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NO. 6 UNIT OF THE KAWASAKI THERMAL POWER STATION, TOKYO ELECTRIC POWER CO.

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I. INTRODUCTION

In October 1965, Fuji Electric constructed the No. 5 unit—175,000 kw thermal power generating equipment—for the Kawasaki Thermal Power Station of the Tokyo Electric Co., and on the 15th of Novemver, 1968, the No. 6 unit generating equipment of the same capacity began operation.

The No. 5 unit was constructed on the basis of European technology used for the first time in commercial thermal power equipment in Japan. The No. 6 unit was designed on the basis of the same technology. A few changes were made to innovations occurring in the last few years, the special features of the No. 6 unit and the experience gained with the No. 5 unit, but fundamentally the two units are the same.

Fuji Electric manufactured the steam turbine, alternator, electrical equipment, instrumentation and precipitation equipment for the unit, while the steam generator was made by Kawasaki Heavy Industries Ltd.

II. PLANT DESIGN

1. Main Equipment Specifications

The specifications of the main pieces of equipment are as follows.

1) Steam generator

Type:	Benson boiler
Steam conditions:	(super heater outlet) 195 kg/cm² 543°C (reheater outlet) 543°C
Steam generation:	590 t/hr

2) Turbine

Type:	3-casing double-flow reheat condensing type
Output:	175,000 kw
Steam conditions:	(inlet of main stop valve) 190 kg/cm² 538°C (inlet of reheat stop valve) 37 kg/cm² 538°C
Exhaust vacuum:	722 mmHg
Speed:	3000 rpm

3) Generator

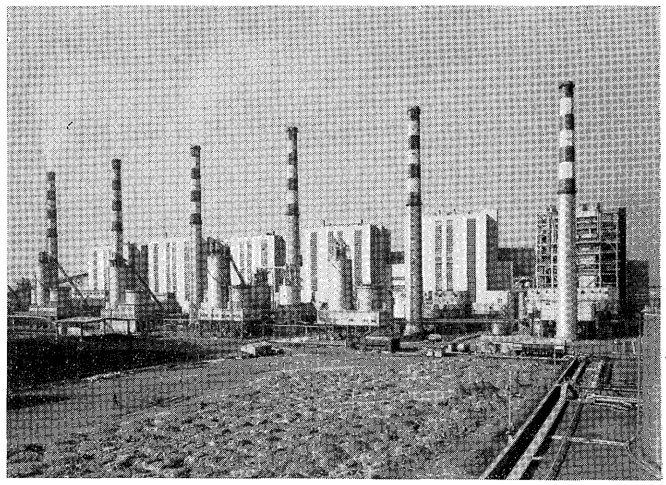


Fig. 1 Kawasaki Thermal Power Station

Type:	Horizontal-shaft rotating-field hydrogen-cooled type
Capacity:	224,000 kva
Voltage:	12,000 v
Power factor:	0.85
Frequency:	50 Hz

2. Fundamental Considerations Concerning Plant Construction

The No. 5 unit had many features when compared with the previously used American type equipment and these features have been carried over into the No. 6 unit.

1) Steam conditions

Previously, the steam conditions used mainly for 175 Mw class equipment were 169 atg 566/538°C, but in this equipment 190 atg 538/538°C has been employed. Raising the steam temperature has proven very effective in improving the thermal efficiency. However, at temperatures around 566°C, it becomes necessary to use austenite steel which is not only very expensive, but also has a very high thermal expansion so that it is essential to keep temperature variations inside the turbine (which are unavoidable because of load variation) to a minimum. Therefore, load variations and starting and stopping have always been severely restricted in 566°C class turbines. In order to avoid such inconvenient restrictions, the

