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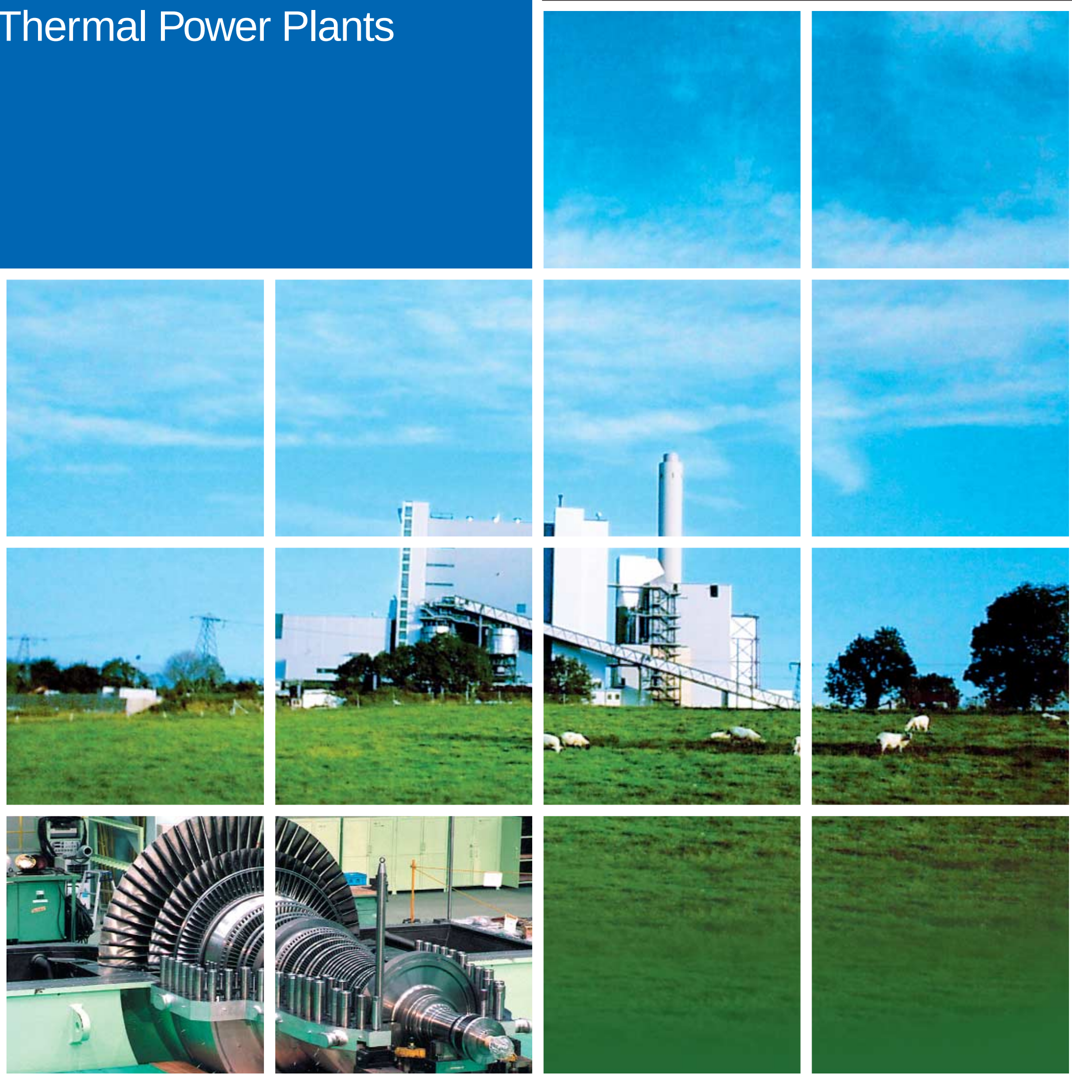
# FUJI ELECTRIC REVIEW

3

2005 VOL.51

## Thermal Power Plants

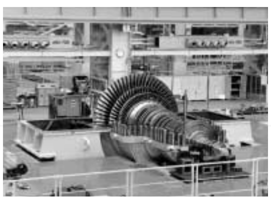


Fuji Electric Group


# Applying our plant "know-how" for the stable supply of electricity


Air-cooled generator


Private-use power producing equipment


Non-reheating steam turbine

Since producing our first steam turbine in 1959, Fuji Electric has manufactured more than 464 steam turbines having a total combined output capacity that exceeds 23,619 MW, and has delivered these turbines to various countries throughout the world. In the industrial sector, Fuji Electric shipped Japan's first supercritical, pure transformation plant in 1973, achieving higher operating efficiency than ever before. This has become the mainstream type of thermal power plant in Japan. Among medium capacity generators, Fuji has also produced and delivered the world's largest class 162 MW single-cylinder steam turbines. In the geothermal power sector, Fuji delivered the first commercial facility in Japan in 1960, and boasts a successful track record of producing generators that exceed 1,661 MW, such as the largest class of 110,000 kW generators. Fuji Electric is counted as one of the leading thermal power equipment manufacturers in the world.

# Fuji Electric's Thermal Power Equipment

FUJI ELECTRIC
# REVIEW

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Thermal Power Plants

## CONTENTS



**Cover photo:**

Thermal power generation in Japan has been affected by the slowdown in demand for electric power and the decline in electric utility rates, and power companies have dramatically curtailed their investment in plants and equipment. IPP power generation has also fallen, and a 1970s-like boom in power generation for private use is not expected.

Overseas in countries such as China, India and Brazil, however, the potential for future growth is seen as large, and the construction of new power plants brisk.

As part of this trend toward supplying plants and equipment overseas, the cover photo shows Ireland's West Offaly Power Station, which was delivered as a full-fledged coal-fired thermal power plant. The design has cleared the preliminary safety protocols common to both Europe and North America, and is a model of the power plant technology to be constructed overseas in the future. Also shown on the cover is a compact-size, non-reheating turbine, for which rapid growth is anticipated in the overseas markets.

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# Trends and Future Outlook for Thermal Power Plants

**Hiroshi Nishigaki**

## 1. Introduction

Recent events have caused modern society to appreciate anew the benefits it derives from electricity. A wide-ranging massive power outage extending from the northeastern United States to Canada and a power failure throughout all of Italy have occurred, and have had large impacts on the life of residents in those areas. In Shanghai, rotating power outages have been implemented for years and are a large impediment to normal business activities. In Japan, a stoppage of the operation of all nuclear power plants owned by The Tokyo Electric Power Co., Inc. caused a great deal of anxiety, but aided by the cool summer weather, ultimately did not result in a power outage. When a large-scale power outage occurs, trivial problems gradually increase and may potentially cause the collapse of large systems.

Power plants are part of the infrastructure of modern society and it is essential that these power plant facilities by constructed so as to achieve a higher level of reliability. Moreover, it is the mandate of companies involved in this industry to contribute to society by realizing higher performance and lower cost.

## 2. Market Trends

The climate surrounding Japan's domestic electric utility industry is as severe as ever due to sluggish growth in the demand for electrical power, the ongoing decrease in electrical power rates, the advancement of electric utility deregulation, the establishment of new environmental taxes, and the rapid rise in prices of such fuels as oil and coal. Power generation by means of renewable energy has been favored following the enforcement of the "Special Measures Law Concerning the Use of New Energy by Electric Utilities" (RPS law) and then the Kyoto Protocol, which came into effect in February 2005. However this market sector will be stalled in a wait-and-see situation for the next 1 to 2 years, during which time, efforts to develop new power sources are expected to idle.

In overseas markets, there is strong demand for electrical power in both the public and private sectors of the BRICs (Brazil, Russia, India and China) where there has been a significant increase in demand for electrical power, for Libya which has recently returned to the international arena, and the Southeast Asian countries of Indonesia and Vietnam. In these countries, the supply of electrical power has not caught up with the speed of economic growth and industrialization, and this demand for many new power generating plants is expected to continue for several years. These power plants will be mainly medium and small capacity facilities, which is Fuji Electric's area of expertise. Fuji Electric has a track record of many successful applications including pure power generation and cogeneration plants based mainly on coal-fired power generation, and combined cycle power generation achieved by connecting an add-on to an existing gas turbine.

