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HIGH-HEAD FRANCIS TURBINE AND GENERATOR FOR WOH POWER STATION, MALAYSIA

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I. INTRODUCTION

Fuji Electric Co., Ltd. received an order from the National Electricity Board of Malaya (N.E.B.) for three complete sets of 87,500 hp high head Francis turbine coupled to 55,500 kva vertical shaft synchronous generators complete with five sets of spherical valves and four sets of butterfly valves for operation, all auxiliary machines, and a 125 ton electrically operated overhead crane for erection and maintenance.

Fuji Electric was responsible for complete design, manufacture, transportation, installation, and final testing at the site and is also responsible for maintenance for a period of one year.

Fuji Electric recently completed the major portion of the contract and is now engaged in installation work at the site in Malaysia.

This power plant has many distinctive and outstanding features, the main ones of which are as follows.

The turbine is one of the largest high-head, Francis turbines in the world. Owing to civil construction, the draft head has been limited to −3.4 meters occasioning very careful runner design.

The water for this power plant is greatly contaminated and contains as much as 5500 p.p.m. of solids in the flood season. Special consideration has, therefore, been paid to the sealing devices to prevent leakage of muddy water through the runner labyrinth which would easily cause wear. For prevention of blockade of the cooling water pipes caused by iron reducing bacteria, a solution of sodium hypochloride is injected into the cooling water system by special equipment to maintain chlorine ions in the cooling water.

As the existing power system of N.E.B. contains only 110,000 kw (hydraulic power) and 12,600 kw (diesel engine power), the Woh Power Plant with a total capacity of 150,000 kw will become the country's leading power plant and maintain stability of the power system.

For this reason the generator must have a large flywheel effect beyond that of a normal generator of similar capacity.

Consequently, the rotor has to be designed with a large diameter, and at runaway speed of the turbine the peripheral speed of the rotor is 171 m/s which is the highest rotor rim speed ever attained in the world.

The outline of the scheme and the machines is as follows.

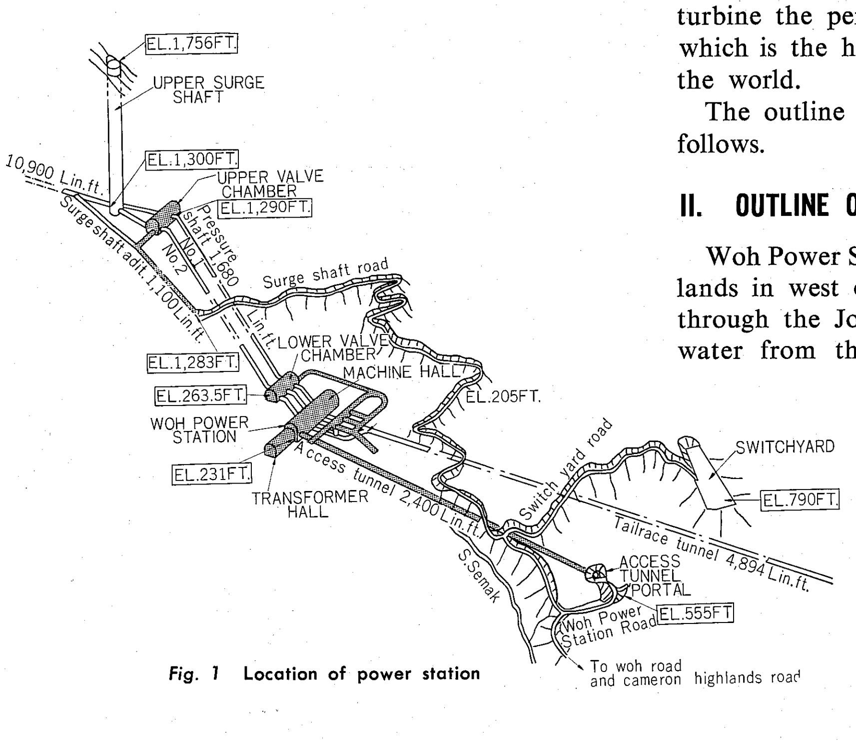

Fig. 1 Location of power station

II. OUTLINE OF THE POWER PLANT

Woh Power Station is located in the Cameron Highlands in west central Malaysia. The water passing through the Jor Power Station is combined with the water from the Batang Padang River valley at a dam known as the Jor Dam which provides limited water storage, and is then led through a tunnel to a surge chamber and directed via two steel-lined pressure shafts to the lower valve chamber, from where the water is led into three inlet pipes and fed to the turbines.

The upper valve chamber, at the upper ends of the pressure

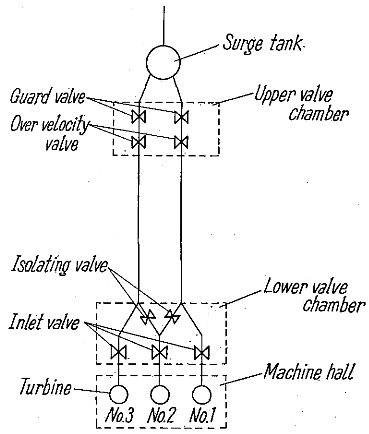

Fig. 2 **Arrangment of power station**

shaft, contains two butterfly type guard valves and two butterfly type over velocity valves.

Two spherical type isolating valves and three spherical type inlet valves are provided in the lower valve chamber.

Each steel-lined pressure shaft is so designed that it has sufficient capacity to supply water for the full load of two turbines.

When inspecting from one pressure shaft while running the turbines from the other shaft, water pressure on the isolating valve on the former shaft will be reversed. Therefore the isolating valve used is a double sealed spherical type which provides both up and down stream sealing.

Woh Power Station is normally remote controlled from the Jor Power Station and operated as a peak load station.

The turbines are also required for spinning reserve operation in order to meet a quick rising demand for power and an air compressor system is provided in the runner chamber for water depression during this operation.

The power house, and the upper and lower valve chambers are all located underground, and the control room and switch yard are located above ground.

As the power station is in a damp and tropical climate (i.e., temperature varies between 36°C and 18°C, and relative humidity between 80% and 100%), the machines have been carefuly designed and manufactured to withstand these conditions.

The separate cooling systems of the machines have ample capacity when using cooling water at a maximum temperature of 30°C.

III. WATER TURBINE

1. Rating of Water Turbine

Number	3 sets
Type	Vertical shaft Francis turbine
Output	Maximum output under max. head; 87,500 hp (65,300 kw)
	Full opening output under normal head; 68,500 hp (51,100 kw)
Head	Max. effective head; 1380 ft (421 m)
	Normal effective head; 1165 ft (356 m)
Discharge	Under max. head 608.4 cusecs
	Under normal head 558.3 cusecs
Speed	600 rpm
Specific speed	23.1 ft-hp

2. Characteristics of Water Turbine

Studies had been thoroughly carried out by model tests on turbine efficiency, cavitation runaway speed, admission of air into draft tube, and hydraulic thrust force, with highly satisfactory results.

Particular care was taken on the cavitation characteristics to meet the cavitation guarantee under the restricted draft head.