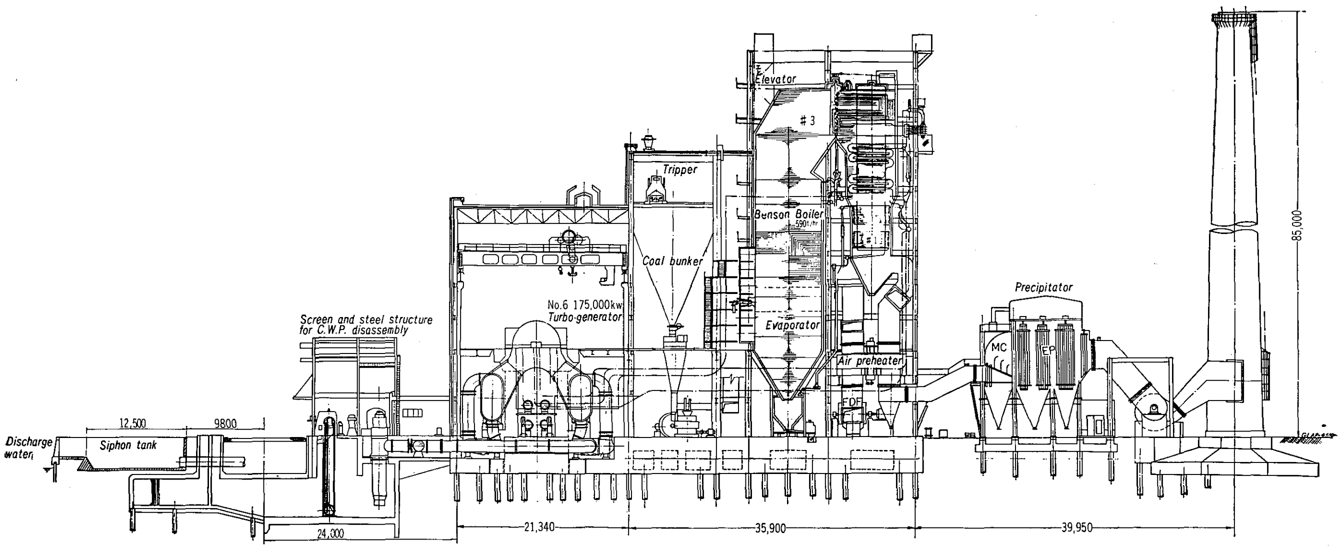


Fig. 2 Sectional view of the Power Station

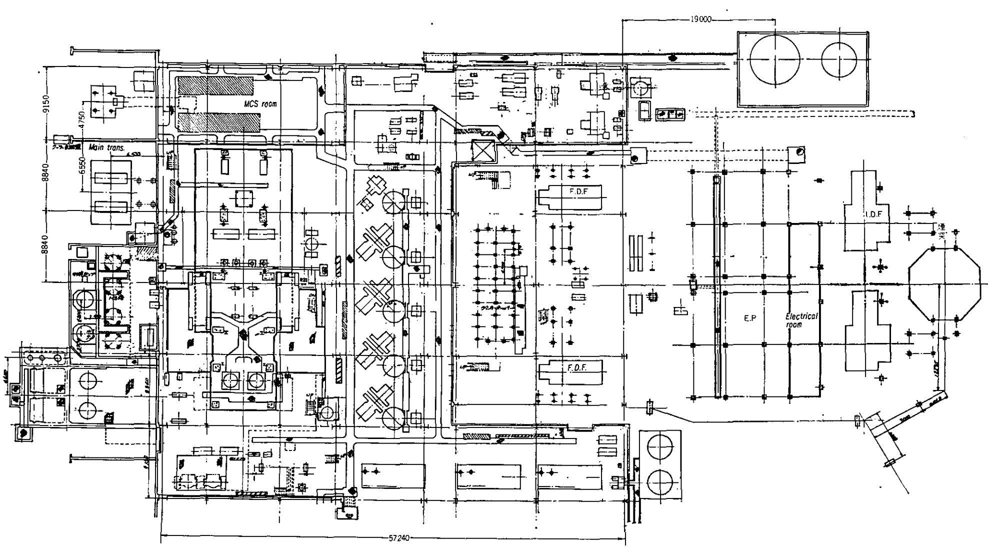


Fig. 3 1st floor disposition

steam temperature has been kept down to around 538°C. This, along with the fact that the steam pressure has been increased mainly to improve the thermal efficiency, is on of the main features of this plant.

Due to the type of system used, the steam generator and turbine have to be constructed for use with high pressure. A combination of a Benson boiler and pot-type turbine was found to be the most appropriate for these conditions.

2) Operating conditions

The load variation conditions required in thermal power stations become more severe every year. It will not be long before 175 and 350 MW class thermal power equipment will be shut down daily during the late night hours. Therefore, this plant must be suitable for rapid starting and stopping and load variations.

Figs. 5 and *6* are the standard starting diagrams for this equipment. The time required from ignition

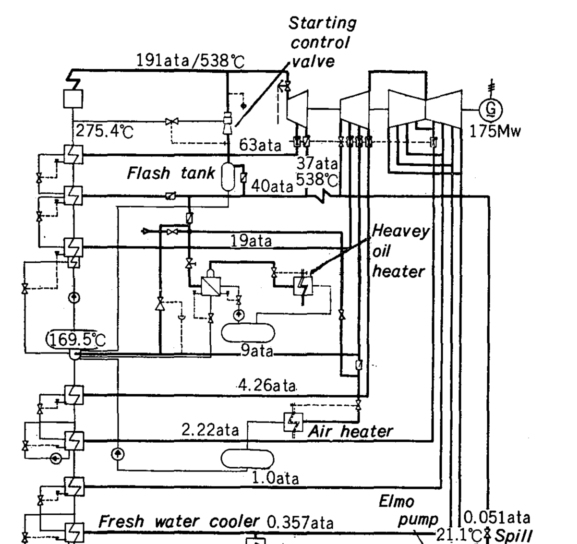


Fig. 4 Schematic diagram

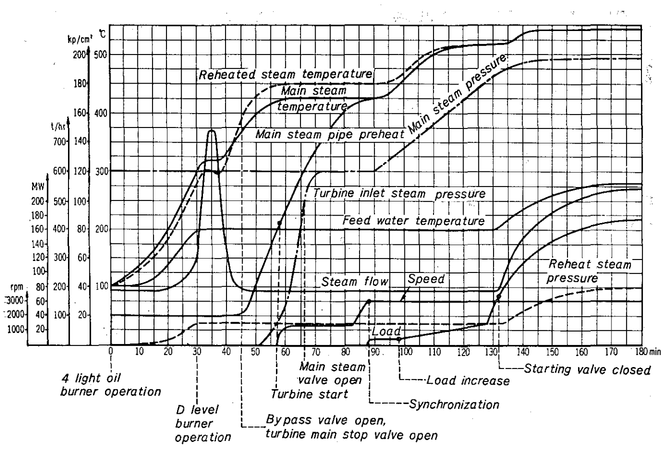


Fig. 5 Starting curve (cold start)

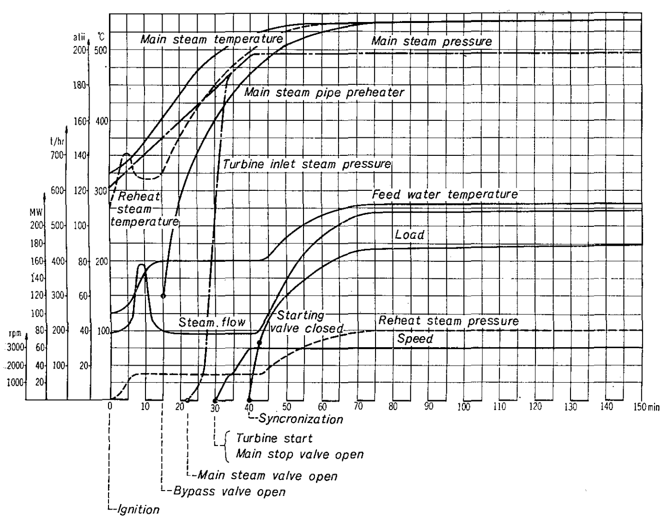


Fig. 6 Starting curve (hot start)

to full load is only about 1/2 of that required in previous plants of the same capacity. Therefore, this plant performs satisfactorily even at peak loads and has been designed with both present and future power requirements in mind.

3) Overall efficiency

As was described above, the steam temperature is lower than in previous plants of the same type but the steam pressure is kept high in order to maintain a high thermal efficiency for the plant. Before the plant went into commercial operation, performance tests were conducted and the results showed that the generator terminal efficiency based on lower heat values was 42.7% for coal firing and 43.3% for oil firing.

4) Steam line

As is shown in *Fig. 4,* there are 8 levels of extraction from the turbine, and the steam generator feed water temperature is 275.4°C. The boiler starting equipment consists of a starting control valve (steam converting valve) which makes a bypass from the main steam pipe to the cold reheat pipe and a spill-over valve which makes a bypass from the hot reheat pipe to the condenser. These valves always operate even at full steam generator capacity and since they also function when the turbine is tripped, safety valve operation is not required.

III. STEAM GENERATING EQUIPMENT

1. Boiler Features

The general advantages of the Benson boiler are as follows.