## 3. Technical Trends

Fuji Electric was founded approximately 80 years ago through a partnership between The Furukawa Electric Co., Ltd. and Siemens AG., to introduce European technology to Japan at a time when US technology was already widespread. Fuji Electric has been involved in the production of thermal power plants for approximately 40 years and has supplied many distinctive products by introducing technology from Siemens during construction of mainly utility thermal power plants. Table 1 shows the history of growth in Fuji Electric's main technologies and businesses. Recently, Fuji Electric has delivered a ultra-supercritical pressure steam turbine to the Isogo Thermal Power Station of The Electric Power Development Co. (EPDC). This ultra supercritical pressure steam turbine increases the efficiency of the power plant, or in other words, reduces the environmental load. Figure 1 shows a view of the entire EPDC Isogo Thermal Power Station Unit No. 1.

Meanwhile, with the deregulation of the electric power industry, power plants are now being constructed by independent power producers (IPPs) and Fuji Electric is supplying various types of economically beneficial equipment to these plants.

Table 1 History of changes in Fuji Electric's main technologies and businesses

| Category \ Era | 1970s | 1980s | 1990s | 2000s |
|---|---|---|---|---|
| Thermal power plants for utility in Japan | ▼TEPCO Ooi Thermal Power Station, Unit No. 3 (first pure sliding pressure operation in Japan) | ▼EPDC Ishikawa Coal Thermal Power Station, Unit Nos. 1 and 2 (high-temperature turbine)<br>▼Okinawa Electric Power Makiminato, Unit No.9 (Fully automated oil thermal power)<br>▼Kansai Electric Power Miyazu Energy Research Center, Unit No.2 (DSS operation) | ▼Tohoku Electric Power Noshiro Thermal Power Station, Unit No.1 (50 Hz, 600 MW large-capacity tandem machine) | ▼EPDC Isogo Thermal Power Station, new Unit No.1 (600 MW ultra-supercritical pressure plant) |
| Thermal power plants for private use and IPP plants in Japan | | ▼UBE Industries, Ube plant (145 MW, largest private-use power plant in Japan) | ▼Fuji Electric Gas Turbine Research Center (69 MW gas turbine made by Siemens)<br>▼Kobe Steel, Kakogawa Works (axial flow exhaust turbine) | ▼UBE Power Center (60 Hz max. global vacuum pressure impregnated insulation air-cooled generator) |
| Overseas thermal power plants | ▼Philippines: Battan, Unit No.2 (full-scale entry into overseas business of thermal power plant for utility)<br>▼Australia: Gladstone Unit Nos. 1 to 4 (direct hydrogen-cooled generator) | ▼Thailand: Mae Moh, Unit Nos. 4 to 13 (largest thermal power plant in Southeast Asia)<br>▼Pakistan: Jamshoro Unit No.1 (largest indirect hydrogen-cooled generator) | ▼Taiwan: FPCC FP-1, Unit Nos. 1 to 4 (60 Hz, 600 MW large-capacity tandem machine) | ▼Bangladesh: Meghnaghat (combined-used turbine, large-capacity air-cooled generator) |
| Geothermal power plants | ▼EPDC Onikobe Geothermal Power Plant (generator delivered) | ▼El Salvador: Ahuachapan, Unit No.3 (full-scale entry into geothermal power plant business)<br>▼USA: Coso Geothermal Power Plant, Unit Nos. 2 to 9 (modular turbo-set) | | ▼Indonesia: Wayang Windhu, Unit No. 1 (world's largest single-casing geothermal turbine)<br>▼TEPCO, Hachijojima Geothermal Power Station |
| Technical development | ▼Direct hydrogen-cooling method<br>▼Global vacuum pressure impregnating facility for medium and small-size generator | ▼High-temperature 12Cr rotor<br>▼22 kV-class F resin/ F insulation<br>▼F resin/ F II insulation | ▼Improved 12Cr rotor for high temperature<br>▼Experimental prototype of 126 MVA air-cooled generator<br>▼Global vacuum pressure impregnating facility for large-size | ▼Completion of new Shiraishi Factory<br>▼Automated stator winding machine<br>▼22 kV-class global vacuum pressure impregnated insulation system |

Fig.1 EPDC Isogo Thermal Power Station new Unit No. 1

Fig.2 View of the entire UBE Power Center Plant

The construction of utility thermal power plants in Japan has reached as standstill at present and is not expected to recover soon. Additionally, IPP planning has also become saturated. Figure 2 shows a view of the entire UBE Power Center Plant that was constructed as an IPP plant. Fuji Electric will continue to develop products while carefully monitoring these market trends in the future. The technical trends of medium and small capacity power plant equipment, which are Fuji Electric's main products at present, are described below.

### 3.1 New small-capacity non-reheat steam turbines

Fuji Electric has newly developed a steam turbine (FET-N type) having a simple configuration suitable for small capacity (25 to 50 MW) applications. A first unit is already in operation in China, and a second unit has already been shipped and is being installed onsite.

### 3.2 Large non-reheat steam turbines

Fuji Electric's expertise is greatest in the technical field that involves private-use power plants. These plants have multiple steam processes and require complex control. In a turbine, the process steam flow rate is controlled as required, and at the same time the electrical power output is adjusted. In the past, the output power was approximately several tens of MW but, in response to market needs, technology has been developed to achieve larger turbines capable of greater than 160 MW output.

### 3.3 Single-casing reheat steam turbines

Fuji Electric has developed a reheat steam turbine configured with a single casing instead of the conventional two-casing construction, and a first unit has already been placed in service. Shortening the length of the turbine shaft has enabled a reduction in construction costs, including civil engineering work, and the realization of a more economical plant.

### 3.4 New digital control system

A new digital control system (TGR) that provides integrated control for a turbine and generator, and uses Fuji Electric's MICREX-SX, which is a high-performance PLC, has been placed into commercial operation and it being applied to other plants.

### 3.5 Remote monitoring

A remote monitoring system has been developed that periodically gathers operating status data from power generating equipment that has been delivered to a remote overseas location and transmits that data via the Internet to a maintenance department, where it is received. Thus, even when a failure occurs in remote onsite equipment, the customer can be instructed quickly as to the appropriate measures, thereby minimizing downtime and reducing the customer's loss. Moreover, appropriate advice concerning preventative maintenance is also provided in order to avoid downtime due to mechanical failure.

## 4. Steam Turbines

Various improvements to steam turbine technology have been previously requested in order to enhance the thermal efficiency and space efficiency of thermal power plant facilities. In the large-capacity generator sector, Fuji Electric has advanced the development of 600 MW-class supercritical pressure steam turbines, and together with the improved thermal efficiency due to higher temperature and pressure steam conditions and the development of large turbine blades, has reduced the number of low-pressure turbine casings to realize more compact turbines. In the medium and small-capacity generator sector, technology has been developed to increase the efficiency, compactness and serviceability of steam turbines, enabling smaller initial investment and higher reliability. Fuji Electric has continued to improve the space efficiency by migrating from the conventional three-casing structure to a two-casing structure and then to a single-casing structure. With the increase in capacity, the ability to maintain stability of the shaft system as the distance between bearings increases in a steam turbine and measures to prevent erosion of the low-pressure blades presented technical challenges that have since been overcome due to greater analytical precision and structural improvements. A single casing turbine of 165 MW maximum capacity has already been brought to market and is achieving good operating results. In order to reduce the construction costs associated with a combined cycle steam turbine, axial flow steam turbines are being widely used. Fuji Electric will continue to advance the development of technology to improve efficiency and lower the cost of medium and small capacity turbines.

## 5. Generators

Air-cooled generators, due to their low construction cost, short production time and ease of operation and maintenance, are gradually beginning to be used in applications traditionally associated with hydrogen-cooled generators. At present, Fuji Electric's air-cooled generators are suitable for applications ranging up to 280 MVA for 60 Hz generators and 300 MVA for 50 Hz generators. Because air, which has lower cooling performance than hydrogen, is used as a coolant with larger capacity generators, Fuji Electric implemented a technical verification test by fabricating a 126 MVA experimental generator and taking on-line measurements at more than 1,000 on the stator and rotor. The results of this test demonstrated that it was possible to manufacture a large-capacity air-cooled generator having sufficient reliability.

