Development of Tandem-Compound 1,000-MW Steam Turbine and Generator

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ABSTRACT: Investment in the construction of fossil-thermal power plants has had to be optimized. This has meant rationalizing equipment while at the same time guaranteeing high reliability and efficiency. This rationalization has produced a clear tendency to change from cross-compound to tandem-compound 1,000-MW fossil steam turbines and generators. Hitachi has already developed all the necessary component technologies for tandem-compound 1,000-MW steam turbines and generators to meet the demands of the electrical power market. A tandem-compound four-flow steam turbine with 40-inch last stage blades and a tandem-compound four-flow steam turbine with 43-inch last stage blades can be applied for 60-Hz use and 50-Hz use, respectively. This paper outlines the technological developments of components for tandem-compound 1,000-MW steam turbines and generators

INTRODUCTION

THE rationalization of thermal power plants and the construction of highly efficient plant equipment was necessary before IPP (Independent Power Producer) participation in the Japanese power market, due to recent changes in Japanese regulations.

Hitachi has been applying cross-compound four-flow (CC4F) steam turbines to 1,000-MW fossil power plants, because 40-inch and 43-inch full-speed long blades were not previously available.

A feature of the CC4F steam turbine is the combination of a primary rotor portion and a secondary rotor portion. The primary rotor portion consists of a high-pressure (HP) section, an intermediate-pressure (IP) section, and a 2-pole generator running at 3,000 r/min and 3,600 r/min; the secondary rotor portion consists of two low-pressure (LP) sections and a 4-pole generator running at 1,500 r/min and 1,800 r/min. The LP last stage (L-0) blade running at half speed with a suitable exhaust annulus area can be obtained more easily than that running at full speed for the 1,000-MW steam turbine, because the centrifugal force

TABLE 1. Development of Large-Capacity Steam Turbines for Fossil Thermal Power Plant
The maximum unit output in the cross-compound and tandem-compound types is 1,000 MW and 700 MW, respectively.

Item	Customer	Unit no.	Output (MW)	Turbine type	Rotating speed (r /min)	Steam condition (MPa-°C/ °C)	First operation year
Tandem compound	Kyushu Electric Power Co., Inc.	Matsuura No. 1	700	TC4F-33.5	3,600	24.1-538/566	1989
	Chubu Electric Power Co., Inc.	Hekinan No. 2	700	TC4F-40	3,600	24.1-538/566	1992
	Later	Later	700	TC4F-43	3,000	25.0-600/600	(2003)
Cross compound	Electric Power Development Co., Ltd.	Takehara No. 1	700	CC4F-38	3,600/1,800	24.1-538/538	1983
	Tokyo Electric Power Co., Inc.	Sodegaura No. 3	1,000	CC4F-41	3,000/1,500	24.1-538/566	1977
	Tokyo Electric Power Co., Inc.	Hirono No. 3	1,000	CC4F-41	3,000/1,500	24.1-538/566	1989
	Soma Kyodo Power Co., Ltd.	Shinchi No. 1	1,000	CC4F-41	3,000/1,500	24.1-538/566	1994
	Tohoku Electric Power Co., Inc.	Haramachi No. 2	1,000	CC4F-41	3,000/1,500	24.5-600/600	(1998)
	Tokyo Electric Power Co., Inc.	Hitachi-Naka No. 1	1,000	CC4F-41	3,000/1,500	24.5-600/600	(2002)