1) The weight of the pressurized portions is small.
2) The steam temperature at the superheater outlet is constant over the complete operating range.
3) Rapid starting and stopping are possible.

The boiler used in No. 6 unit has these additional features.

1) The meander tube system is used over the complete surface of the water walls which means that there is less pressure loss inside the tubes and the weights of the water tube and header have been reduced.
2) The front firing system was used and the construction is such that complete combustion in the furnace is possible for both coal or oil firing without the use of a dividing wall.

2. Construction Outline

1) Boiler unit

The No. 5 unit boiler was of the indoor type, while that of the No. 6 unit is of the outdoor type so as to save on construction costs.

The boiler consists of two lines from the inlet to the superheater outlet and the two lines are never combined. The reheater also consists of two lines.

The furnace evaporator is very special in this boiler for the following reasons.

(1) Since the meander tube system is employed, the water flow is only in the horizontal or upward directions. There is no downflow.
(2) All the parallel pipes in the furnace are arranged for as uniform heat absorption as possible regardless of the combustion conditions.
(3) In order to provide stable flow inside the furnace evaporator, the feed water flow rate at the evaporator inlet is maintained above a constant value.
(4) The evaporator unit is suspended from the upper iron beams by means of a back stay and thermal expansion can occur freely in the downward direction was considered beforehand.
(5) The parallel pipes are all constructed so that there is no mutual constraint due to thermal expansion.

With the above mentioned construction, it is unnecessary to use a large number of headers as was the case with the previous riser/downflow system, and a high flow stability is achieved.

The meander tube system is also used with the No. 1, No. 2, and No. 3 super heaters, and in the end super heater, the plate type meander tube system is employed. The reheater is of the coiled tube contact type.

2) Starting and stopping equipment

Starting control valves, flash tank and spill-over valves are provided for boiler starting and stopping. As was described previously, this equipment is not only used during stating and stopping but also serves as a turbine bypass when the turbine is tripped. For this reason, the operation of the safety valves is kept to a minimum.

3) Precipitator

The precipitator is a combined mechanical/electrical system. Performance requirements for precipitators have become more and more severe. In the No. 5 unit, an excellent overall daily capture ratio of 97.96% has been achieved for coal firing only, but this figure had to be improved even more for the No. 6 unit. For this reason, the size of the precipitator chamber was increased and special consideration was given to increase the electrical resistance of the ash in accordance with the improved combustion efficiency and the longer time which the gas is present. As a result, an extremely high capture ratio of 98.07% has been achieved.

Since the heavy oil mixed firing rate has been increased, the weight of the ash has been decreased but the exhaust gas dew point is higher. When this type of gas enters the precipitator, there are adverse effects such as corrosion and dust accumulation. However, the precipitator must be operated even when heavy oil firing is used because of the danger of public hazard. Therefore, this equipment contains ammonia injection equipment and it is possible to operate the precipitator even during only oil firing by lowering the dew point temperature using the ammonia. In this way, a capture ratio of over 80% has been achieved for oil firing only.

IV. STEAM TURBINE

1. Features of the Steam Tubine

The steam turbine of the No. 6 unit has the following features.

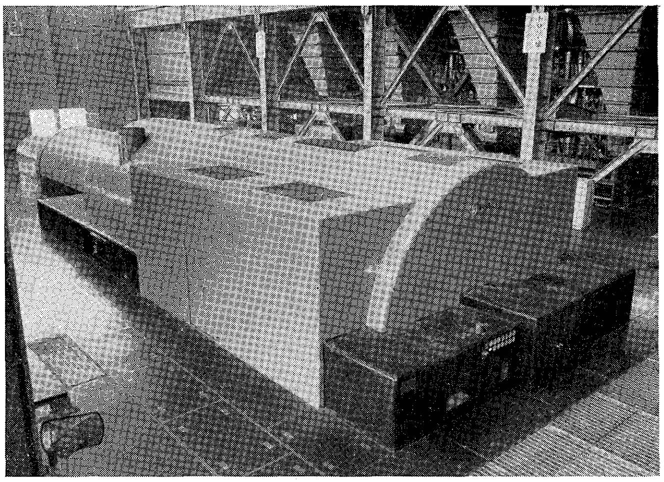


Fig. 7 Turbo set

1) A high, medium and low pressure type 3-casing system is used. The high pressure turbine is of the pot type.
2) For greater economy and better performance, a steam temperature (538°C) was employed which permits the use of low-alloyed ferrite steel. By utilizing advantages of a Benson boiler and pot-type turbine combination, the steam pressure becomes 190 atg.
3) The rotor critical speed is much higher than the usual speed and a rigid shaft is achieved.
4) The moving blades are all constructed separately and no joints with riveted shroud rings, etc., are used.
5) Drainage station valves which can be remote controlled electrically are employed.
6) All operations including starting and stopping can be carried out from a central control room.
7) Spill-over equipment is provided.
8) Elmo vacuum pump with an air ejector is used.
9) An elastic support, lightweight turbine stand is employed.

The above features all result in a very high level of performance.