For hydrogen-cooled generators, indirect cooling is also being used instead conventional direct cooling. Indirect cooling is the method of cooling used in air-cooled generators, and technology acquired during the development of air-cooled generators is also being applied to hydrogen-cooled generators. At present, the applicable range for indirect hydrogen-cooled generators has an upper limit of 450 MVA.

## 6. Geothermal Power Plants

There are presently no plans for the construction of geothermal power plants in Japan. The reason for this lack of plans is the high cost due to risks associated with underground resources, the large initial investment that is required, and the long lead time required to coordinate and reach a consensus concerning treatment of national parks and existing hot springs. However, small-scale binary power generation that utilizes previously unused steam and hot water from a hot springs region is a promising model for economical geothermal power plants because there are no drilling costs and the lead time is short. The RPS law has been enforced since 2003, obligating electrical power suppliers to use renewable energy. Because geothermal binary power generation is also included in this category, the construction of geothermal power plants is expected to gain momentum.

Overseas, due to the slowdown in the global economy that began with the Asian currency crisis from 1997 through 1998, developing countries postponed or froze almost all their geothermal development plans that required an initial investment or involved investment risk. However, in response to the increase in demand for electrical power that accompanied the subsequent economic recovery, plans that use public funds such as yen loans or financing from the Asian Development Bank for investigating geothermal resources and constructing geothermal power plants have been reinvigorated.

In the past, geothermal power plants commonly adopted affordably-priced single-flash cycle. In order to achieve a more efficient use of resources, double-flash cycle, combination with binary cycle using brine from flash cycle and cogeneration of hot water for house heating using exhaust or extracted steam are adopted.

In order to improve plant efficiency and the utilization rate of geothermal turbines, the following technologies are recognized as important for geothermal power plants: technology for preventing the adhesion of and removing silica scale from turbines, monitoring techniques and easy maintenance, and measures to prevent the adhesion of silica on re-injection piping or a re-injection well. Geothermal steam contains a minute amount of hydro-sulfuric gas and, as environmental quality standards become stricter, an increase is expected in the number of installations of equipment for removing this hydro-sulfuric gas, which previously had been released into the atmosphere.

## 7. After-sales Service

After-sales service has been implement thus far in a close working relationship with the user, mainly by providing periodic inspections of delivered equipment and replacing or repairing parts for preventative maintenance. These activities include responding to incidences of sporadic failure and also providing various suggestions for improvements. Periodic inspections are necessary to ensure the safety of a plant, and in Japan, this is a characteristic of a regulated industry protected by laws. As the relaxation of regulations results in a shift from mandatory periodic inspections to voluntary inspections, technical suggestions by manufacturers are being closely scrutinized based on economic criteria to determine whether they are absolutely necessary for ensuring stable operation. Against this backdrop, specialized maintenance service companies have already begun operating in Europe and the US. The necessity for periodic inspections is also being recognized in Southeastern Asia, and these European and US maintenance companies are early participants in those markets. Fuji Electric intends to leverage its reliable and responsive after-sales service in order to insure the stable operation of power plants, and to compete as an equipment manufacturer against these specialized maintenance companies.

After-sales service for an aged plant can encompass plans for major renovations or renovation of the entire plant in order to reuse the plant's facilities. These types of plans can be diverse and may involve conversion of the type of fuel that was used originally at the time of construction, massive renovation of the entire plant—such as changing the operating principle of the power plant, and repairing or replacing worn out parts to prolong the service life of the equipment or reducing maintenance cost and enhancing the efficiency of the plant. Technology has also made great advances since the time of the initial construction and a wide range of measures are available for problem solving.

## 8. Conclusion

Thermal power plants are industrial goods that produce electricity. Moreover, these plants are important to customers and are presumed to have a service life of greater than twenty years. Accordingly, the reliability of a power plant is considered most important, followed by after-sales service and then economic efficiency. As demand for electrical power increases throughout the world, Fuji Electric intends to continue to strive to supply power plants that provide reliability, high performance and low price in accordance with the needs of customers.

# Fuji Electric's Medium-capacity Steam Turbines "FET Series"

Koya Yoshie
Michio Abe
Hiroyuki Kojima

## 1. Introduction

Recently, de-regulation of the electric power industry and rising needs for advanced solutions to environmental concerns, have caused a great change in the area of thermal power generation. Further improvement for higher efficiency, a more compact design, optimal operating performance, and better maintainability and higher reliability is increasingly requested of the steam turbine industry.

For medium capacity steam turbines, there has been an increase in the use of combined cycle plants, in addition to their conventional use for private power generation. Accordingly, larger capacity single units, combined with advanced technology for higher efficiency, have been more in demand. Moreover, the axial flow exhaust type and the upward exhaust type steam turbine configurations are more favorable and popular, due to their lower construction costs.

Features of Fuji Electric's "FET Series" of standard medium capacity steam turbines , which achieves high efficiency with low-cost, are introduced below.

## 2. Concept of the FET Model Series

### 2.1 Applicable range

Specific demands for medium capacity steam turbines concern not only power generation, but also relate to industrial applications that provide the function of extracting steam for various uses such as plant processes or utilities. The medium capacity steam turbine FET Series is a standardized model series suitable for a wide range of steam and output conditions.

The types of steam turbines, applicable steam conditions, output range and the rotational speed of the steam turbines are listed in Table 1.

Table 1 Range of Fuji Electric's medium capacity steam turbine "FET Series"

| | |
|---|---|
| Type | ○ Condensing type<br>○ Back pressure type<br>○ Single / Double controlled extraction condensing type<br>○ Single / Double controlled extraction back pressure type<br>Operable as a mixed pressure type or an extraction / mixed pressure type. |
| Range of output | 20 MW to 180 MW |
| Steam condition | Main steam pressure : 130 bar or less<br>Main steam temperature : 540°C or less |
| Rotational speed | 50 $s^{-1}$ (3,000 rpm) or<br>60 $s^{-1}$ (3,600 rpm) |

### 2.2 Block design system

The standard FET Series of steam turbines utilizes a modular "block design system" in which suitable blocks are selected from several standardized components (Fig. 1) corresponding to the various required specifications and steam conditions of each project. This type of modular system design enables the best selection of blocks over a wide application range.