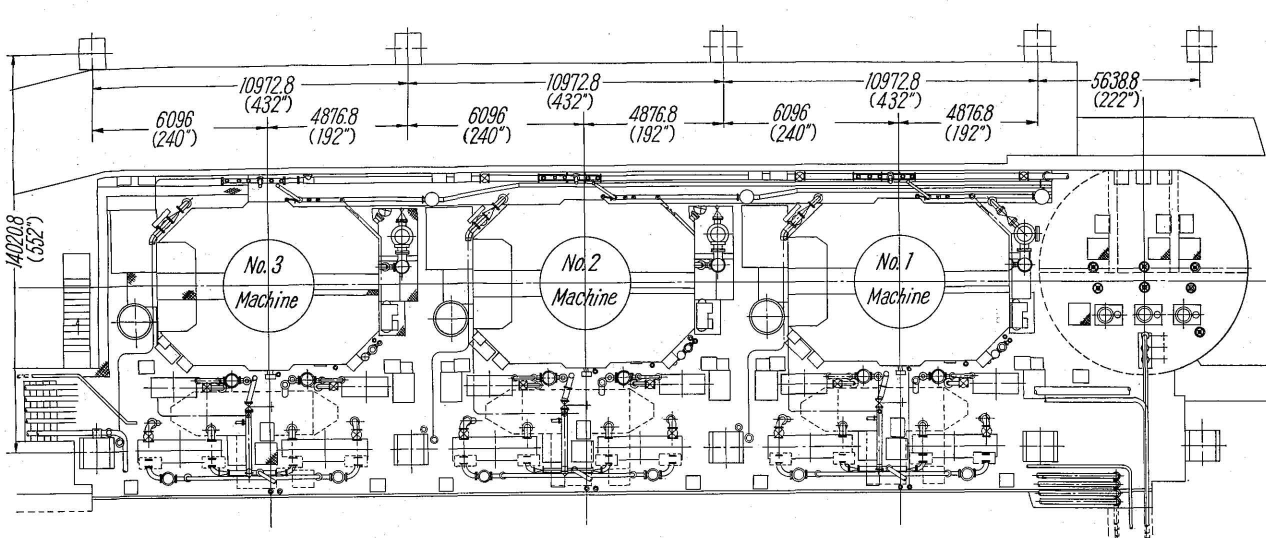

Fig. 3 **Equipment layout in machine hall**

That is, only 15% reduction in runner blade thickness at any point was allowable for cavitation pitting after 8000 hours of operation, of which not more than 800 hours was as low as 30% of rated output and 40 hours was at maximum output under a draft head of −3.4 m.

The turbines were further subjected to efficiency tests using Gibson's method and runaway speed tests at the site after installation during taking over.

3. Construction of the Water Turbine

As the turbines are among the highest head Francis turbines in the world, many special design features were adopted during construction and special attention was given to dealing with high amounts of contaminants in the water, which can easily cause wear of the runner labyrinths, a vital part of high-head Francis turbines.

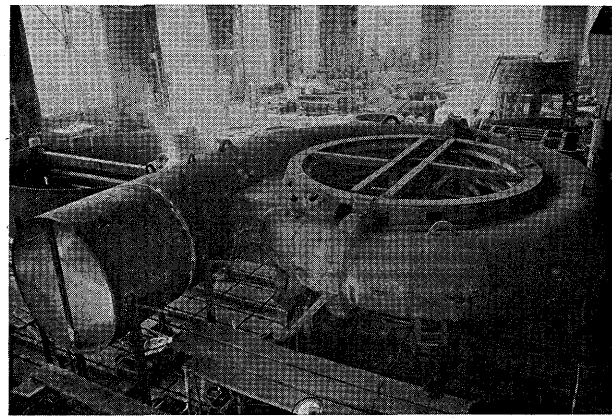

Fig. 5 Scroll case under assembly at factory

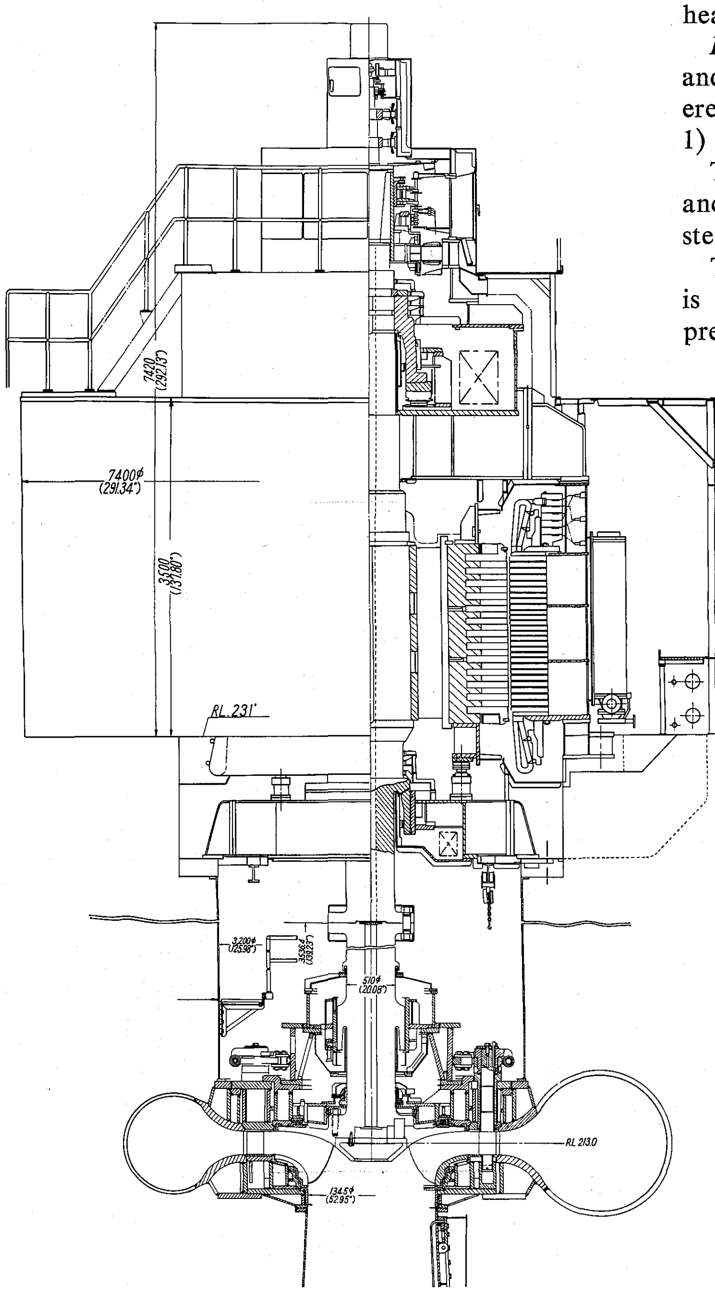

Fig. 4 Cross-section of water turbine and generator

Fig. 4 shows the cross-section of the water turbine and generator; in *Fig.* 6 one of the turbines in the erection shop can be seen.

1) Scroll case and speed ring

The scroll case having an inlet diameter of 1450 mm and the speed ring are both fabricated from SB46BSR steel plate.

The thickness of the steel plate for the scroll case is 50 mm in consideration of the 58.5 kg/cm^2 design pressure and 76.2 kg/cm^2 hydraulic test pressure.

Careful attention was given to turbine welding and, in addition to magnaflux tests and X-ray examinations, destruction tests were carried out for the specially important welded parts by attaching test run-off pieces to the mother plate.

The scroll case and speed ring were divided into two sections due to the transportation limit and the inlet of the scroll case is welded

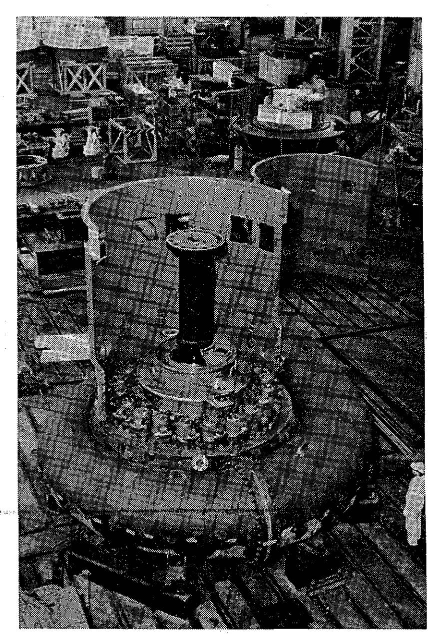

Fig. 6 Shop assembling of water turbine

to the inlet pipe at the site.

The upper two-thirds of the scroll case is covered by a resilient blanket to provide for change of dimensions when empty or when subjected to extreme water hammering.