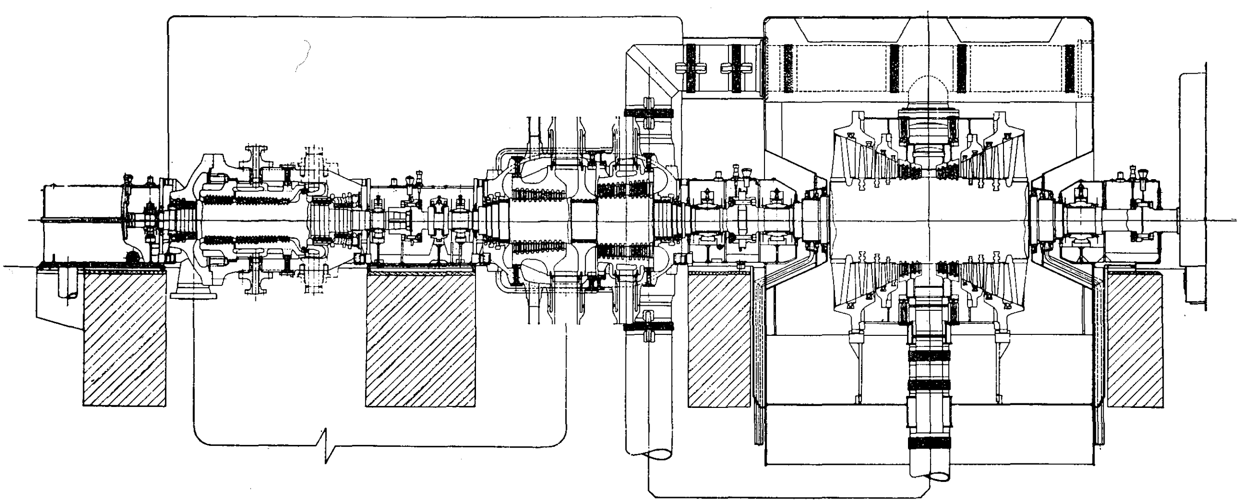


Fig. 8 Turbine cross-section

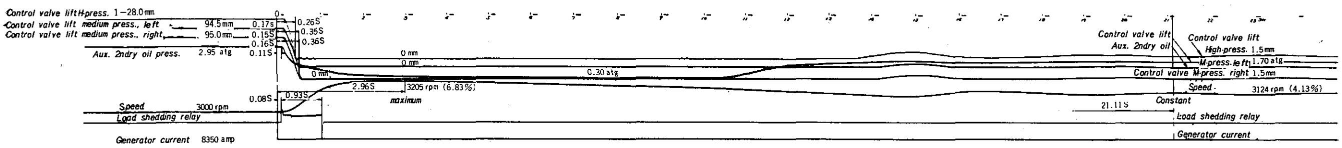


Fig. 9 100% load dump test oscillogram

2. Main Turbine Unit

1) High pressure turbine

The construction of the high pressure portion is mainly determined in respect to suitability for the turbine load variations. With the pot-type turbine, thermal stress and deformation due to load variations are very low so that large load variations are possible. An even greater feature is that there is no horizontal flange, and a ring type flange is used only in the low pressure end. Therefore, there are no flanges at all in the high pressure portion so that thermal stress and steam leaks which might result from flanges cannot occur. The casing is almost completely cylindrical.

The stationary blades are attached to a blade holder inside the casing but the mass of the blade holder is such that there will be no mutual differences in thermal expansion with the rotor to cause unbalancing. Therefore, the differences in elongation due to load changes can be kept to a minimum. Since a radial labyrinth gland is employed, the degree of freedom in respect to elongation can be increased.

2) Medium and low pressure turbines

The medium pressure turbine is of the double casing type. Reheated steam enters from the center of the casing and flows forward, reverses and then flows backward. In this way, non-uniform temperature variations due to load changes can be avoided.

The low pressure turbine is of the double flow type and the casing is double with welded steel plates.

3) Blades

Impulse blades are used only in the first high pressure stage, i.e., the governing stage. All the rest are reaction blades. There are no riveted shround plates or lashing wires used in the moving blades in any level. When a shroud is used, it forms a single unit with the blade. The low pressure blade undergoes a special gas hardening to prevent erosion due to the draining. To avoid resonance caused by the steam power, the inherent number of vibrations are regulated for each blade.

3. Control Equipment

The governor is of the oil pressure type. The oil pressure signal caused by the governor impeller is amplified in two stages and sent to the pilot valve for the 4 control valves. When there is a rapid load reduction of 65% or more, a load shedding relay detects this change electrically and causes the control valves to close before operation of the governor begins. Due to the rapid response of the oil pressure governor unit and the combined action with the load shedding relay, speed increases can be kept within limits even with full load tripping.

V. GENERATOR AND MAIN CIRCUITS

1. Generator and Exciter

The generator capacity is 224 Mva at a hydrogen gas pressure of 3 kg/cm²g. The stator employs the indirect hydrogen gas cooling system while the rotor uses direct hydrogen gas cooling. The field conductor consists of two U-shaped sections arranged facing each other and rectangular cooling holes are provided in the conductors. Four coolers are arranged in the axial direction on top of the stator frame and cooling is by means of hydrogen gas.

The exciter is coupled to the main generator shaft via the planetary reduction gear. The continuous capacity is 1100 kw.

2. Exciting Device and AVR

The generator exciting system is shown in *Fig. 10*. The main exciter and the 3-phase synchronous generator for AVR and the manual exciting source are coupled with the main generator via a reduction gear. This system allows for a marked improvement in power source reliability when compared to a separately installed exciting device with independent power source drive.

The AVR consists of a magnetic amplifier for 1st stage voltage and second stage power amplification, and a zener diode bridge-type voltage detector. It features a static type high gain. In parallel with the

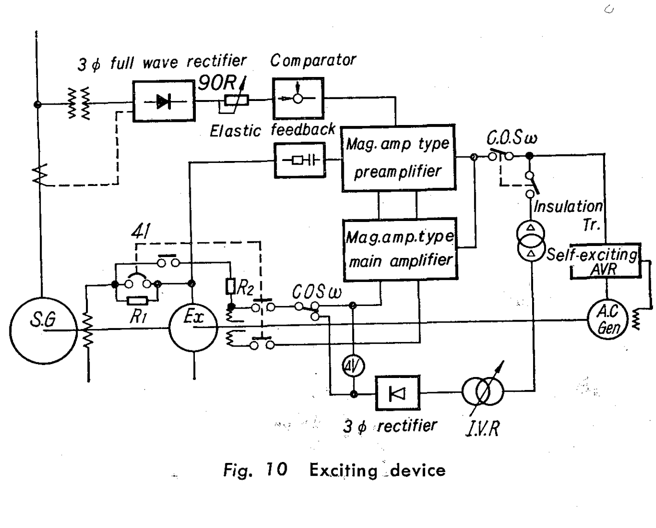


Fig. 10 Exciting device

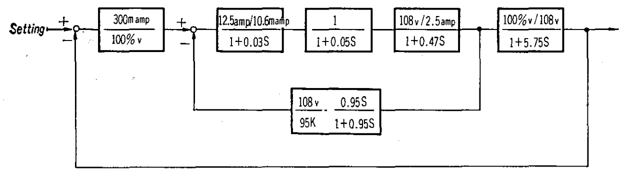


Fig. 11 **Block diagram for exciting system**

AVR, there is a manual voltage regulating circuit which consists of a motor drive induction voltage regulator and a 3-phase full wave rectifier. This is used during initial voltage generation and extinction or AVR breakdowns.

Shockless switching between the AVR and the manual exciter is performed by means of a motor drive overlap type changeover switch when a zero indication is confirmed by the differential-type voltmeter (ΔV) on the central control board.

A block diagram (for no-load conditions) of the AVR and exciting system is shown in *Fig. 11*, and a Bode diagram is given in *Fig. 12*. Oscillograms for the generator voltage setting sudden change test, 4/4 load cut test and rapid de-excitation test are shown in *Figs. 13* (a), and (c), respectively.