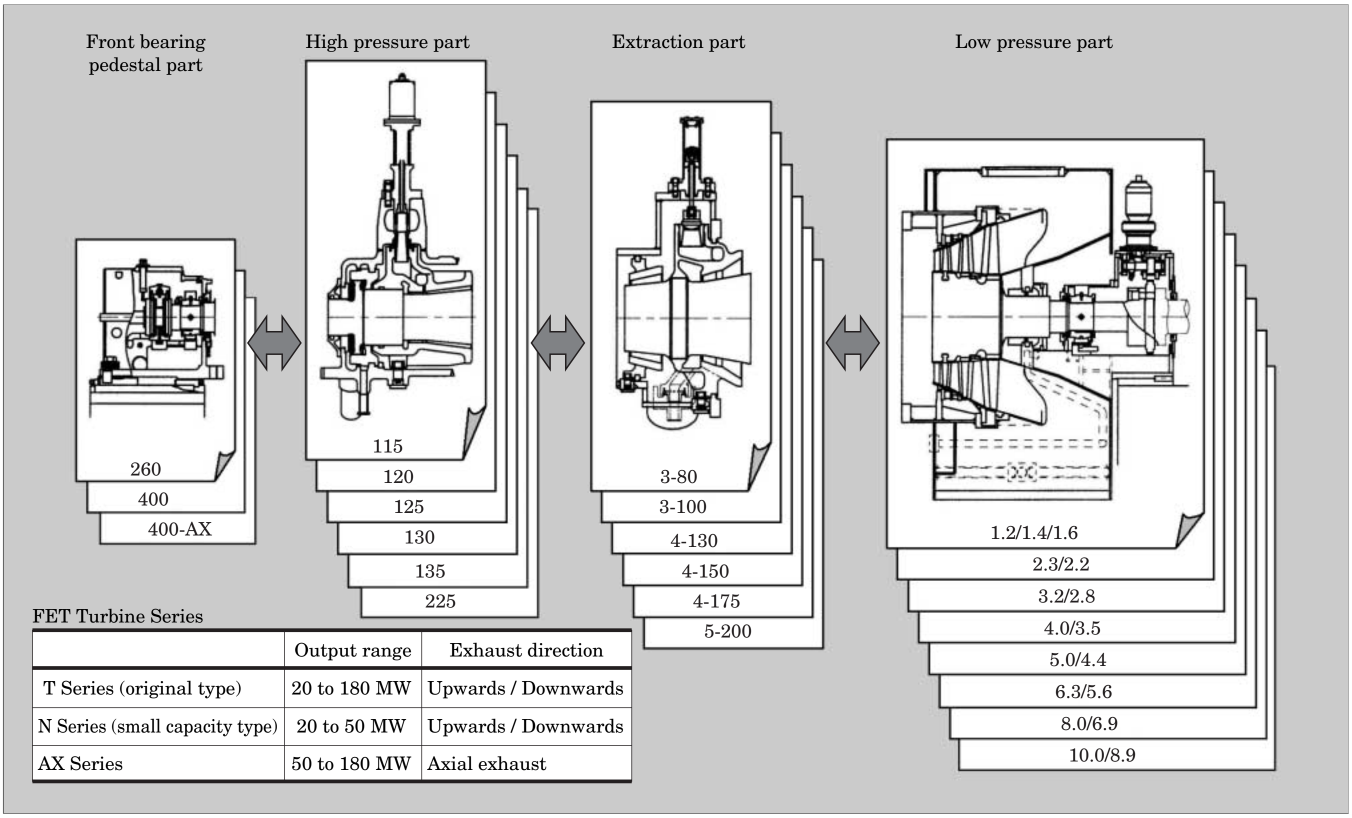
Each standard component has a proven track record of success, and a highly efficient turbine model can be realized by the proper selection of the optimum blocks. Standardization by means of this block design system will shorten the production lead-time and reduce the production cost. As a result, a steam turbine that satisfies customer requirements can be provided with a shortened delivery time.

## 3. Scaling-up to Larger Capacity FET Turbines

Many steam turbines for private power generation-use and having the capability to provide process steam have been furnished. Due to the worldwide trend toward de-regulation of the supply of electric power, private companies are increasingly joining IPPs (Independent Power Producers), and the need to scale-up the unit capacity of steam turbines has increased.

After the 101 MW FET turbine was put into operation in 1994, larger capacity units have been successively developed within the FET series, in accordance with market trends. The cross-sectional drawing of a recent FET steam turbine is shown in Fig. 2, and the specifications of these turbines are listed in Table 2.

Fig.1 Block design system of the FET Series




FET Turbine Series

| | Output range | Exhaust direction |
|---|---|---|
| T Series (original type) | 20 to 180 MW | Upwards / Downwards |
| N Series (small capacity type) | 20 to 50 MW | Upwards / Downwards |
| AX Series | 50 to 180 MW | Axial exhaust |

Fig.2 161.99 MW steam turbine, assembled cross-sectional drawing

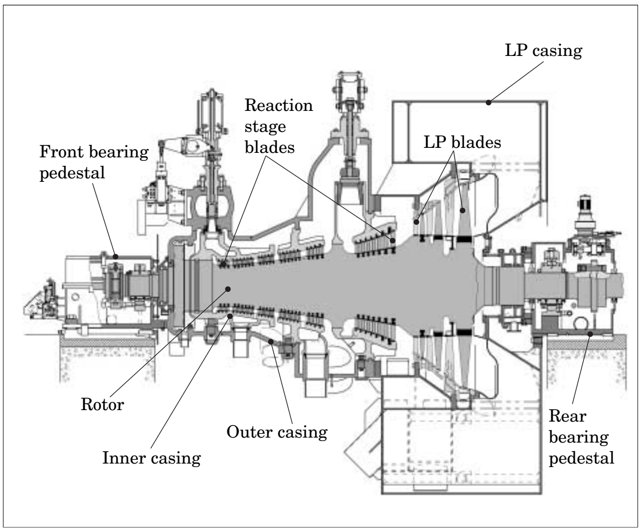
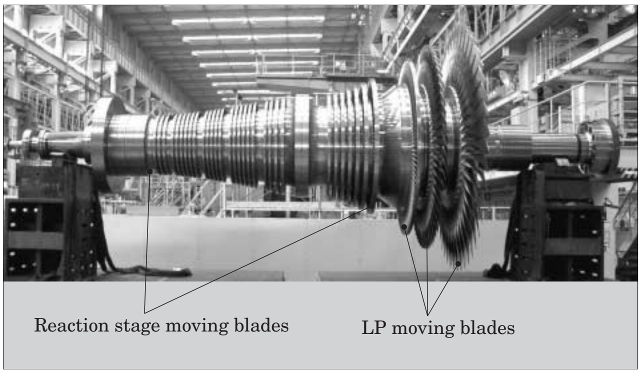



Table 2 Steam turbine specifications

| | Formosa Chemicals & Fibre Corporation SK-G4 (Taiwan) | Formosa Power (Ningbo) Ltd. Co. NB-1 (China) |
|---|---|---|
| Model | Single-extraction condensing | Single-extraction condensing |
| Output | 147.88 MW | 161.99 MW |
| Steam condition extraction pressure | 123.6 bar / 538°C / 7.7 bar | 123.6 bar / 538°C / 8.3 bar |
| Vacuum | 0.088 bar | 0.088 bar |
| Rotational speed | 60 $s^{-1}$ (3,600 rpm) | 50 $s^{-1}$ (3,000 rpm) |
| Operation start date | May 2000 | July 2004 |

Fig.3 Reaction type steam turbine rotor




### 3.1 Highest internal efficiency with throttle governing system

The FET steam turbine has adopted a design that features a throttle governing system and a double shell casing structure with outer and inner casings, similar to that of large capacity turbines for utility power generating use. This design achieves higher efficiency by utilizing reaction blades in all stages, and does not use a nozzle governing impulse blades with partial admission loss (see Fig. 3). Moreover, wear due to the

Fig.4 Advanced series low pressure blades

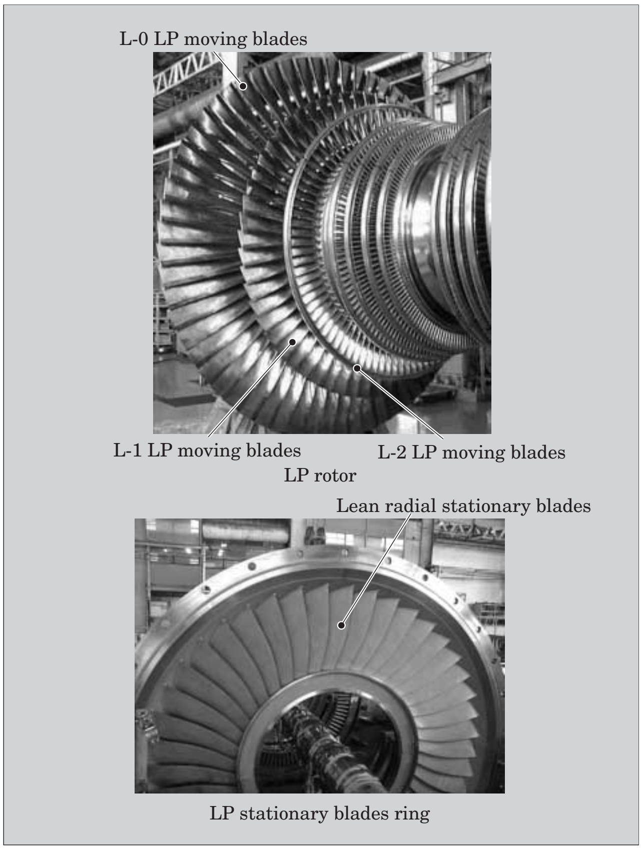
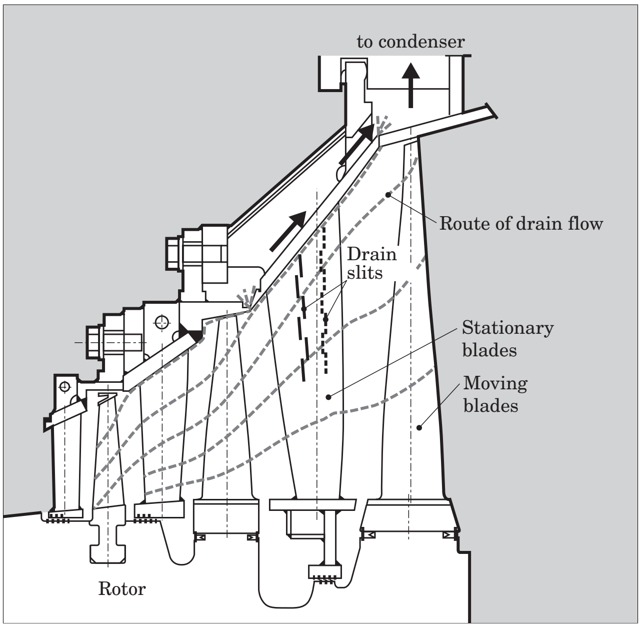