After assembly on the permanent foundations at the site, the scroll case was filled with water and subjected to an internal hydrostatic test pressure of 76.2 kg/cm² for two hours. The pressure was then reduced to 35 kg/cm² and maintained for prestressing of the scroll case while it is embedded in the concrete for 14 days.

The internal surface of the scroll case which is exposed to flow of water is heavily protected by zinc-rich paint and a bitumen enamel epoxy-resin compound.

2) Runner

The runner is made of 13% chrome stainless cast steel (BS 1630 Grade A) having a 2000 mm inlet diameter. A cone of stainless cast steel (SCS 1) is attached to the runner crown to guide the water as it leaves the runner. The wear rings of stainless steel are of a different hardness from that of facing plates on the stationary parts provided on the runner crown and the runner band to prevent galling or tearing of the metal in case of rubbing.

The runner is spigotted to the main shaft and attached to it by installation bolts and torque pins. Balance holes are provided on the runner crown which also serve as air inlets and outlets for depressing water in runner the chamber during spinning reserve operation.

As interchangeability of three runners and one spare runner is requested, all runners and shafts have been drilled with an accurately machined template and interchangeability of any shaft with any runner was successfully demonstrated.

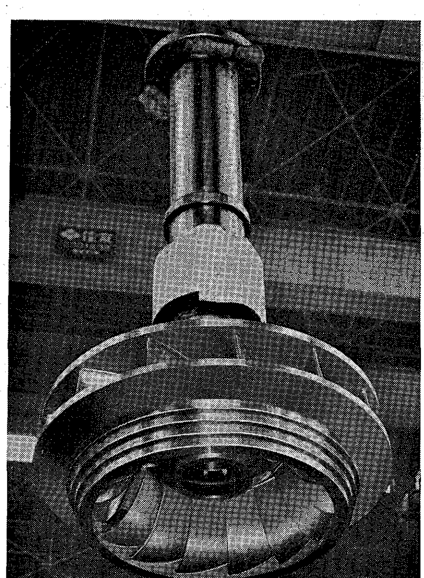

Fig. 7 Runner with shaft

3) Shaft and turbine bearing

The main shaft is made of forged, low carbon, open hearth steel and has a 510 mm diameter with integrally forged flange conforming to A. S. A. Standard B.49.1–1947 "Shaft Couplings, Integrally Forged, Flanged Type for Hydro-electric Units".

The coupling with the generator shaft is secured by fitted bolts. Shaft runout was checked together with the generator shaft in the works, and the amount of runout was confirmed as being within the tolerance recommended in NEMA "Standards for Vertical Hydraulic-Turbine Generator Shaft Runout Tolerances".

The turbine guide bearing is self-lubricated and designed to withstsand safely and without damage natural retardation of the turbine and generator from maximum runaway speed to rest without use of the generator brake.

Pumping action is created by the principle of viscosity pumps. Six oil grooves of special form are provided on the sliding surface of the bearing for this purpose.

A separate type oil cooler is provided on the outside of the generator barrel and connected to the bearing housing with pipes.

4) Guide vanes and regulating gear

The guide vanes are of 13% chrome stainless cast steel (SCS2) with integrally cast spindles. Each guide vane is provided with three bronze bushings; a grease lubricated guide bearing is provided in the bottom ring and two more in the top cover. Between the upper and lower part of the guide vanes is provided a break link.

On this link, screws are provided for adjusting the relative position between the upper and lower arms so that the guide vane positions can be adjusted individually to ensure close contact with adjacent guide vanes when closed, and equal simultaneous opening of all guide vanes.

The guide vane linkages are designed so that pure tensile force takes place on the breaking links in the event of blockage of guide vanes so as to ensure the breaking of links with a pre-determined force.

In the event of breaking of the links, the angular movement of the guide vanes is limited by a stop to prevent interference with the operation of the others. A suitable lever aligning device is provided for pulling guide vane levers into any operating position without changing the load on the turbine, and with the guide-vane temporarily locked at any guide-vane opening, so that a broken link may be replaced. Limit switches are provided to indicate breakage of the links.

5) Top cover and bottom ring

The top cover is fabricated from steel plate and cast steel and divided into two sections, i.e., outer and inner covers, so as to facilitate dismantling and to permit installation and removal of the runner and shaft as a unit without disturbing the guide vanes.

Both the outer and inner top covers are sectionalized into upper and lower chambers. The upper chamber is used as a path to deal with leakage water from the stuffing box, and the lower chamber serves as a part of equalizing pipe, which reduces the pressure in the region above the runner in consequence of equlizing it with the pressure in the draft tube.

The bottom ring is fabricated from steel plate. On the top cover and bottom ring, a three stage labyrinth is provided.

As described previously, a special sealing water system is applied to the runner labyrinths, i.e., the water taken from the scroll case is filtered by special fine mesh 0.25 mm filter and is fed to the labyrinths from inside the turbine cover through holes which are provided in both upper and lower labyrinths; this prevents the leakage of water through the labyrinth which contains a great deal of contaminants and wear of the labyrinth at a vital point.

The holes on the labyrinths also feed cooling water to the runner during spinning reserve operation.

6) Stuffing box

An axial carbon-ring type packing is adopted. The coaxial double carbon rings are mounted in a holder, and bear on the sliding plate on the shaft flange. The holder is designed so that vertical movement is free to a small degree within the housing, and is kept in a balanced position due to opposite directional forces; one of which is caused by hydraulic pressure in the upper region of the runner and coil springs, which acts as a downward force to thrust the holder against the sliding plate, and the other by hydraulic pressure of the sealing water, which acts as an upward force to lift the holder away from the sliding plate.

During turbine operation, as the turbine shaft moves slightly downward, the clearance between the sliding plate and the carbon ring becomes larger, permitting greater sealing water flow than in the previous condition. Since this induces a decrease of pressure of the sealing water, the upward force to lift the carbon-ring holder becomes smaller.

Consequently, the holder moves downward so as to thrust itself against the sliding plate.

If the turbine shaft moves a little upward, a movement contrary to the above will appear. As the result of these movements, it can be considered that the main shaft seal has self adjusting ability.

7) Draft tube liner

The draft tube is an elbow type provided with a steel fabricated liner with an overall length of 3353 mm horizontally from the turbine center. The draft tube liner consists of an upper and lower part.

The upper draft tube is provided with a manhole through which a person can enter the runner chamber. The manhole door is fitted to the upper draft tube liner with double hinges, and the internal surface of the door is flush with of the draft tube liner. The manhole door opens inward and downward to the inside of draft tube and becomes a platform for runner inspection.

4. Governor and Pressure Oil System

1) Specifications

Governor

Type of actuator: MA–65 mechanical type
Capacity of main servomotor: 9600 kg-m

Pressure oil system

Type of oil pump:	Vertical shaft screw pump
Pump drive:	Motor driven (one ac motor and one dc motor)
Discharge:	70 l/m (each)
Oil pressure:	22.5 kg/cm^2～24.5 kg/cm^2
Pressure tank volume:	2170 l
Sump tank volume:	3200 l

2) Construction of governor

(1) Actuator

A newly developed mechanical type governor is adopted for this plant. The governor is an oil pressure actuator type with an electrically driven governor head.

The actuator is enclosed in a compact metal cabinet of rigid construction, neat appearance, and mounted on the oil sump tank made of steel plate together with the main distributing valve and pressure oil pumps.

The actuator is composed of the speeder, pilot valve, auxiliary servomotor, speed changing device, load limiting device, speed droop adjusting device, and shut-down device, all of which are remote controlled from the local control desk or the main control switchboard installed in the remote control room; hand operating handles are also provided on the governor cabinet suitable for manual starting and stopping from the governor cabinet.

(2) Guide vane servomotor

Two double acting type guide vane servomotors are provided on the outside of generator barrel and operate the regulating ring by means of operating rods.

The cylinders are cast steel and the pistons are ductile cast iron with three piston rings.