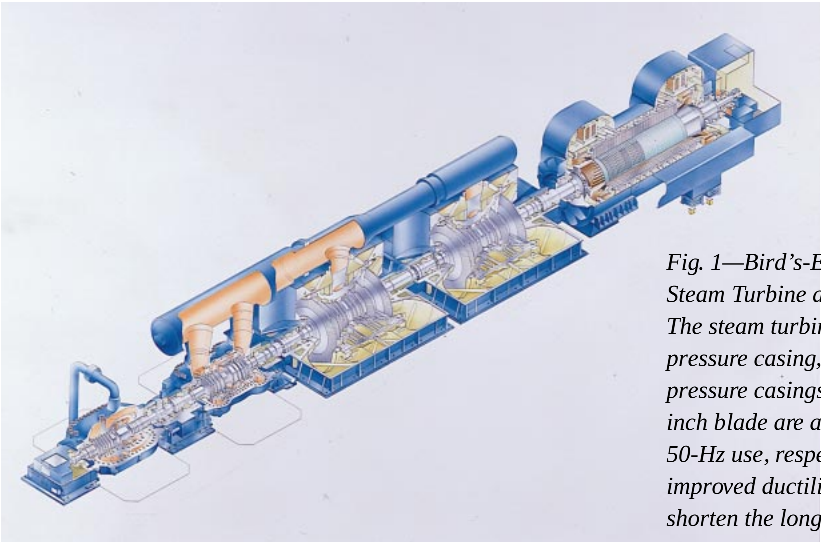


Fig. 1—Bird's-Eye View of Tandem-Compound 1,000-MW Steam Turbine and Generator.
The steam turbine consists of four turbine casings: a high-pressure casing, an intermediate-pressure casing, and two low-pressure casings. A Ti-alloy 40-inch blade and a 12Cr-alloy 43-inch blade are applied to the last stage blade for 60-Hz use and 50-Hz use, respectively. A large diameter rotor made of improved ductility high-strength shaft material is adopted to shorten the longer rotor length of the generator.

on the L-0 blade running at half speed is smaller than that running at full speed. However, the CC4F steam turbine needs two generators for the primary and the secondary rotor portions as well as a larger building and foundation, which results in a higher investment.

While the latest CC4F 1,000-MW steam turbine is the Haramachi No. 2 unit of Tohoku Electric Power Co., Inc., the largest capacity tandem-compound steam turbine is 700 MW. The technology necessary to increase this capacity to 1,000 MW has been developed.

In this paper, we outline the application of the tandem-compound 1,000-MW steam turbine and generator and the new technology Hitachi has developed.

TECHNOLOGY OF TANDEM-COMPOUND 1,000-MW STEAM TURBINE

The large-capacity steam turbines for fossil power plants developed to date are shown in Table 1. Hitachi has developed a 1,000-MW steam turbine of the cross-compound type for 50-Hz use, and has already developed technology applicable to tandem-compound 1,000-MW steam turbines. A bird's-eye view of the tandem-compound 1,000-MW steam turbine and generator is shown in Fig. 1. The following are the details of the technology.

The correlation between unit output and turbine exhaust annulus area is shown in Fig. 2. The tandem-compound four-flow type with 40-inch last stage blades (TC4F-40) and the tandem-compound four-flow type with 43-inch last stage blades (TC4F-43) can be applied to 60-Hz use and 50-Hz use, respectively.