Fig.5 Erosion-resistant structure




impact of solid particles (particle erosion) or deterioration of the blade surface can be reduced and deterioration of performance with aging will be minimal, due to the lower steam velocity with reaction blades than in the impulse stages.

### 3.2 Adoption of advanced series low-pressure blades

Highly efficient low-pressure blades, designed using compressible supersonic flow analysis (three-dimensional time marching method), are utilized. A lean radial stationary blade, which curves toward the direction of the circumference is adopted in the final stage (L-0) (see lower half of Fig. 4). Moreover, enhanced performance is achieved by adopting a shroud ring in the first stage (L-2) moving blade, while continuing to maintain the wide range frequency allowance of −5 to +3 %, which has been a characteristic feature of existing free standing blades (see upper half of Fig. 4).

### 3.3 Erosion prevention

Operated in wet steam, low pressure moving blades erode due to the impact of water droplets, and this erosion increases in severity as the blade length grows larger. To reduce this damage, the following measures have been implemented (see Fig. 5).

(1) The leading edges of the moving blades have been flame hardened, and the surface hardness of the blade material has been improved.

(2) The final stationary blade (L-0) of larger models has a hollow structure with drain slits provided on its surface in order to drain the water droplets away to the condenser, thereby reducing the drain attack on latter-stage moving blades.

(3) The axial clearance after the trailing edge of stationary blades has been enlarged sufficiently to decrease the size of water droplets that adhere from the steam flow onto the stationary blades, thereby reducing the drain attack on following moving blades.

(4) The trailing edge of the stationary blades has been made thinner, so as to minimize the size of water droplets from the edge of the blades, thereby reducing the drain attack on following moving blades.

### 3.4 Adoption of 2 % Cr steel rotor

According to the increase in rotor diameter and LP blade length corresponding to larger steam turbine capacity, the centrifugal loads on the rotor have grown larger. The strength under actual operating conditions was evaluated using finite element analysis and fracture mechanics procedures. Accordingly, differential heat-treated 2 % Cr forged steel was selected for the shaft material of a 60 $s^{-1}$ machine in which the stress in the core part will be very high. Figure 6 shows the creep rupture test results of this material.

## 4. Compact FET Turbine (N Series)

The selection of small capacity FET turbines has been improved with the development of the N Series, which was started and completed in 2002.

Figure 7 shows a cross-sectional drawing and typical specifications of the N Series.

Fig.6 Creep rupture test result of 2 % Cr steel

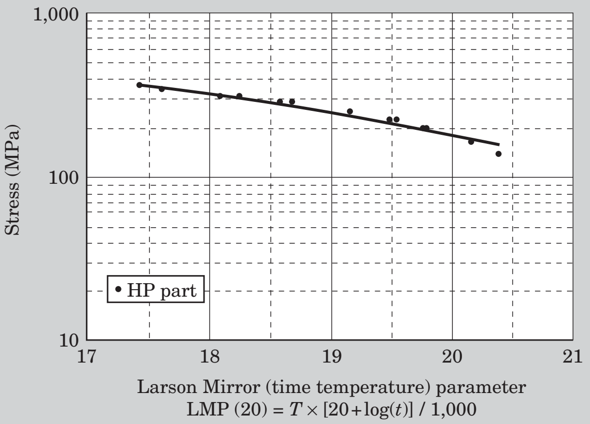
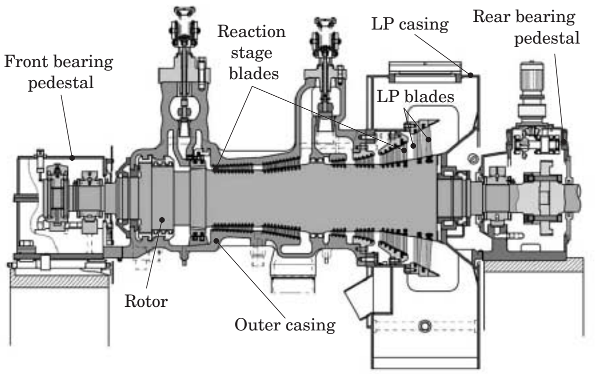



Fig.7 N Series steam turbine, assembled cross-sectional drawing




Steam turbine for Shanghai Chung Loong Paper Co., Ltd. (China).

| | |
|---|---|
| Model | Single extraction condensing type |
| Output | 26 MW |
| Steam condition extraction pressure | 123.6 bar/538°C/9.8 bar |
| Vacuum | 0.079 bar |
| Rotational speed | 50 $s^{-1}$ (3,000 rpm) |
| Operation started since | March 2005 |

Fig.8 Overview of the N Series casing

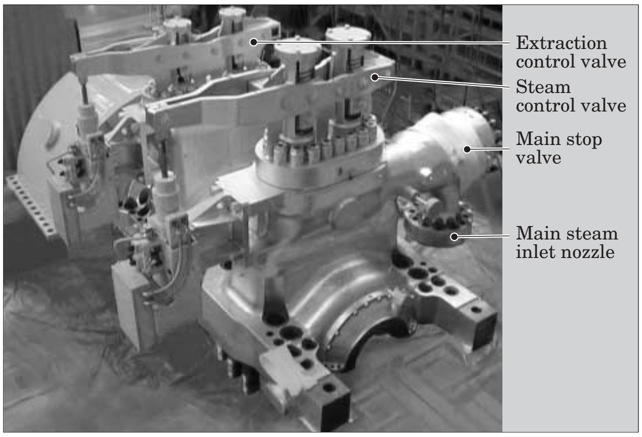
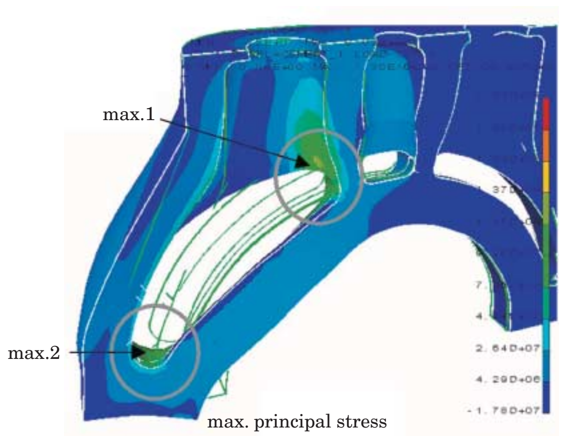



Fig.9 Analysis of inlet part with temperature distribution




### 4.1 Compact design by nozzle governing impulse stages for the small capacity model

The normal FET turbine has a throttle governing system and double shell casing structure as shown above. However, better flexibility for load change by day and night is requested for small-capacity, private power generation turbines, and thus the nozzle governing system will be more suitable for these conditions.

The FET N Series has adopted a nozzle governing system and single shell casing as the most compact and suitable system for this application (see Fig. 8).

The FET N Series has been developed for high efficiency by maintaining the same high steam conditions as the medium class FET (up to 130 bar/538°C). Reliability of the design was confirmed by simulating the operating conditions, including the analysis of temperature and stress distributions or deformations on the casing, on the basis of plenty of well proven FET turbines (see Fig. 9).