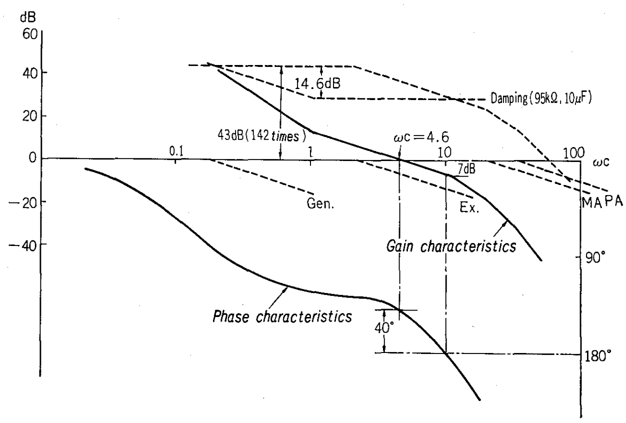


Fig. 12 **Bode diagram of exciting system**

In the Bode diagram in *Fig. 12*, the cut off frequency $\omega_c=4.6$ and therefore T_p, the time required until the maximum value of the initial response is as follows:

$$T_p \doteqdot \frac{3}{\omega_c}=0.65 \text{ (sec)}$$

This value is approximately the same as the 0.7 sec shown in *Fig. 13* (a).

As can be seen from *Fig. 13* (b), the voltage rise

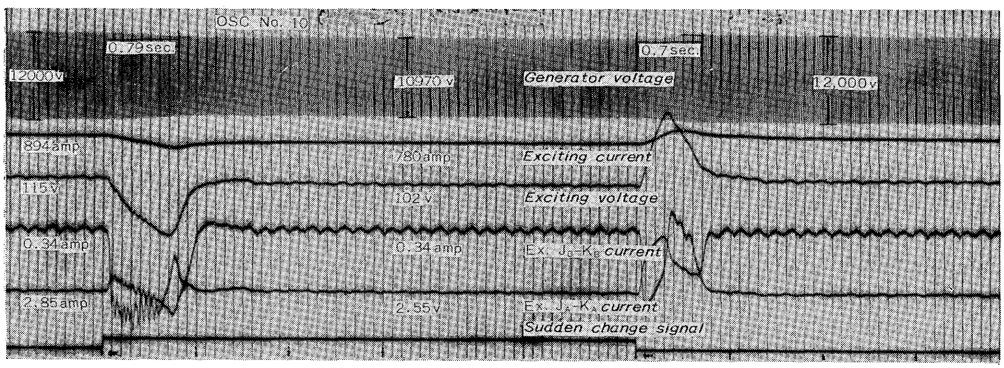


Fig. 13(a) **Oscillogram for voltage setting sudden change test**

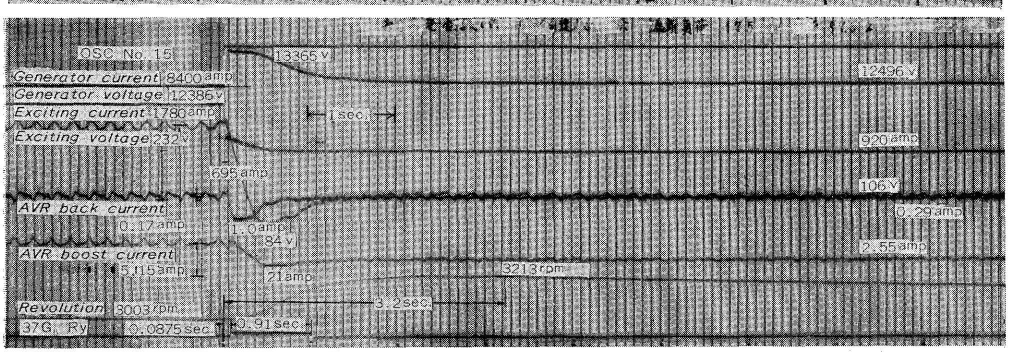


Fig. 13(b) **Oscillogram for 4/4 load cut test**

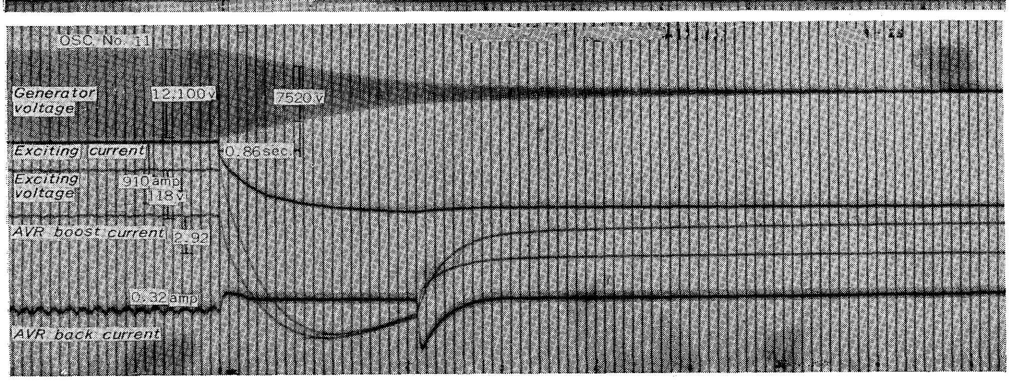


Fig. 13(c) **Oscillogram for rapid de-excitation test** reaches a maximum of 8% at the instant of a full load cutting and the voltage increase due to the influence of subsequent speed increases, etc. is rapidly suppressed when the back-side lower signal arrives. As a result, this exciting system is sufficiently rapid in operation as a exciting system having dc exciter.

From the Bode diagram it can be seen that the gain margin is 7 dB and the phase margin is 40°. In the automatic regulator control system, these values are sufficient.

The de-excitation method generally consists of inserting a parallel resistance in the main generator field and opening the field breaker. Here as in the No. 5 unit, when the de-excitation signal appears, the field breaker is opened and the de-excitation resistance which is connected to both of the main contacts is inserted in the circuit. The counter electromotive force which arises in the main field winding passes through the field winding of the dc exciter and reverses the exciter voltage, so that the main field current is rapidly de-excited. This is the so-called rapid de-excitation system.

Fig. 13 (c) shows an oscillogram for de-excitation from the main generator no-load rated voltage generation. It is evident that the generator voltage is extinguished in about 2 seconds.

