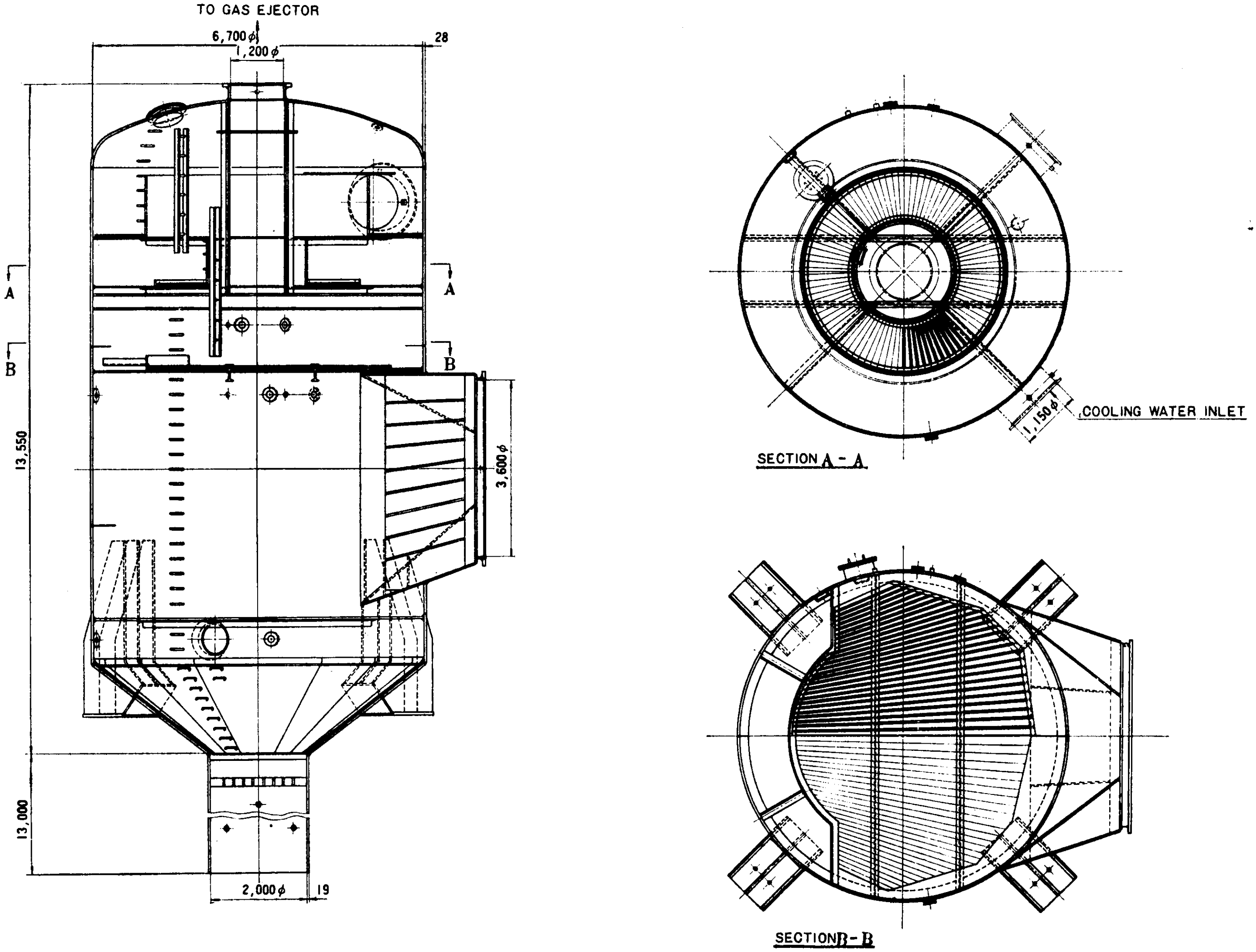

FIG. 6. — *Condenser assembly of Cerro Prieto.*

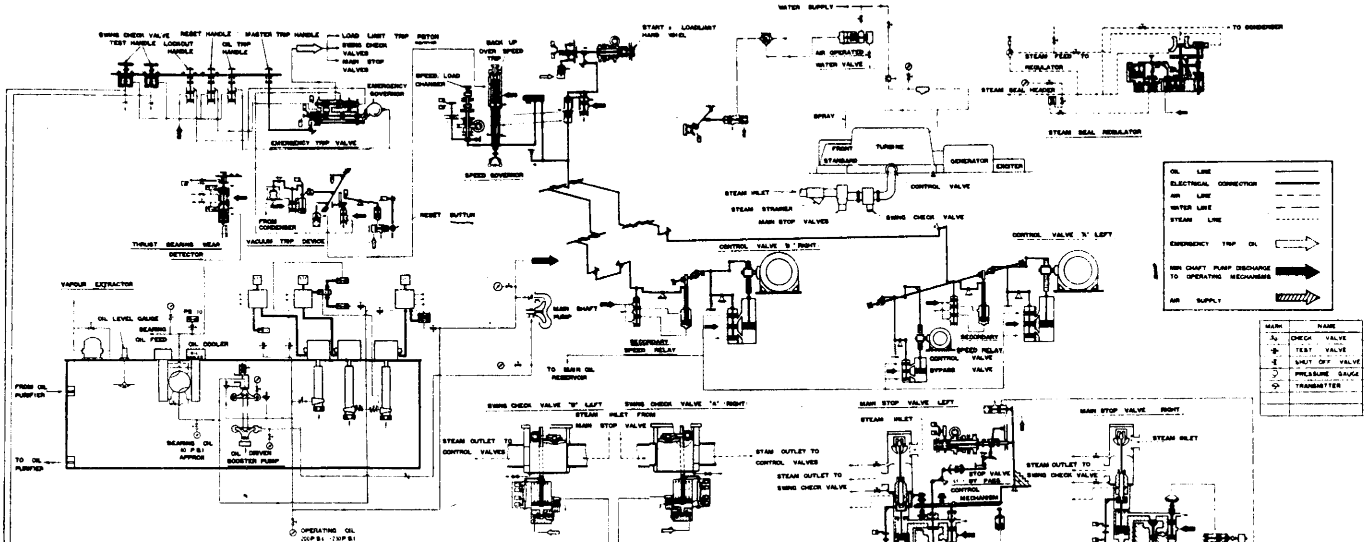

FIG. 7. — *Control diagram of The Geysers.*

largest in condensing capacity and size (Table 5 and Figure 6).

A technical difficulty is how to decrease the pressure drop in the vessel. A model simulating the load and vacuum per unit area as an actual assembly was tested by altering the inner structure. An ordinary type which has several trays does not obtain the required result as it blows up the cooling water and consequently a greater pressure drop is unavoidable.

The condenser has a water spray shelf with numerous slits and steam will flow upward and condense without passing through the cooling water curtain crosswise.

The field test results indicated that pressure loss was within the foreseen 5 mm Hg and the required condensing capacity was satisfied.

Extracting gas to maintain a vacuum only causes leakage in conventional plant equipment. However, the geothermal plant has the remarkable characteristic that the gas quantity is approximately 100 times greater than in conventional plants and may change with the blowing condition of each well. Extraction is carried out with a mechanical pump and a steam ejector. The steam ejector is a simple construction which can prevent corrosion briefly and ease operation. But operating steam pressure limits efficiency.

TABLE 5. — *Data of condensing plant (per unit).*

Plant		Cerro Prieto	Matsukawa
Condensing load	kg/h	286,180	194,000
Pressure in condenser	mmHg	84	95
Cooling water inlet temperature	^{0}C	32	25 4,320
Cooling water quantity	t/h	10,710	2,234
Dry gas extracting capacity	kg/h	3,990	3.5