### 4.2 Adoption of high efficiency impulse stages

With the adoption of a nozzle governing system, a Curtis stage is applied as the top stage in order to reduce the wheel chamber pressure and temperature effectively. In an effort to reduce the secondary loss of the Curtis stage, a three-dimensional blade profile design is used in which the profile is curved in the direction of the circumference in order to maintain the characteristic high efficiency of the FET turbine (see Fig. 10).

As a result, a 1.7 % improvement is expected in stage efficiency, compared to the existing blade design.

Fig.10 Three-dimensional impulse stage

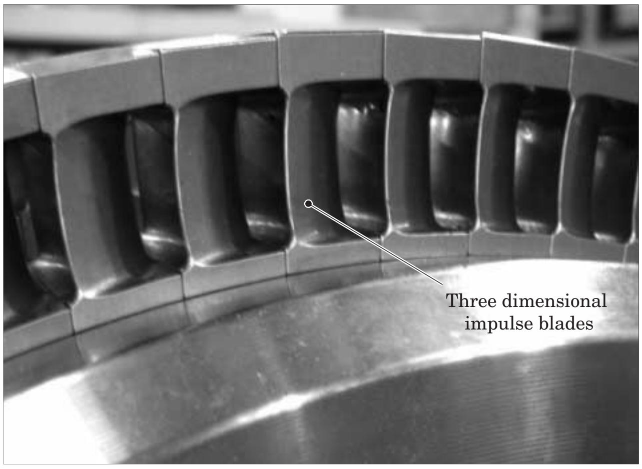
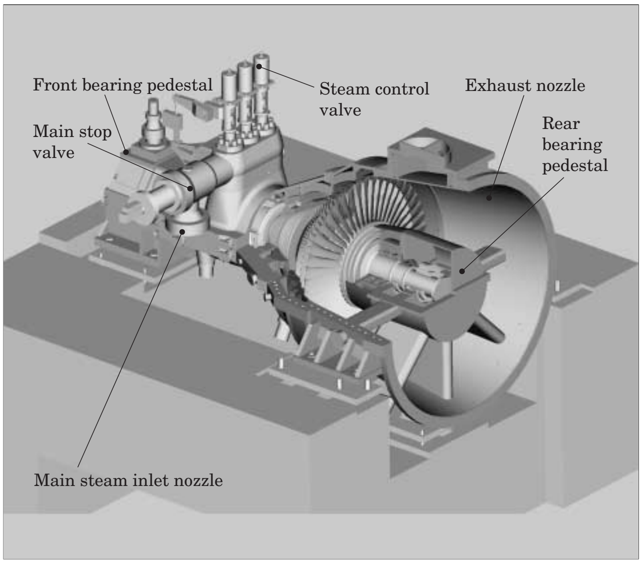



Fig.11 Axial exhaust type AX Series steam turbine

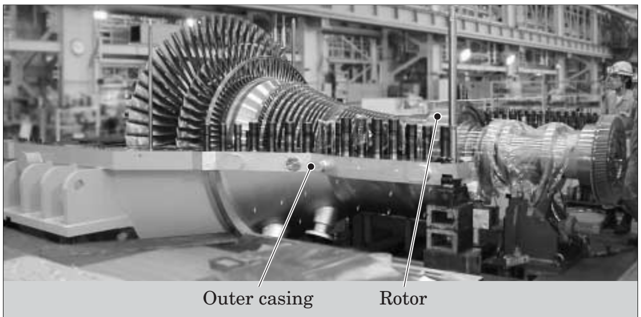



## 5. Use in Combined Cycle Plants

Due to the growing global environmental awareness in recent years, the major application of thermal power generation equipment has shifted to combined cycle plants (CCPPs), which use gas and steam turbines in combination to achieve higher thermal efficiency. According to this market trend, variations that combine use with a 100 to 200 MW class gas turbine have also been added. For CCPPs, there is great demand for axial flow exhaust type turbines since the cost and period for construction can be reduced greatly by this structure. Accordingly, the axial flow exhaust type AX Series FET was developed, based on existing downward exhaust type FET turbine technology (see Fig. 11).

CCPPs tend to be constructed in the vicinity of the consumers in order to reduce the power transmission loss. An air-cooled condenser is a suitable choice then, since it allows for the unrestricted selection of site

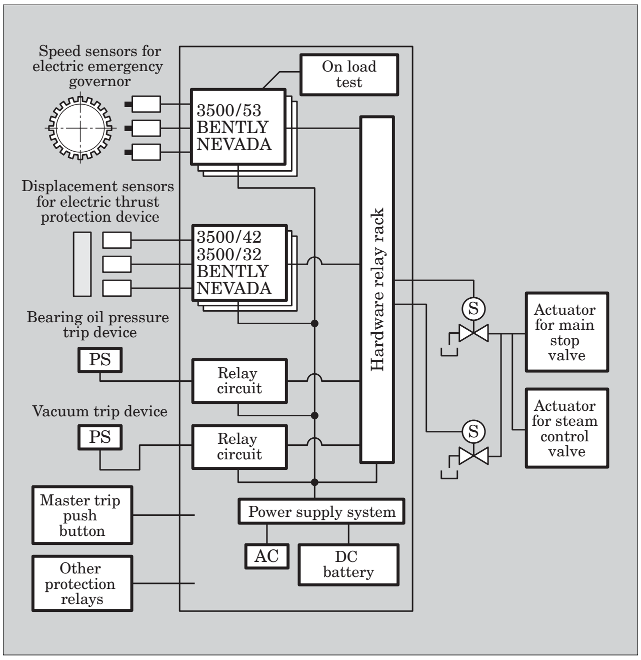
Fig.12 AX Series steam turbine during assembly




Central Geradora Termelétrica Fortaleza S.A. steam turbine (Brazil)

| | |
|---|---|
| Model | Mixed pressure condensing type |
| Output | 117.8 MW |
| Steam condition | 73.3 bar/517°C |
| Vacuum | 0.065 bar |
| Rotational speed | 60 $s^{-1}$ (3,600 rpm) |
| Operation start date | February 2004 |

Fig.13 Concept of fully-electric protection device



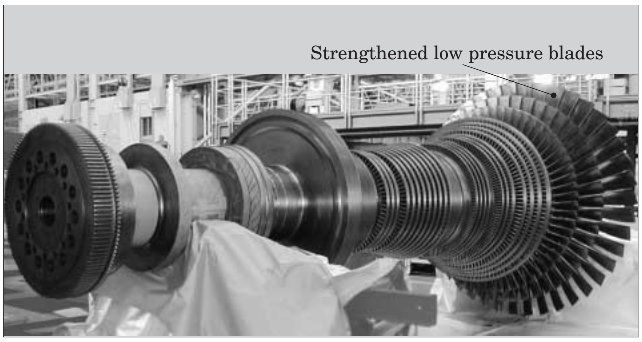

locations for the power plant, compared to a water-cooled condenser which requires access to a large amount of river or sea water. In order to operate compatibly with the higher exhaust pressure limitation of an air-cooled system, a low vacuum type steam turbine series was added.

### 5.1 Axial flow exhaust type FET steam turbine

Development of the axial exhaust type AX Series was completed and the first unit was put into operation in 1999. The AX Series has been utilized in many CCPPs.

Figure 12 shows a photograph and lists the specifi-

Fig.14 Strengthened low pressure blades




cations of an AX Series turbine.

### 5.2 Utilization of fully electric protection devices

With the axial flow exhaust type turbine, the shaft coupling for the generator, turning motor and protection device are installed in the front pedestal because the rear pedestal is located in the exhaust hood. Therefore, to simplify the front pedestal as much as possible and to improve the maintenance, all protection devices, such as the over-speed governor and thrust failure protection system have adopted a fully electric configuration (see Fig. 13).

These electric protection devices are also used in Fuji Electric's larger capacity steam turbines, in common with the FET turbines.

### 5.3 Correspondence to air-cooled condenser

The vacuum obtained by an air-cooled condenser is less than that of a water-cooled condenser.