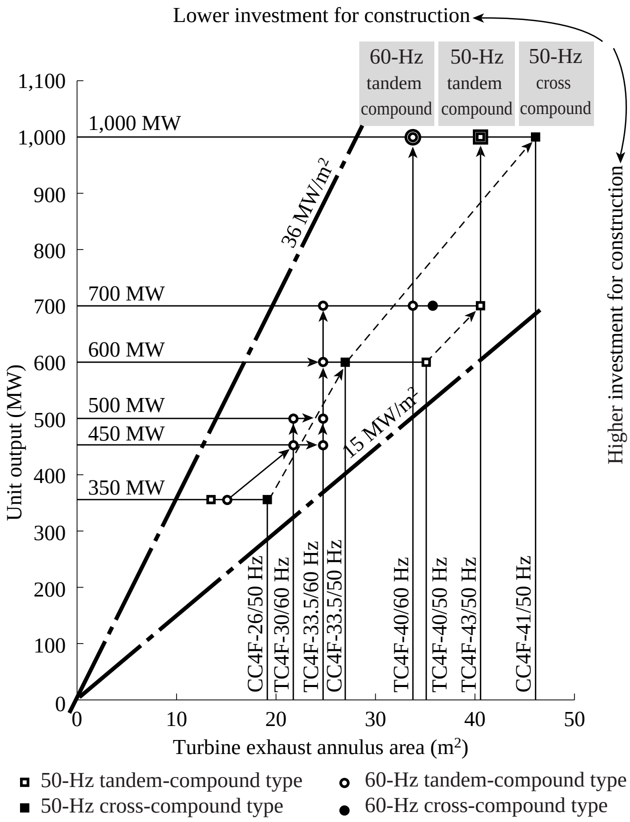
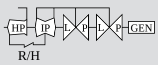
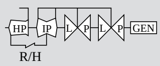
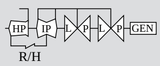
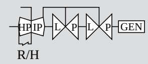
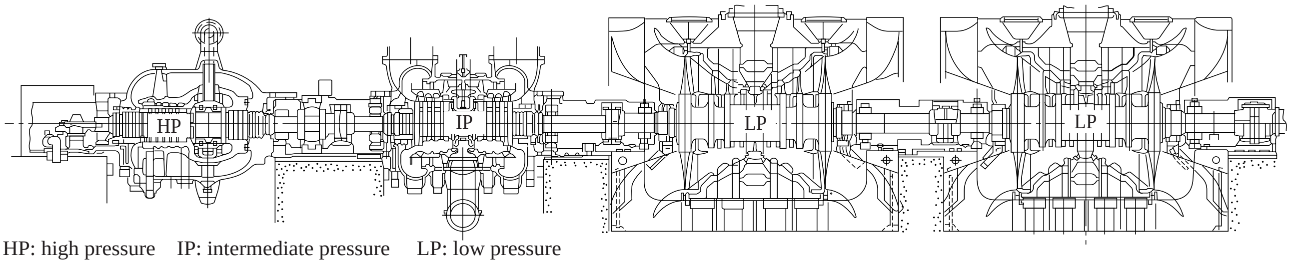


Fig. 2—Correlation Between Unit Output and Turbine Exhaust Annulus Area.
For a 1,000-MW unit, adopting TC4F-40 for 60-Hz use and TC4F-43 for 50-Hz use enables a lower construction cost than that for the CC4F-41 for 50-Hz use.

Table 2. Technical Specification of Tandem-Compound 1,000-MW Steam Turbine for 60-Hz Use and 50-Hz Use
Comparison of technical specification between the new 1,000-MW unit and the conventional 700-MW is shown.