When the servomotors close the guide vanes, a special mechanism comes into operation at the half closed position which slows down the operation and gradually closes the guide vanes.

(3) Pressure oil system

A unit type pressure oil system is adopted for each unit. Two motor-driven oil pumps each having a capacity of 70 l/m are mounted on a base formed by the oil sump tank. Both oil pumps are screw types and are directly connected to the driving motor. One motor is a squirrel cage, low starting current, induction motor. The other is a dc motor.

The two pumps are interconnected so that (if the ac supply fails) the dc motor driven pump is started automatically and stopped by the initiation of the oil pressure switch on the pressure tank. When the ac voltage recoveres, the ac motor driven pump takes over automatically. The ac motor driven pump runs continuously and maintains oil pressure by means of an unloading valve when the turbine is in operation. When the turbine stops, the ac motor driven pump is controlled by the pressure switch, and is started when oil pressure in the pressure tank drops to a predetermined value and stopped when oil pressure rises to a predetermined value.

The oil pressure tank has welded construction, and is designed, constructed, and tested to meet specifications set forth in BS1500 "Fusion welded pressure vessels for use in chemical, petroleum, and allied industries."

The oil tank is equipped with a changeover valve (float type) which controls air volume in the oil pressure tank and keeps oil at a predetermined level.

On the bottom of the oil pressure tank, a check valve of float type is provided to prevent

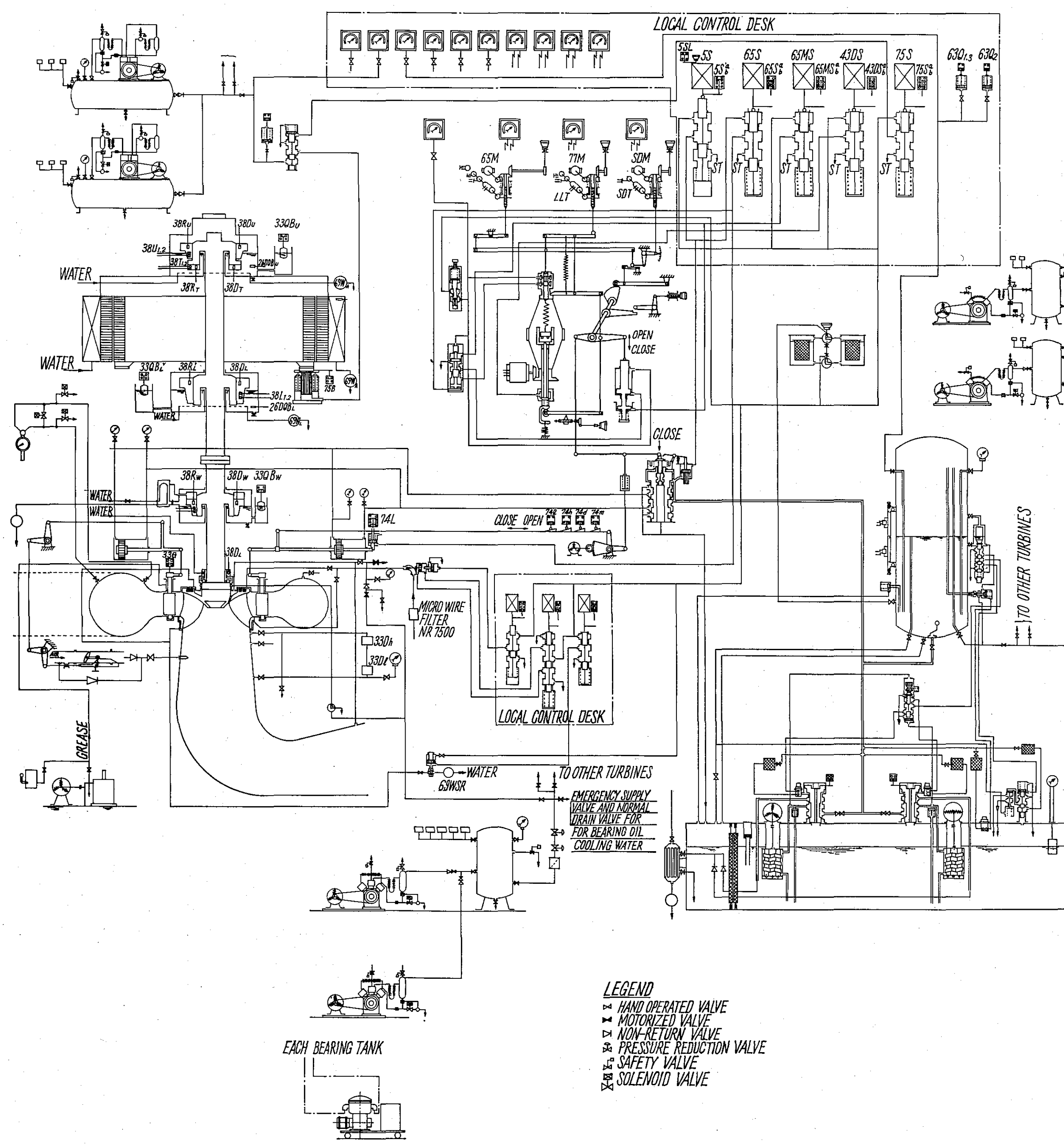

Fig. 8 **Schematic diagram of automatic control of water turbine**

air from entering the piping when the oil level becomes low.

5. Control System

As a separate pressure oil system for turbines and valves is provided, the control system of the turbine and valves are connected only electrically.

The magnetic solenoid valves are contained in the local control desk and can be controlled from the main control desk and the control desk in the Jor Power Station, and also from the local control desk.

The Woh Power Station is required for quick loading operation in order to meet a rapidly rising load demand in addition to normal starting and stopping operation.

Each turbine is provided with reserve spinning facilities such as a low pressure air compressor system, automatic air vent valve, automatic water level control, and special quick-opening inlet valve.

When under reserve spinning operation, the main inlet valve together with the bypass valve are shut off and the guide vanes are closed. The specially provided bypass valve on the inlet valve is opened to maintain water pressure in the scroll case so as to minimize loss of water. The water in the runner space and upper draft tube is depressed by the air compressor so that the runner operates in air.

For quick loading from spinning reserve operation to full load, the air in the runner space is released and the inlet valve and guide vanes are quickly opened to full opening. The turbine takes full load within 30 seconds.

6. Valves

Two penstocks are provided at the Woh Power Station for the three units as shown in *Fig. 2.* In