This higher exhaust pressure severely stresses the low-pressure blades in the steam turbine exhaust part. The development of strengthened low pressure blades has solved this issue (see Fig. 14).

## 6. Conclusion

The medium-capacity steam turbine FET Series has been expanded so as to be applicable to a wide-ranging market. Due to continuous requests for advanced solutions in response to global environmental needs and de-regulation of the electric power supply industry, the demand for equipment with higher efficiency and lower-cost will increase more and more in the future. Fuji Electric intends to continue to advance technical development in order to accommodate these growing needs.

# Present Developmental Status of Fuji Electric's Turbine Generator

Hiromichi Hiwasa
Toru Hase
Kohji Haga

## 1. Introduction

The capacities of air-cooled, two-pole turbine generators have increased dramatically. About 10 years ago, hydrogen-cooled generator was used in 150 MVA-class turbine generators, but nowadays, air-cooled generator is even being used in 200 MVA-class and above turbine generators.

Meanwhile, at combined cycle power plants, 400 MVA-class generators are being coupled to single-shaft or multi-shaft type steam turbines, and the directly hydrogen-cooled stator winding type or the directly water-cooled stator winding type are applied for the generators. Based on customer needs for economy, maintainability and operability, the generator having the indirectly hydrogen-cooled stator winding (hereafter referred to as indirectly hydrogen-cooled generators) is most suitable. Fuji Electric has developed a series of 300 MVA air-cooled generators and up-to-450 MVA indirectly hydrogen-cooled generators that use a global vacuum pressure impregnated insulation system (F resin/GⅡ), (hereafter referred to as the Global VPI insulation system).

An overview of the technical development in involved in the creation of this product series, important developments of the Global VPI insulation system for high voltage large-capacity generators, and automatic manufacturing technology are described below.

Fig.1 280 MVA air-cooled turbine generator

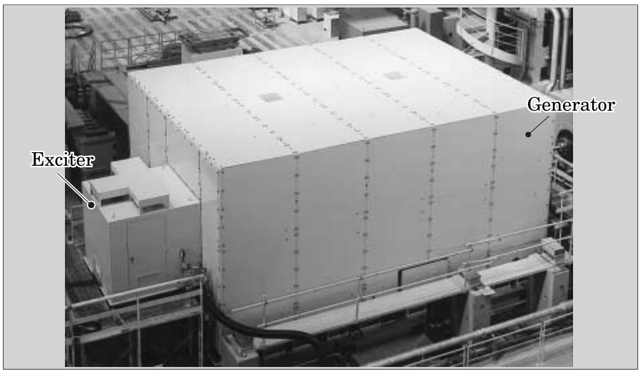
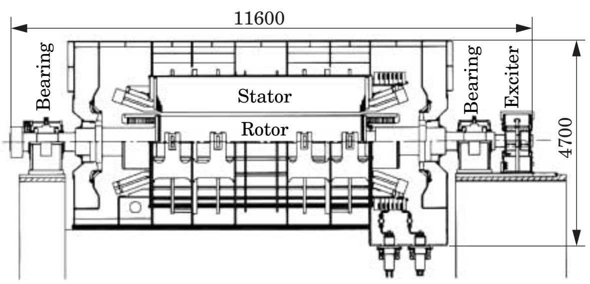



Fig.2 Cross-sectional view of 280 MVA air-cooled turbine generator




## 2. Practical Application of Large-capacity Air-cooled Generators

Air-cooled generators have a simpler structure than hydrogen-cooled generators and because they require no auxiliary systems such as a hydrogen gas supply system or a sealing oil supply system, the installation, operation and maintenance of air-cooled generators is quick and easy. Furthermore, air-cooled generators are advantageous because their production lead-time is short and initial investment cost is low. Based on the results of verification testing of a 126 MVA prototype generator built in 1999, Fuji Electric has worked to develop larger capacity air-cooled generators and has shiped 50 Hz, 280 MVA air-cooled generator into practical use. Figures 1 and 2 show a photograph of the external appearance and a drawing of the cross-section of this generator.

### 2.1 Technical features

As regards the cooling methods, the indirect cooling is applied for the stator winding and the direct cooling (radial flow) is applied for the rotor winding. And air coolers are installed in the side of the stator frame. The rotor is supported by two bearing pedestals positioned on a bed plate, and the exciter or the collector rings are mounted on the anti-turbine side shaft.

For the stator winding, Global VPI insulation system is applied. The stator winding is impregnated

Table 1 Factory test results of 280 MVA air-cooled turbine generator

| | | |
|---|---|---|
| Specification | Output | 280 MVA |
| | Voltage | 14.7 kV |
| | Current | 10,997 A |
| | Power factor | 0.9 |
| | Rotating speed | 3,000 r/min |
| | Frequency | 50 Hz |
| | Thermal class | 155 (F class) |
| | Coolant temperature | 40°C |
| | Excitation system | Thyristor excitation |
| | Standard | IEC60034-3 |
| Factory test results | Stator winding temperature rise | ≦ 81 K |
| | Rotor winding temperature rise | ≦ 80 K |
| | Short circuit ratio | 0.52 |
| | Transient reactance | 26.7 % unsaturated value |
| | Sub-transient reactance | 20.1 % unsaturated value |
| | Efficiency | 98.82 % conventional efficiency |

with epoxy resin throughout the entire stator after stator winding insertion into the stator core.

The following analysis and evaluation techniques were used to advance the increase in capacity of air-cooled generators.

(1) Evaluation of stator and rotor winding temperature using three-dimensional flow and temperature analytical techniques utilizing the finite element method (FEM)
(2) Analysis of stray load loss using electromagnetic field analytical techniques utilizing FEM
(3) Evaluation of fatigue strength of the rotor using strength analytical techniques utilizing FEM

### 2.2 Shop test results of the 280 MVA air-cooled turbine generator

In the abovementioned 50 Hz, 280 MVA air-cooled turbine generator, the type rating was tested with no-load characteristic test, short circuit characteristic test, temperature rise test, and by measurement of the loss. Type rating specifications and the shop test results for this generator are listed in Table 1. All the results are satisfactory and demonstrate that the required performance has been achieved. Additionally, as part of the shop test, the rotor winding temperature distribution, the stator winding temperature distribution and the stator vibration were measured. These measured results were then compared to the design values and to data measurements from previously manufactured generators, and then evaluated. Based on the comparisons and evaluation, the excellent characteristics and high reliability of this generator have been verified.

Fig.3 Cross-sectional view of 450 MVA indirectly hydrogen-cooled turbine generator

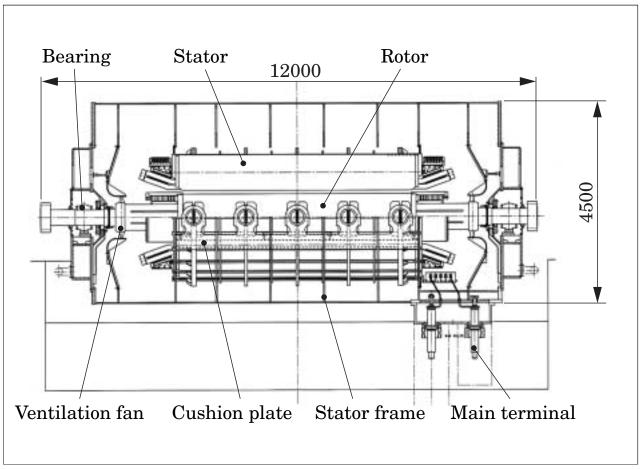



Table 2 Specifications of the 450 MVA indirectly hydrogen-cooled turbine generator

| | |
|---|---|
| Output | 450 MVA |
| Voltage | 21 kV |
| Current | 12,372 A |
| Power factor | 0.85 |
| Rotating speed | 3,600 r/min |
| Frequency | 60 Hz |
| Thermal class | 155 (F class) |
| Coolant temperature | 40°C |
| Coolant pressure | 400 kPa (g) |
| Excitation system | Thyristor excitation |
| Standard | IEC60034-3 |

## 3. Technology for Enlargement in the Capacity of Indirectly Hydrogen-cooled Turbine Generators

A 400 MVA-class indirectly hydrogen-cooled turbine generator in which Global VPI insulation system is applied to the stator winding has been developed. As a representative example, Fig. 3 shows a cross-sectional view and Table 2 lists the ratings and specifications of a 450 MVA generator.