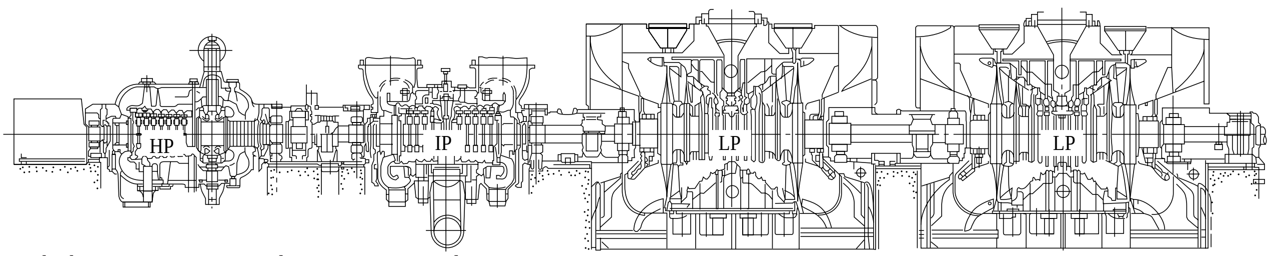
Item			Unit	60 Hz		50 Hz	
				1,000-MW unit (New)	700-MW unit (Hekinan No. 2)	1,000-MW unit (New)	700-MW unit (Customer later)
Turbine type			–	TC4F-40	←	TC4F-43	←
Rotating speed			r/min	3,600	←	3,000	←
Steam condition			MPa	24.5	24.1	24.5	25
			ºC	600 / 600	538 / 566	600 / 600	600 / 600
Specification of steam turbine							
	Arrangement of turbine and generator						
	HP 1st stage	Moving blade		Double flow type tangential entry dovetail	←	Double flow type tangential entry dovetail	Single flow type axial entry dovetail
		Nozzle box	–	Double flow type	←	Double flow type	Single flow type
	LP last stage blade	Length	mm	1,016.0	←	1,092.2	←
		PCD	mm	2,641.6	←	2,646.4	←
		Annulus area	m^2	33.37	←	40.44	←
		Material	–	Ti-6Al-4V Alloy	←	Cr-Mo-Ni-V Steel	←
	Number of stages	HP	–	1 × 2 flow + 6	←	1 × 2 flow + 8	8
		IP	–	5 × 2 flow	←	6 × 2 flow	6
		LP	–	5 × 4 flow	←	6 × 4 flow	6 × 4 flow
		Total (number of wheels)		17 (38)	←	21 (45)	20 (38)
	Size of main valves	MSV	–	ϕ 11 inch × 4	ϕ 9 inch × 4	ϕ 11 inch × 4	ϕ 11 inch × 4
		CV	–	ϕ 9 inch × 4	ϕ 8 inch × 4	ϕ 9 inch × 4	ϕ 9 inch × 4
		CRV (ICV/RSV)	–	(ϕ 34.5 inch/ϕ 30 inch) × 2	(ϕ 29.5 inch/ϕ 26.5 inch) × 2	(ϕ 34.5 inch/ϕ 30 inch) × 2	(ϕ 29.5 inch/ϕ 26.5 inch) × 2
	Total turbine span		m	34.54	33.79	34.54	27.72
Material for main components							
	Main valve casing	MSV	–	9Cr forged steel	Cr-Mo-V forged steel	9Cr forged steel	←
		CV	–	9Cr forged steel	Cr-Mo-V forged steel	9Cr forged steel	←
		CRV	–	9Cr forged steel	Cr-Mo-V forged steel	9Cr forged steel	←
	Rotor	HP	–	New 12Cr forged steel	Cr-Mo-V forged steel	New 12Cr forged steel	← (combined HIP)
		IP	–	New 12Cr forged steel	←	New 12Cr forged steel	N/A
		LP	–	Ni-Cr-Mo-V forged steel (Super clean type)	←	Ni-Cr-Mo-V forged steel (super clean type)	←
	Protection for journal and thrust color			Over-lay welded	N/A	Over-lay welded	←
	Nozzle box		–	12Cr forged steel	Cr-Mo-V cast steel	12Cr forged steel	←
	Moving blade	HP 1st stage	–	New 12Cr forged steel	Cr-Mo-Nb-V steel	New 12Cr forged steel	←
		IP 1st stage	–	New 12Cr forged steel	Cr-Mo-Nb-V steel	New 12Cr forged steel	←
	Turbine casing	HP outer	–	Cr-Mo-V cast steel	←	Cr-Mo-V cast steel	←
		HP inner	–	Cr-Mo-V-B cast steel	Cr-Mo-V cast steel	Cr-Mo-V-B cast steel	12Cr cast steel
		IP outer	–	Cr-Mo-V cast steel	Cr-Mo-V cast steel	Cr-Mo-V cast steel	N/A (combined HIP)
		IP inner	–	12Cr cast steel	←	12Cr cast steel	N/A

HP: high pressure　IP: intermediate pressure　LP: low pressure　GEN: generator　ICV: intercept valve
R/H: reheater　MSV: main stop valve　CV: control valve　CRV: combined reheat valve　RSV: reheat stop valve



HP: high pressure IP: intermediate pressure LP: low pressure

Fig. 3—Sectional Arrangement of TC4F-40 1,000-MW Steam Turbine for 60-Hz Use.
1,000-MW steam turbine has almost the same structure as a conventional 700-MW steam turbine except a slightly longer span because of higher main steam temperature and pressure.



HP: high pressure IP: intermediate pressure LP: low pressure

Fig. 4—Sectional Arrangement of TC4F-43 1,000-MW Steam Turbine for 50-Hz Use.
1,000-MW steam turbine has a separated high-pressure turbine and intermediate-pressure turbine, while a conventional 700-MW steam turbine has an integral high-pressure and intermediate-pressure turbine.

Outline of TC4F-40 1,000-MW Steam Turbine for 60-Hz Use

The design of the tandem-compound 1,000-MW steam turbine for 60-Hz use is based on the TC4F-40 700-MW steam turbine which has already been operated at the Hekinan power plant of Chubu Electric Power Co., Inc. in Japan. The technical specification of the TC4F-40 1,000-MW and 700-MW steam turbines is shown in Table 2. The details of the tandem-compound 1,000-MW steam turbine are as follows.