3. Main Circuit Protection

The main circuit of the No. 6 unit is shown in *Fig. 14*. The house source circuits differ considerably from those in units No. 1~5. In units No. 1~5, there is one starting transformer for every 2~3 devices and 2 unit transformers to form the so-called unit system. In the No. 6 unit, only one house transformer is provided by checking of the house load on the basis of experience gained with the No. 5 unit. Therefore, this system also serves as a starting transformer by receiving power directly from the 154 kv bus line. With this system considerable savings could be made in the power station construction costs.

VI. INSTRUMENTATION

1. Instrumentation Features

The main instrumentation features are completely electronic operation using the Fuji TELEPERM-system, the fact that the load can be automatically increased in accordance with turbine characteristics when the plant is started, boiler and turbine control can be carried out entirely from a central control room, and all operations can be performed within this room. An outline and the main features of this instrumentation will be given here.

2. Basic Equipment Design

The operating characteristics of the Benson boiler were considered and the instrumentation was designed on this basis. The main points of difference from the drum boiler are given below.

1) Output changes can be made to agree with the turbine characteristics automatically from the central control room.

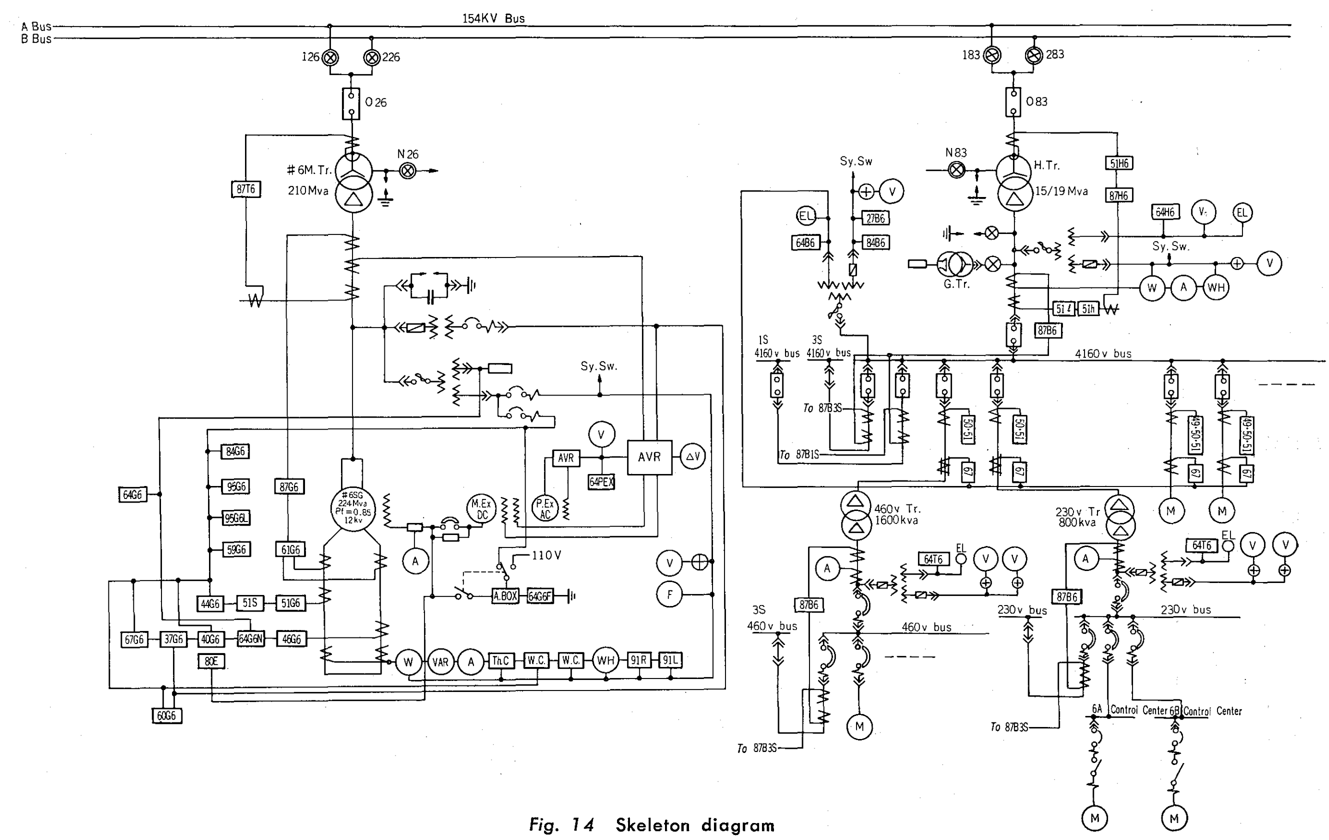


Fig. 14 Skeleton diagram

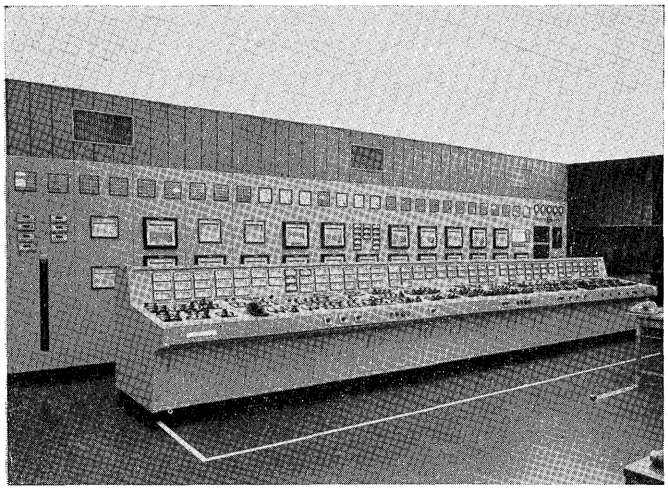


Fig. 15 Central control room with Fuji TELEPERM system

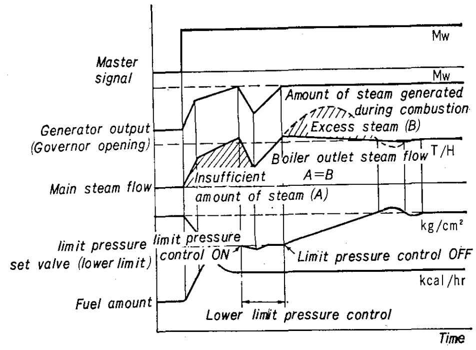


Fig. 17 Transient behavior for limit pressure control

2) Transmitters, computers and operating devices are electrical.
3) The master signal of the overall control system is the generator output and not the boiler outlet steam pressure.
4) Main (reheat) steam temperature control is all performed with the spray water only.
5) There is a special Benson boiler starting/stopping control device.