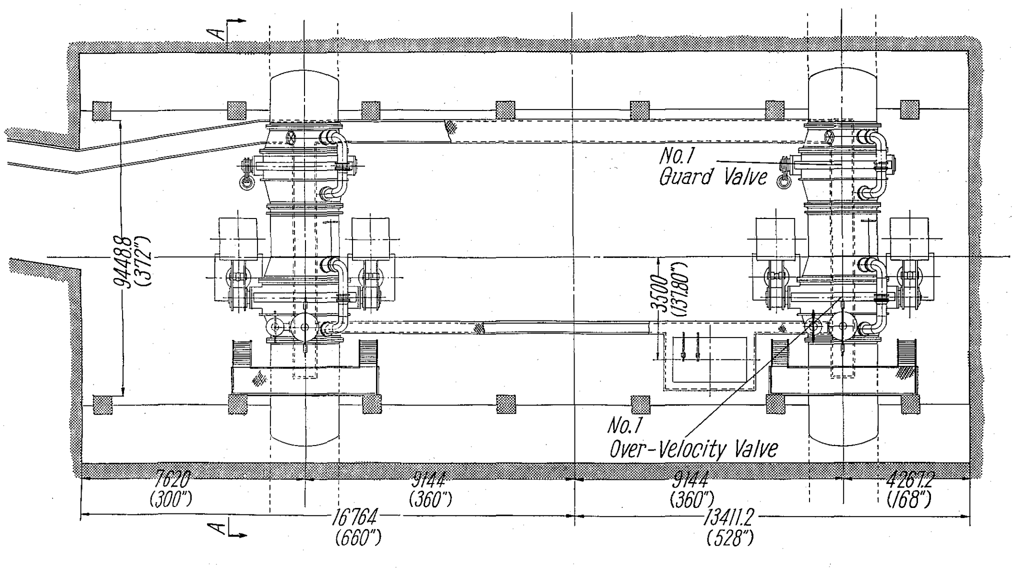

Fig. 9 Layout of valves in upper valve chamber

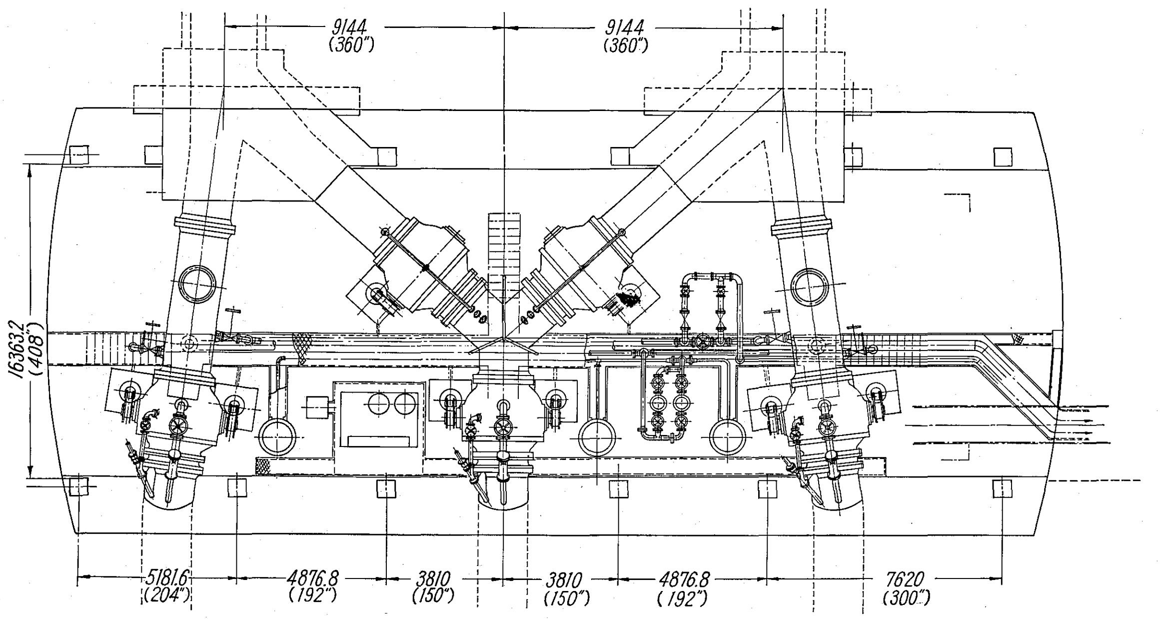

Fig. 10 Layout of valves in lower valve chamber

the upper valve chamber, an over velocity valve and a guard valve are provided for each penstock; in the lower valve chamber, two isolating valves and three inlet valves are provided for the three units.

1) Guard valve

The butterfly type guard valve of 2660 mm bore is fitted to facilitate dismantling of over velocity valves or inspection of the penstock and is located just upstream of each over velocity valve. This valve is provided with oil servomotors which are operated by a hand operated oil pump.

A three sectioned make-up piece of fabricated steel plate is provided between the guard valve and the over velocity valve, and welded together at the site to ensure accurate assembly of both valves.

2) Over velocity valve

The butterfly type weight-operated over velocity valve of fabricated steel plate construction has a

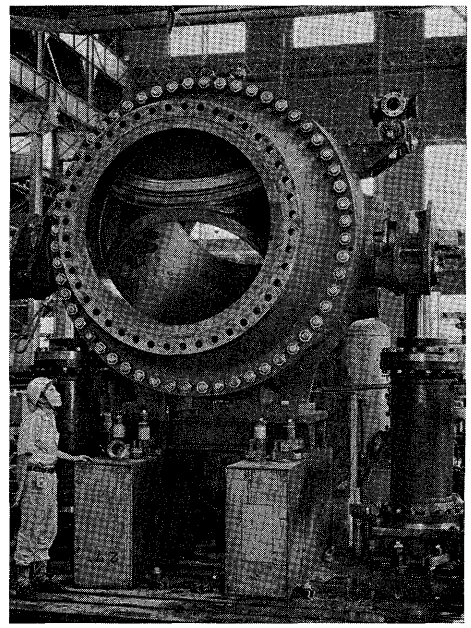

Fig. 11 Shop assembling of inlet valve

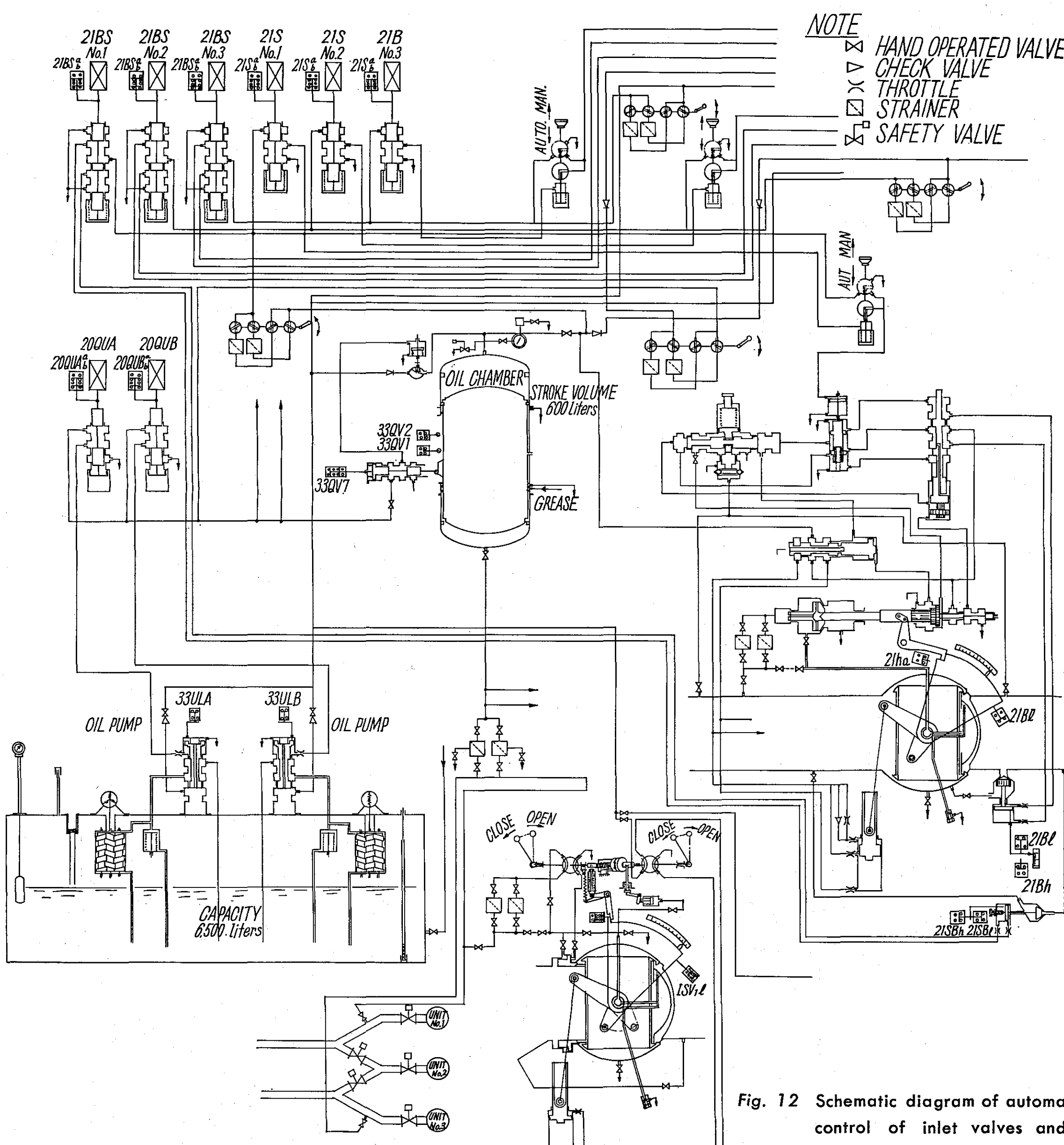

Fig. 12 Schematic diagram of automatic control of inlet valves and isolating valves

bore of 2770 mm and is provided for each penstock to shut off flow automatically if the velocity of flow goes beyond a predetermined value, as might occur in the event of a penstock or scroll case damage. Servomotors are provided on the valve for opening by hand; closing is made by weights controlled by a dash pot.