(1) A Ti-alloy 40-inch last stage blade has been applied to the Hekinan No. 2 unit of Chubu Electric Power Co., Inc.[1)]

(2) A 22-inch-diameter journal bearing has already been developed.

(3) The thermal efficiency has been improved by adopting the elevated steam condition first applied to the Haramachi No. 2 unit of Tohoku Electric Power Co., Inc.: 24.5 MPa-600°C/600°C[2)]

(4) New Advanced Vortex Stage (AVS) [3)]

Fig. 3 shows the sectional arrangement of the TC4F-40 1,000-MW steam turbine for 60-Hz use.

Outline of TC4F-43 1,000-MW Steam Turbine for 50-Hz Use

The design of the tandem-compound 1,000-MW steam turbine for 50-Hz use adopts a 43-inch last stage blade. This has been applied to the TC4F-43 700-MW steam turbine in Japan. The technical specification of the TC4F-43 1,000-MW and 700-MW steam turbines is also shown in Table 2. The features of the tandem-compound 1,000-MW steam turbine are as follows.

(1) A 11.75 Cr-2.5 Ni-2.25 Mo- 0.28V- 0.1 Nb steel 43-inch last stage blade used on a TC4F- 43 700-MW steam turbine.

(2) A 24-inch-diameter journal bearing.

In addition to the above, items (3) and (4) for the 60-Hz type are also applied. Fig. 4 shows the sectional arrangement of the TC4F-43 1,000-MW steam turbine for 50-Hz use.

Development of 43-inch Last Stage Blade for 3,000 r/min Application

Hitachi has recently developed its longest 43-inch last stage blade made of 12 Cr steel for 3,000 r/min application. (A 40-inch last stage blade was previously the longest.)

This 43-inch blade was developed by using higher strength material than the conventional 12 Cr steel. This was done by optimizing the chemical composition of the conventional 12 Cr steel so that it could be quenched more easily. Furthermore, CCB (continuous cover blade) construction equipped with an integral shroud cover and tie-boss has been adopted for stable

Fig. 5—New 43-inch Long Blade for 50-Hz Use
Adopting improved high-strength 12Cr steel, this blade has been developed as Hitachi's longest blade where 12Cr steel material is used.

vibration characteristics.

The 43-inch last stage blade and the rotational vibration test with the full-scale model rotor are shown respectively in Figs. 5 and 6.

TURBINE GENERATOR TECHNOLOGY FOR TANDEM- COMPOUND 1,000-MW MACHINE

A cross-compound 1,000-MW generator burdens the power output with two generators, while the tandem-compound generator generates an output

Fig. 6—Rotational Vibration Test of New 43-inch Blade with Full-scale Model Rotor.
The reliability of the design and structure features of the new 43-inch long blade was confirmed in a rotational vibration test with a full-scale model rotor.

TABLE 3. Basic Specification of 1,000-MW Generator
Major specifications of 1,000-MW generators for 50/60-Hz cross-compound and 50-Hz tandem-compound are compared.

Item	1,000 MW						700 MW
	60 Hz			50 Hz			60 Hz
	Tandem compound	Cross compound		Tandem compound	Cross compound		Tandem compound
		Primary	Secondary		Primary	Secondary	
Capacity (MVA)	1,120	690	450	1,120	675	488	800
Power factor	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Short circuit ratio	0.58	0.58	0.58	0.6	0.6	0.6	0.58
Voltage (kV)	26	22	22	25	19	19	25
Current (A)	24,871	18,108	11,810	25,866	20,512	14,829	18,475
No. of poles	2	2	4	2	2	4	2
Speed (r/min)	3,600	3,600	1,800	3,000	3,000	1,500	3,600
Hydrogen press. (MPa)	0.52	0.41	0.31	0.52	0.41	0.31	0.41
Cooling							
Stator winding	Direct water	Direct water	Direct water	Direct water	Direct water	Direct water	Direct water
Rotor winding	Direct H_2	Direct H_2	Direct H_2	Direct H_2	Direct H_2	Direct H_2	Direct H_2
Excitation system	Static	Static	Static	Static	Static	Static	Static
Generator length (%)	109	98	85	114	98	95	100
Rotor diameter (%)	106	93	138	111	96	145	100