3. Automatic Control Equipment

1) Power control equipment

The following five methods combined in the power control equipment serve as operating methods of this unit.

(1) Power control

At some constant load variation rate, the load is raised or lowered automatically to the required load, and the load is held constant with the governor in the " free " state.

(2) Load control

The automatic load follow-up equipment for power control is disconnected and power regulation is performed directly by the governor control switch. In this case, due to operating considerations, all power setters receive the device output which is in agreement with the generator power.

(3) Turbine inlet pressure control

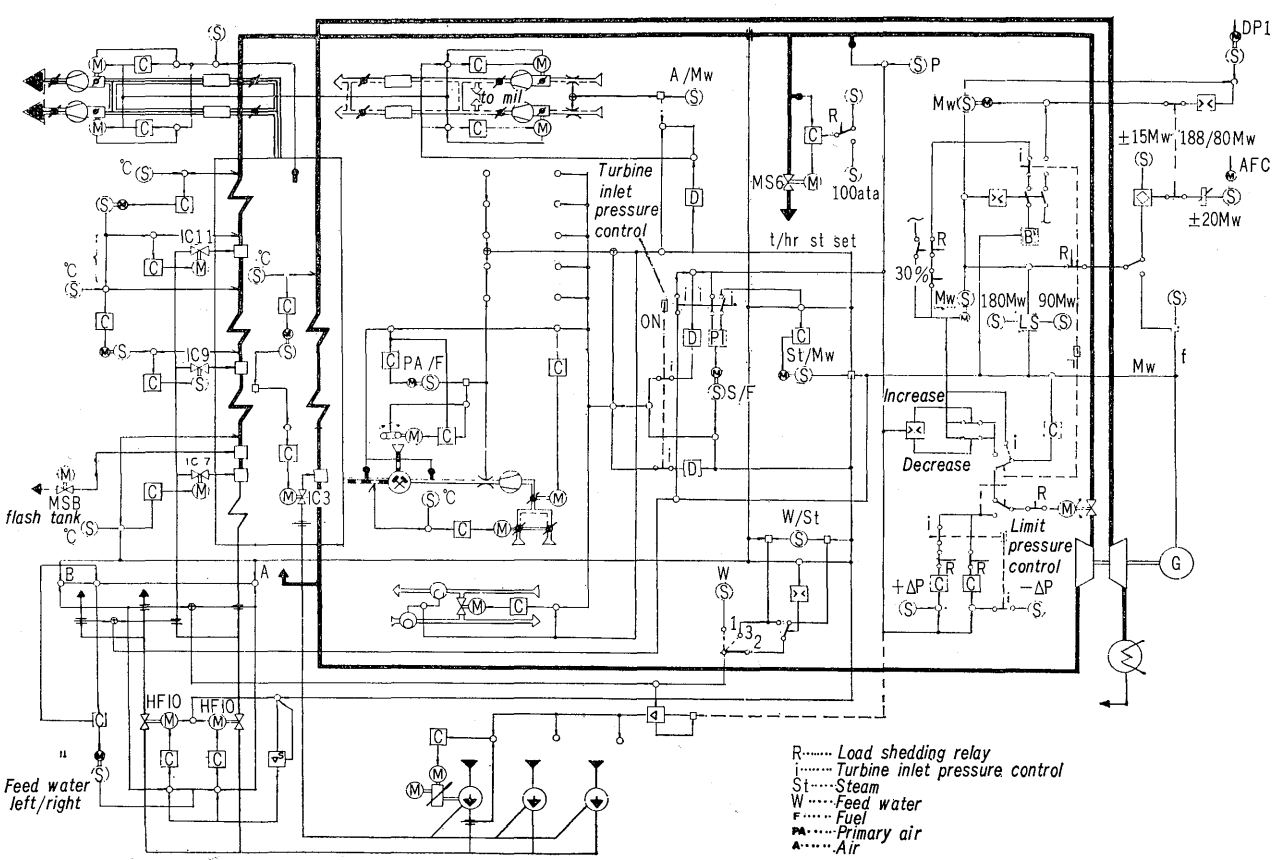


Fig. 16 Basic control diagram

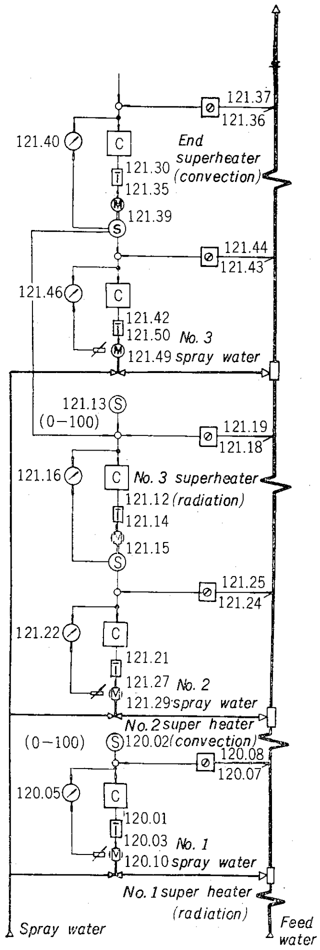


Fig. 18 Diagram of steam temperature control system

The governor is switched independently of the net so as to keep the turbine inlet pressure always constant. The control is employed when boiler starting operation or when boiler operation has priority over turbine output.

(4) Limiting pressure control

When the boiler outlet pressure is raised (or lowered) to the limited value, the governor maintains this limited value. This system is shown in *Fig. 18*.

(5) Frequency influence power control

The automatic frequency control (AFC) signal and the dispatch power control (DPC) signal from the central power station are connected to power control and when the frequency differs from 50 Hz, the output is either increased or decreased corresponding to this deviation value.

2) Feed water control

Feed water flow control is performed by altering the FWP speed and controlling the exhaust pressure. Control is also by means of a feed water adjustment valve which adjusts the amount of feed water in the two lines.

(1) Feed water flow control

The feed water control can be selected from among the following three types according to unit conditions using a changeover switch.

(a) Control in which the amount of feed water flow is adjusted by the master signal.

The feed water is controlled by comparing the amount of feed water flow with a signal composed of the master signal plus the main steam pressure deviation. This method is used under normal operating conditions.

(b) Control in which the amount of feed water flow is adjusted in accordance with a set value.

The signals of the feed water setter and feed water transmitter are compared. If there is a deviation, the feed water is controlled by the operation of the feed water pump regulating device via all the feed water pump controllers. This method is employed during starting and stopping.

(c) Control in which the amount of feed water flow is adjusted in accordance with the main steam flow.