For both guard and over velocity valves, a combined metal and synthetic rubber seal are provided which is adjustable from downstream with the valve door closed against full head.

Between the over velocity valve and penstock flange, a removable distance pipe is provided to enable a trolley to be brought in for inspection of the penstock.

3) Inlet valve

The inlet valve is a spherical type with 1524 mm diameter and operated by oil pressure. The oil pressure is created by a hydraulic/oil pressure converter in which water pressure taken from penstock is converted to oil pressure. The hydraulic/oil pressure converter is used in common for the three inlet valves and two isolating valves.

Valve seats are provided on the downstream side of the valve body and the choking plate.

The choking plate is operated by water pressure taken from the penstock through a strainer, and its operation is interlocked with operation of the servomotors which control rotating of the valve. That is, the choking plate can move independently after completion of the servomotor stroke to the end limit of the valve closing position.

The inlet valve and its bypass valve are controlled remotely by electrical remote control from an automatic control system, and can also be operated locally by hand.

4) Isolating valve

The isolating valve is a double sealed spherical type having the same inside diameter as the inlet valve, and is operated manually by oil servomotors.

A valve seat is provided on the sleeve mounted on the upstream side of the valve body and the rotating valve door; the downstream side seal is the same as that of the inlet valves.

The operation of the upstream side sleeve and the choking plate on the downstream side is performed by hydraulic pressure taken from the penstock, and controlled manually.

5) Pressure oil system for valves

A pressure oil system operated by a hydraulic/oil pressure converter is provided for the three inlet valves and two isolating valves.

The system consists of a double piston type accumulator, an ac motor driven oil pump, a dc motor driven oil pump as a stand by, and a sump tank which forms the base of the oil pumps.

To the lower side of the piston, pressure water from the penstock is fed, the water pushes up the piston and creates oil pressure on the upper oil side of the piston.

With consumption of oil by operation of valves, the oil volume in the oil chamber decreases; consequently the piston moves up according to this decrease of oil volume. The control valve and solenoid valve of oil pump are initiated by a limit switch which acts by the displacement of the piston; the oil pump then starts feeding oil into the oil chamber of the hydraulic/oil pressure converter. When the piston returns to the predetermind position, the oil pump stops automatically.

6) Water system

The water system consists of three independent groups:

(1) for generator air and transformer oil cooling system

(2) for bearing cooling water system

(3) for air conditioning system

The generator/transformer cooling water system provides two double ended pumping sets per unit. One of the pumps for each unit draws water through a suction pipe connected to the draft tube and discharges it into a unit header providing cooling water to one generator and its associated transformer; the discharge from both is led to a separate pipe in the sump pit. The other pump for each unit draws from the sump pit through a suction pipe and discharges into the downstream surge chamber. The operation of the pumping set associated with running of the turbine and the discharge of both pumps are controlled automatically according to the water level in the water discharge sump pit.

The bearing cooling water system provides three supply pumps and three drainage pumps. Two pumps have a total capacity of sufficient to supply the three units by two pumps, the remaining one pump acting as standby.

The water is drawn from the draft tube through fine mesh self-cleaning type strainers and is fed to a water tank which is erected on top of the roof of the machine hall. The discharge from each bearing of the units is led to the main pump. In the main sump, three vertical shaft drainage pumps are provided and discharge the water to the downstream surge shaft.

These drainage pumps are controlled so that all pumps start sequentially when the water level in the main sump rises beyond a predetermined level. For emergency or failure of the bearing cooling water supply pump, the generator/transformer cooling water system is designed to be connected to the bearing cooling water system by means of an automatic valve, and supplies water to the bearing coolers.

In consideration of the highly contaminated water, all cooling water systems are provided with self cleaning type strainers of fine mesh (0.2 mm or 0.25 mm).