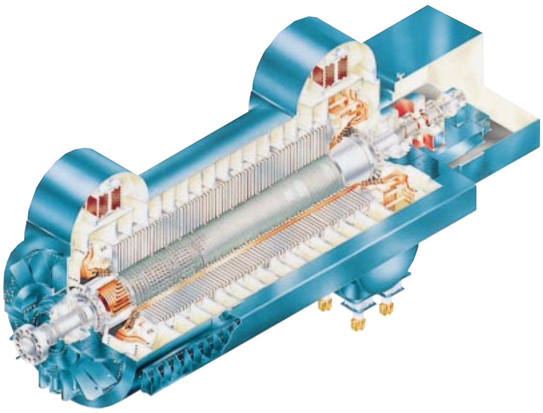


Fig. 7—Bird's-Eye View of Tandem-Compound 1,000-MW Generator.
A balanced design is attained by combining the large-capacity system component technology already being developed for large-capacity thermal and nuclear power plants.

power of l,000 MW by a single generator. The latter requires large-capacity system technology.

Basic Specifications

Table 3 shows the tandem-compound l,000-MW generator, and Fig. 7 shows its bird's eye view. The following items were taken into account to satisfy the large-capacity design of the tandem-compound l,000-MW generator.

(1) Suppression of the current increase by adopting a 25- to 26-kV voltage.
(2) Improved cooling performance by adopting a higher hydrogen pressure of 0.52 MPa.
(3) Shortening of longer rotor length by adopting a large-diameter rotor.

Large-capacity System Component Technology

Table 4 shows the large-capacity system component technology being adopted for the tandem-compound l,000-MW machine. The large-capacity system component technology having been tested and used many times in thermal and nuclear power plants was combined with the design of the 700-MW machine in the Hekinan thermal power plant Unit 2 of the Chubu Electric Power Co., Inc. This combination produced a well balanced design.

For the important large-diameter rotor, a running test was executed by using an actual section sized model of the 60-Hz machine which has a larger

TABLE 4. Large-capacity System Component Technology
The component technology required for a large-capacity system is shown below. The reliability of the rotor was tested using a full-sized rotor model.

Item	Contents
Stator frame (Hydrogen pressure 0.52 MPa)	Adoption of the terminal box and top dome structure being adopted in 1,100-MW generator for nuclear power plants
Stator core end	Adoption of the shunt core being adopted in 1,100-MW generator for nuclear power plants
Supporting system of stator end winding	Adoption of the supporting system having accumulated results in thermal and nuclear power plants
22-inch seal rings	A 26-inch, 3,600-r/min seal ring has already been developed
Rotor shaft	* Adoption of a large-diameter rotor * Adoption of highly durable shaft material * Adoption of rotor thermal balancing (A reliability evaluation test was executed by using a full-sized rotor model)
High-voltage bushing	Adoption of hydrogen direct-cooled bushing having accumulated results in thermal and nuclear power plants