Ejector operating pressure	kg/cm^{2}G	5.27	

Mechanical pumps are of many kinds, but maintenance is troublesome. The steam ejector is adopted at Cerro Prieto and has enough capacity for non-condensing gas of about 1.0% of the steam flow. One set of ejectors has respectively suction chamber, steam nozzle, diffuser and cooler and is arranged with two stages in series. The cooler is a barometric-jet type like the main condenser. The first stage ejector is so gigantic that its length is 7.5 m including suction chamber and diffuser.

Control and protection system. The governor and other control systems are the same as in a conventional power plant, except that the control valves use the butterfly to prevent the sliding surface from seizure caused by scale deposit. The controlling valves consist of two 625 mm diam. main and a 254 mm diam. bypass valves which make synchronous operation easy.

Swing check valves which close on an emergency are set up before the control valves. Considering thermal expansion, there is little clearance between valves and valve seats of control valves.

So, at the beginning of the operation at starting time, the speed of the turbine-generator will be half of that rated, because of steam leakage after opening the swing check valves. Throttle valves at The Geysers, and motor valves at Cerro Prieto are installed to control the low speed range. A control diagram of The Geysers is shown in Figure 7.

Conclusion

We take pleasure in reporting our engineering experiences in the geothermal plant. In the future, by studying new equipment such as the Freon turbine, etc., we wish to contribute to the development of this new energy source.