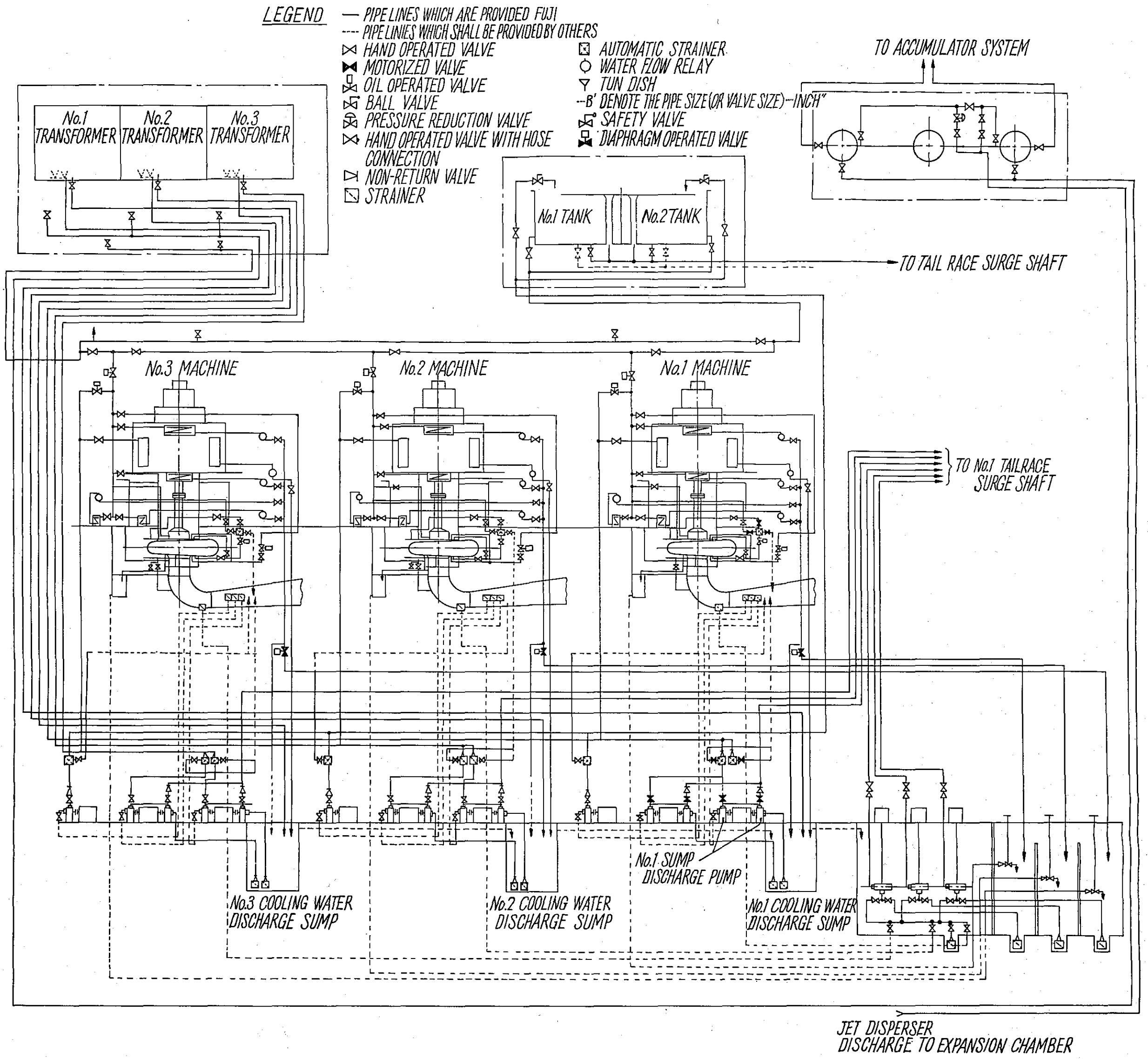

Fig. 13 Schematic diagram of water supply and drainage system

IV. GENERATOR

1. Rating of Generator and Exciter

1) Generator

Type:	Vertical shaft totally enclosed closed-circuit air-cooled synchronous generator
Number:	3 units
Capacity:	C.M.R. 55,500 kva Overload 63,800 kva (90°C rise based on cooling water at 30°C)
Voltage:	11,000 v ±10%
Frequency:	50 cps
Power factor:	0.9
Speed:	600 rpm
Runaway speed:	1090 rpm
GD^2:	331 t-m^2
Rule:	British Standard Specifications

2) Exciter

Capacity:	220 kw
Voltage:	220 v
Ceiling voltage:	440 v

2. General

Recently, the limitation of generator output per pole is being extended considerably due to the advancements in design and development of new materials having greater tensile strength. In 1963, Fuji Electric manufactured and delivered two sets of 74,200 kva 500 rpm generators to Kinugawa P.S. These units have exceeded the output limit of 12 poles generators, and have provided excellent operational results for three years. In addition to this example, Fuji Electric has now broken the record for the limitation of output per pole, and has completed three sets of 63,800 kva 600 rpm generators with successful results, although was encountered greater difficulty in designing and manufacturing than in the case of Kinugawa generators. During

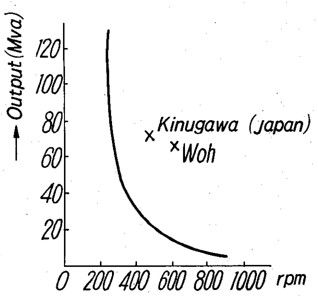

Fig. 14 Relation between output and speed of the water turbine generator built in our country (mean value)

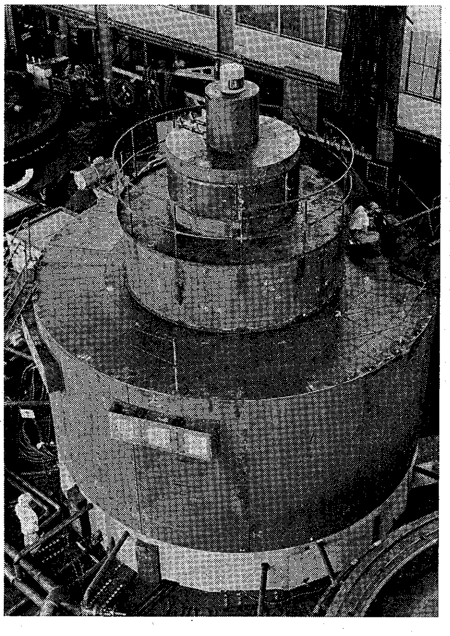

Fig. 15 63,800 kva generator

the design of Woh generators, the problems of the strength of rotating parts versus high peripheral speed, effective air circulation around the armature winding versus relatively large core length, and effective lubrication of bearings versus high speed running were carefuly examined.

In the usual design of generators, rotor diameter is determined so that peripheral speed of the rotor at normal operation is less than 90 m/s considering, windage loss and noise which would increase rapidly if peripheral speed exceeded this value. The peripheral speed at the runaway speed of turbines should be less than 160 m/s in view of strength of materials. In the Woh generator, a large flywheel effect of 331 t-m^2 was requested in view of the stability condition of the transmission system. This value exceeds the natural flywheel effect of the generator. Consequently, the diameter of the rotor was determined at 3000 mm which gives 84 m/s and 171 m/s peripheral speed at nominal running and runaway speed respectively. The peripheral speed of 171 m/s is the highest value ever attained in the world for water-turbine generators. Fuji selected this value with great confidence based upon our experience with the Kinugawa generator.

3. Construction

In basic arrangement, the generator has a vertical shaft with one upper combined thrust and guide bearing and a lower guide bearing. The machine is equipped with a direct-coupled exiter and permanent magnet generator. The shaft extends right through the machine and is flange-fitted to the turbine. A closed-circuit air cooling system is used for the generator and also for the exciter.

1) Stator

The stator frame of fabricated steel plate box type construction is sectioned into three pieces due to transportation limits. The stator frame was so designed that it forms a very rigid structure under the most severe condition and withstands without damage electrical and mechanical forces which result from a bolted 3-phase short-circuit at generator terminals. After completion of the lamination work of the core plate, an induction test was carried out to insure that there was no local heating or local vibration of the stator core and frame.

The core is made up of high permeability low-loss silicon steel plate (0.5 mm thickness) produced by a cold rolling process. After punching, all laminations were annealed to reduce iron loss caused by residual stresses to a minimum, which resulted from the punching process. Each lamination was treated with a special varnish on both sides to insulate eddy current which causes loss. The core was finally assembled and tightly clamped after some few cycles of heating and repressing to avoid noise and vibration caused by loose clamping due to shrinkage of insulation material in the course of time.

The stator windings are star-connected wave-wound parallel circuits. Coils consist of one turn and " Robel " transposition is included to reduce stray load loss. F-resin (Epoxy resin) developed by Fuji Electric was adopted for main insulation of coils for

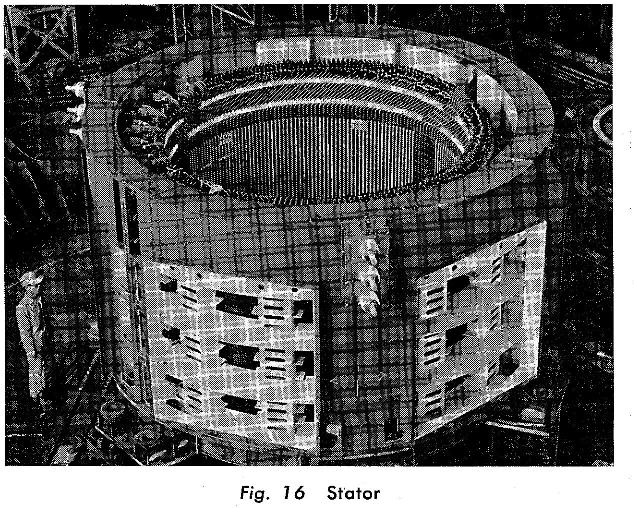

Fig. 16 Stator

superiority of dielectric loss characteristics corresponding to temperature, dielectric loss characteristics corresponding to impressed voltage ($\tan \delta / \Delta V$), durability against corona, non-hygroscopic characteristics and good mechanical properties.

CO^2 fire fighting equipment was deleted in view of non-combustion supporting characteristics of F-resin coils.

The winding was effectively braced to withstand forces set up by single-phase or three-phase short circuits at the terminals, considering the large amount of short-circuit current due to the small reactance of a ten-pole generator.

2) Rotor

Due to the requirements of the flywheel effect of the generator, the diameter of rotor had to be as large aspossible. With the adoption of comb construction, which is capable of withstanding a higher rotor peripheral speed than that of conventional dove tail construction or double T-head construction, the diameter was set at 3000 mm which resulted in 171 m/s peripheral speed at runaway speed. High grade material with good magnetic properties and high strength was used for the rim. The periphery of the rotor is provided with circumferential grooves into which are fitted the comb-shaped extensions of the poles. These are then securely fixed to the rotor body by three tight-fitting axial reamer pins (65 mmϕ). In *Fig. 17*, a complete rotor can be seen. *Fig. 18* shows pole assembly work at our shop.