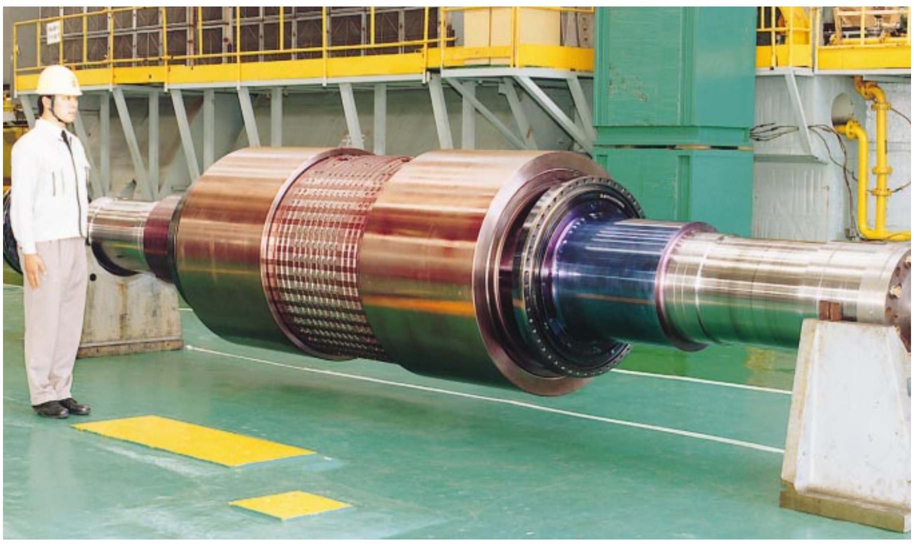


Fig. 8—Full-Sized Model of Large-Diameter Rotor.
A model having the actual section size and a body 1/10 the length of the actual 60-Hz 1,000-MW generator.

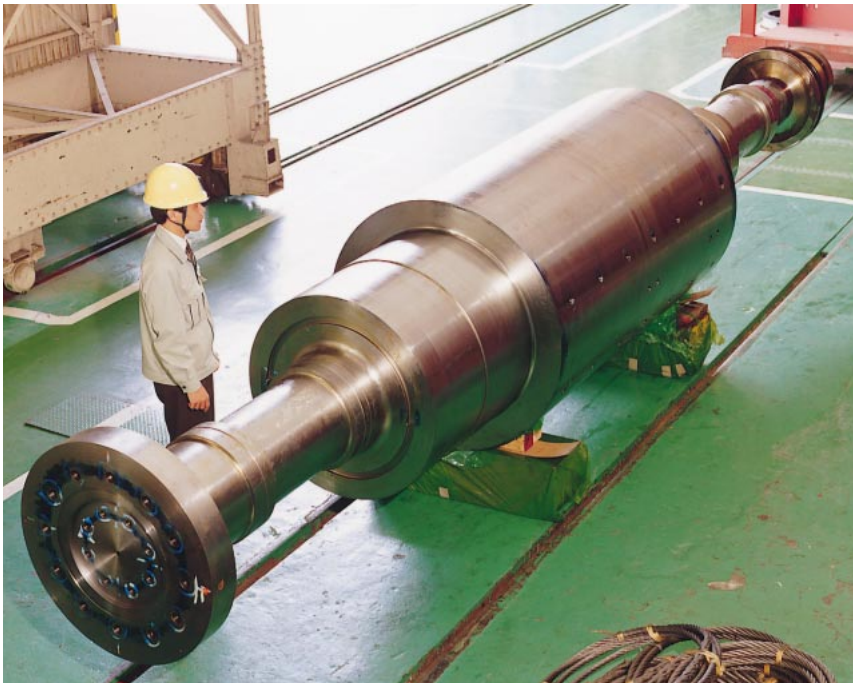


Fig. 9—Finished Improved-Ductility High-Strength Shaft Material.
A shaft material having an actual section size and a body 1/3 the actual length was manufactured, and it was confirmed to obtain the actual tensile strength (center hole) of 1,070 N/mm² and a fracture appearance transition temperature (FATT) of –30°C with reference to the specifications of a tensile strength of 980 N/mm².

centrifugal force compared with 50-Hz machine. The strength against fatigue caused by the start-stop operation and a long-hour running was evaluated to have verified the reliability. Fig. 8 shows the full-sized model of the large-diameter rotor. In addition, an improved ductility high-strength shaft material [tensile strength: 980 N/mm² min., actual tensile strength of bore hole: 1,070 N/mm², fracture appearance transition temperature (FATT): – 30°C] was developed to further improve the reliability. Fig. 9 shows the improved ductility high-strength shaft material.

Manufacturing of a highly reliable tandem-compound l,000-MW generator has become possible based on the above large-capacity system technology.

CONCLUSIONS

Hitachi has completed the development of component technology for tandem-compound 1,000-MW steam turbines and generators to meet the requirement to rationalize equipment in fossil-thermal power plants. Hitachi is continuing its efforts to rationalize the whole of the thermal power plant.

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