When the changeover switch converts the main steam flow, the amount of feed water flow is compared with a value obtained by multiplying the steam flow amount by the set value on the feed/spray water ratio setter, and the feed water is con-

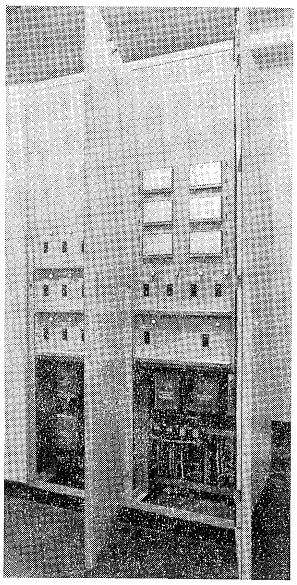


Fig. 19 Cubicle

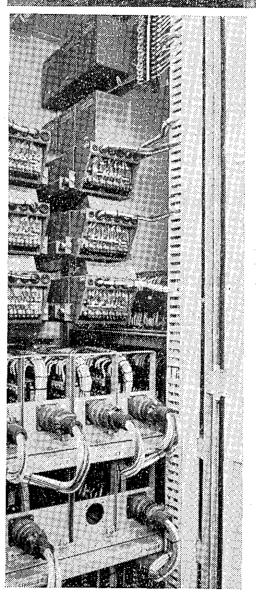


Fig. 20 Back of cubicle

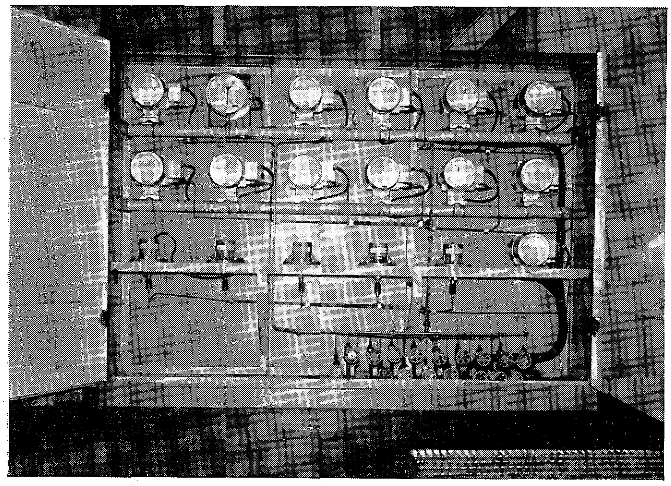


Fig. 21 Local transmitter box

trolled as in method (b) above.

When there is a deviation of about 5% between the master signal and the main steam flow, the main steam flow/load limiter operates, and the feed water is controlled by a signal from the amouut of steam flow. Therefore, mis-operation and carry over are automatically prevented. When the load shedding relay operates, changeover to the steam flow signal is carried out with delay of about 20 sec.

3) Main steam temperature control

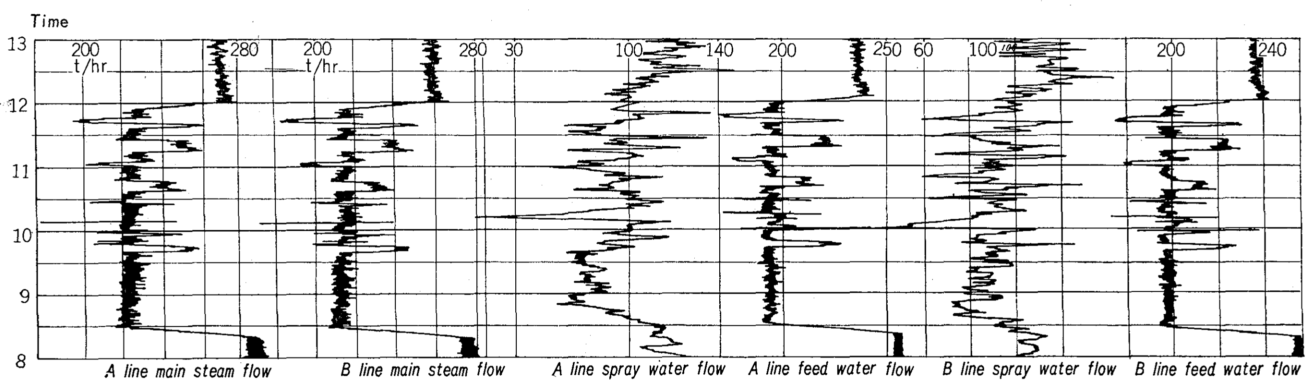
Main steam temperature control is performed only by means of three attemperators. No. 1 spray water control is a set value control and the steam temperature at the No. 2 superheater inlet is held constant. No. 2 spray water is controlled by a cascade system. No. 3 spray water control is also cascade type control because of the time delay of the end superheater. A diagram of the steam temperature control system is shown in *Fig. 19*.

External views of the control device cubicle are shown in *Figs. 20* and *21*.

4. Control Characteristics

Fig. 22 shows the results of automatic control of load tracking tests for oil firing which were carried out on October 15, 1968.

With a base of 140 MW, the load variation rate was 10 Mw/min. As can be seen from the recording charts, the maximum deviation of the main steam pressure was about $\pm 3\ kg/cm^2$ and the main steam temperature was almost constant in spite of the load changes. The control results were judged to be good.



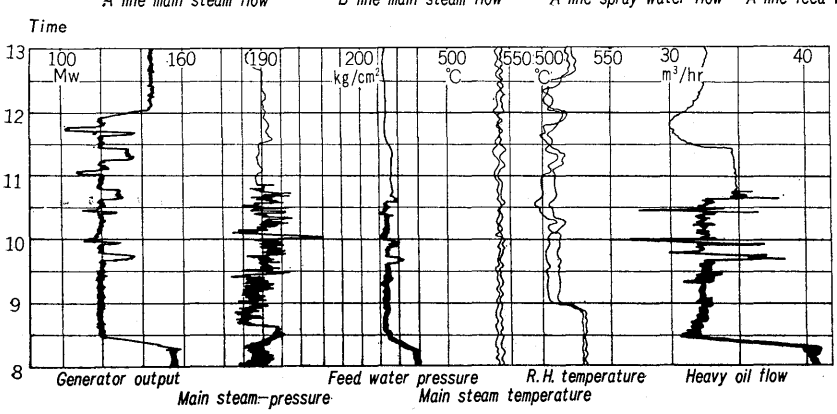


Fig. 22 Recording charts controlled by TELEPERM system