It is desirable to reduce the pole height as much as possible in view of fan action which causes windage loss during running, but this conflicts with the cooling effect of the pole winding due to the reduction of cooling surface. To improve cooling of the field coil, individual turns were arranged so as to project beyond the others in the form of cooling fins.

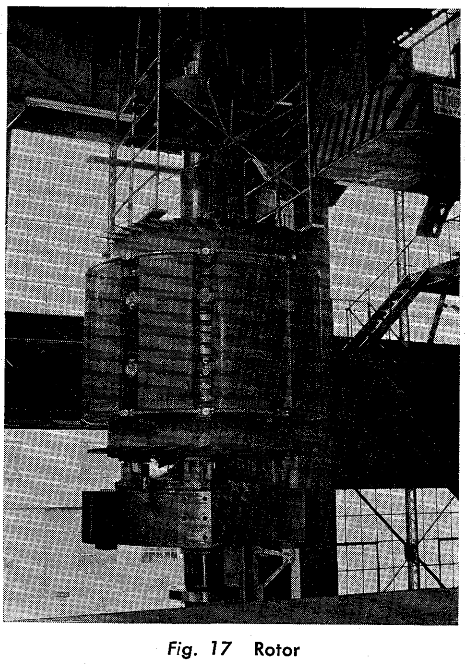

Fig. 17 Rotor

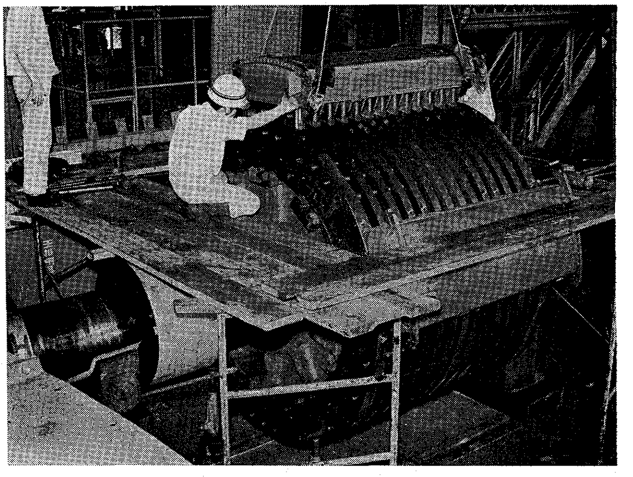

Fig. 18 Pole assembly to yoke

As the field coil consisting of a flat copper strap arranged edge-wise in a single layer is subjected to a huge centrifugal force component acting to press the layer, a special layer insulation of asbestos impregnated with F-resin was adopted. In view of the considerably large centrifugal force component acting tangentially on the field coils and changes in length great enough to cause excessive deformation in a high-speed long-pole machine, a number of field coil braces have been provided in each pole gap in order to allow these lateral force from two coil sides to partly cancel each other. The interconnection of adjacent poles must also be considered, as it must withstand a huge centrifugal force on the connection pieces and allow changes in coil length by thermal elongation; hence special design braces have been provided.

The end segments of the damper winding are secured to the pole end plates to permit the copper bars and segments to expand freely under temperature rise. The segments are jointed from pole to pole by flexible laminated links to allow thermal elongation and these connections are braced on the rotor rims. Special care was taken with regard to disposition of the braces so that resistance to cooling air could be as small as possible. The machine was succesfully shop tested at a runaway speed of 1090 rpm for a period of three minutes. This clearly shows the good design of bracing against an extremely high centrifugal force.

3) Cooling

In the design of machines with a relatively long core length, special attention had to be applied to distribution of cooling air so as to attain homogeneous temperature distribution along the axial direction of the machine. In consideration of windage loss, which occupies a large fraction of total loss in a high-speed generator, cooling air systems were studied to obtain a sufficient cooling effect with maximum efficiency and low loss. Hence the blade angle of the axial-flow fan on both upper and lower ends of the rotor was carefully determined to obtain ideal air flow into the air ducts with an efficient cooling effect.

4) Bearings and lubrication

The thrust bearing (Michel type) is situated directly above the upper bracket. The vertical load, which has to be carried by the thrust bearing, consists of the weight of the turbine runner as well as hydraulic thrust, altogether about 100 tons, and the weight of the complete generator (94 tons). Two guide bearings (cylinder type) are provided on both the upper and lower brackets. All bearings are submerged in oil and are, therefore, automatically lubricated. The thrust bearing and guide bearings are designed to permit the generator to run for 15 minutes without cooling water supply starting with oil at the normal operating temperature, and for five minutes at runaway speed without exceeding the normal temperature of 60°C with supply of cooling water at 30°C.

The peripheral speed of the upper guide bearing (32 m/s at normal running speed) calls for special attention to be paid to lubrication of the bearing. Hence, special-shaped oil grooves on the bearing surface and a device to minimize aeration of the oil (which reduces oil discharge from the self-acting pump) are provided. The special system for equalizing air pressure prevents any oil vapor from entering the cooling air space of the generator.

5) Test results

Exhaustive shop tests were carried out on the first machine. The losses and reactance values were determined, no-load and short-circuit curves plotted, and sudden short-circuit test, temperature rise test and test of the exciter (etc.) were performed. Runaway tests were also made.

(1) Heat run test

The test results are shown in *Table. 1.* The temperature rise is based on cooling water temperature.

(2) Efficiency

The efficiency was determined according to B.S. 2613, with all losses in the exciter, rheostats, and all necessary field equipment included in the determination of efficiency. The results shown in *Fig. 19* fulfilled guaranteed efficiency and this curve shows that, with appropriate design, efficiency for partial loading of a high-speed machine can be improved as much as that of a low-speed machine.

(3) Reactance

Due to the small number of poles, relatively low leakage reactance of each winding was obtained as shown in *Table. 2.*

(4) Waveform

Special attention was paid in design of windings to impove the waveform, specified as 5% in line-to-line and 10% in phase-to-neutral. Test results were 0.9% and 5% respectively.

Table 1. Test Results of Heat-Run Test

Output		55,500 kva	63,800 kva	Guaranteed
Stator winding	E. T. D. R	61.7 °C 62 °C	77.7 °C 79 °C	90 °C
Rotor winding	R	54.6 °C	65 °C	100 °C
Thrust bearing		24.8 °C		30 °C
Upper guide bearing		25.8 °C		30 °C
Lower guide bearing		26.3 °C		30 °C

E. T. D. Embeded temperature detector
R Resistances method

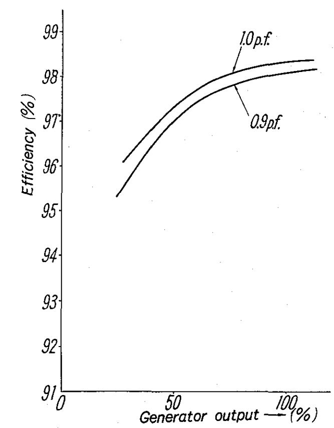

Fig. 19 Efficiency curve

Table 2. Test Results of Reactances and Time Constants

X_d (unsaturated)	112 %
X_d' (50% volt)	27.9%
X_d'' (50% volt)	14.6%
X_2	15.3%
Td_0'	7.1 sec
X_q	67.3%
X_q''	15.4%
X_0	6.67%
Td'	2.05 sec

To sum up the tests, it can be said that the machine very successfully demonstrated all stipulated guarantees.

V. CONCLUSION

In the preceeding, we have outlined planning, design, and production of a unique high-head Francis turbine and high-speed generator for the Woh Power Station in Malaysia. Valuable experience has been gained, which will permit designing and manufacturing of larger high-head Francis turbines and generators with greater peripheral speed.

Work is now proceeding steadily at the site. Two of the three machines are scheduled to go into operation Oct. 31, 1967.