In consideration of the economic reasons and Fuji Electric's proprietary technology and manufacturing facilities, the following guidelines were adopted to during development.

(1) The maximum output of the generator to be developed shall be limited by the capability of Global VPI facility.
(2) The rotor and stator of the generator to be developed shall adopt the same structure or the same production method as an indirect air-cooled turbine generator.
(3) Newly installed manufacturing facilities such as automatic brazing equipment for the rotor wind-

ing (to be described later) shall be used to the maximum extent possible.

### 3.1 Construction

The 400 MVA-class indirectly hydrogen-cooled turbine generator differs from an air-cooled generator in that the stator frame functions as a pressure vessel and bracket type bearings are used, since hydrogen is used as the coolant. The stator and rotor both basically adopt the same construction and manufacturing method as the air-cooled generator, however.

Moreover, similar to the air-cooled generator, the stator winding also utilizes a Global VPI insulation system, which is one of Fuji Electric's principal technologies. In order to realize this configuration, it was necessary to make the Global VPI insulation system compatible with high voltages. The relevant technical development is described in detail in chapter 4.

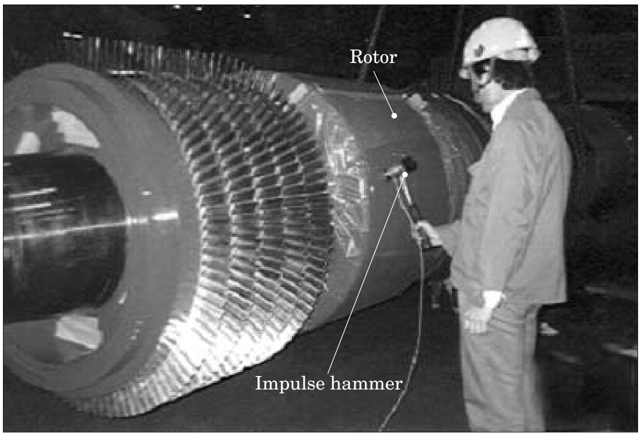
After Global VPI processing, the completed stator is inserted into the cylindrical stator frame, which is a pressure vessel, and secured via a spring plate to the stator frame. The spring plate, stator and stator frame are welded in the same manner as a large air-cooled generator.

The rotor winding utilizes the same radial flow direct cooling as the air-cooled generator, but has a thicker conductor due to the larger field current. In the case of the air-cooled generator, the ventilation hole for the conductor is formed with a punch-process in order to enhance the economic efficiency of the processing. In the case of the indirectly hydrogen-cooled turbine generator, that same punch processing cannot be used due to the deformation of the punch-out part of the conductor, capacity of manufacturing facilities, and other such factors. However, after careful investigation of many factors, including the clearance of the punching die and the sectional profile of the conductor, a punch process was realized for this fabrication step.

### 3.2 Ventilation and cooling

In a large capacity air-cooled turbine generator, ventilation is implemented using a "double flow" design. In this design, in order to achieve a uniform distribution of the stator winding temperature, the middle portion of the stator core is provided with a structure that flows a coolant gas from the outer diameter to the inner diameter of the stator core. On the other hand, since hydrogen gas has a lower density and larger thermal capacity, when the coolant gas passes through the ventilation fan and generator gap, the gas temperature rise is less than in the case of air. Accordingly, ventilation of the 450 MVA indirect hydrogen-cooled turbine generator is implemented with a "single flow" design in which a coolant gas flows only from the inner diameter to the outer diameter of the stator core. In order to optimize the gas flow volume distribution in the axial direction, the optimum thickness and arrangement of the stator core block and the axial arrangement of the rotor winding ventilation hole were determined using analytical techniques that had been verified with the abovementioned 126 MVA prototype generator.

Fig.4 Impulse-force hammer test




### 3.3 Suppressing the vibration of a long rotor

As generator capacities increase, rotors are designed to be longer in the axial direction. Consequently however, mass unbalance and asymmetry in the stiffness of the rotor readily cause the shaft to vibrate. Thus, the issue of vibration must be given due consideration.

In order to verify double frequency vibration caused by asymmetry in the stiffness of the rotor, a factor which cannot be reduced by balancing the rotor, an impulse-force hammer test was performed as shown in Fig. 4 to compute the natural frequency in the principal axis direction of moment of inertia of area, and the asymmetry was compared with the calculation results. The results of this analysis and comparison were reflected in the design of the compensation slit for the rotor pole, which compensates asymmetry in the stiffness of the shaft.

## 4. Insulation Technology for the Stator Winding

Using its Global VPI insulation technology, which has been acquired over many years, and its world-leading Global VPI manufacturing equipment, Fuji Electric has been appling Global VPI insulation technology to turbine generators since 1993, and has subsequently delivered approximately 100 units. As the capacities of the abovementioned indirectly hydrogen-cooled turbine generators increase, the capability to withstand high voltages and provide stable insulation quality are required of Global VPI insulation technology. Accordingly, Fuji Electric has developed a Global VPI insulation system for 22 kV-class rated turbine generators.

### 4.1 Features of Global VPI insulation for turbine generators

Global VPI insulation system is advantageous because the stator windings and the stator core are impregnated and hardened together, thereby improving the cooling performance of the stator windings and reliability against loosening of the windings, and realizing less maintenance work. Figure 5 shows the appearance of a Global VPI insulated stator and Fig. 6 shows the cross-section of the stator winding. This Global VPI insulation for turbine generators utilizes the following insulation technologies in order to ensure the reliability of the insulation.

(1) Highly heat-resistant epoxy resin
(2) Highly pregnable mica paper tape
(3) Internal electric field relaxation layer providing high voltage endurance and a long service life
(4) Thermal stress relaxation layer providing high heat cycle resistance

Fig.5 Appearance of stator after Global VPI (280 MVA air-cooled generator)

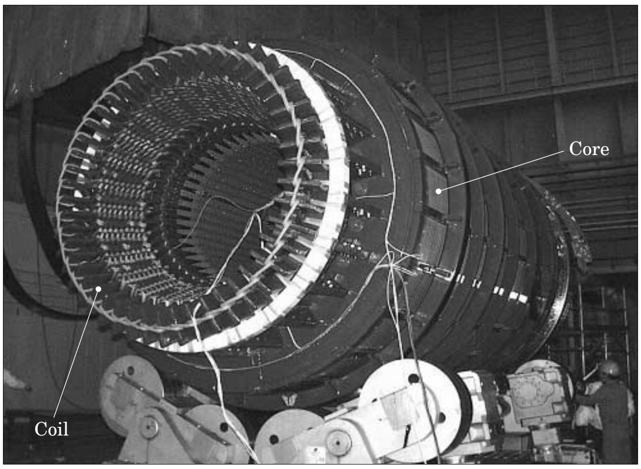
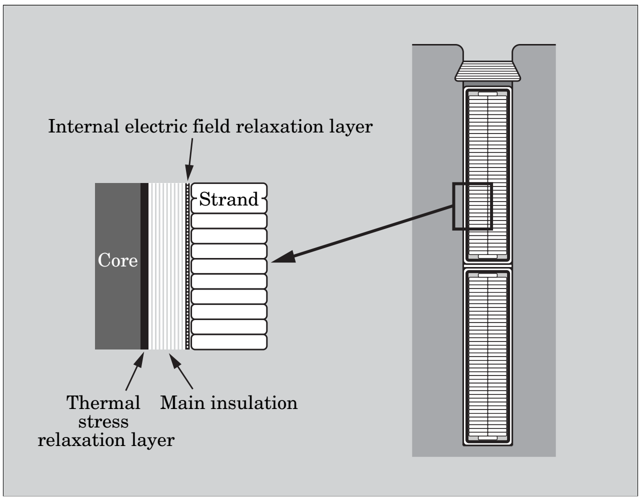



Fig.6 Cross-sectional view of stator winding




### 4.2 Development of 22 kV-class Global VPI insulation for turbine generators

The 22 kV-class Global VPI insulation for application to 400 MVA-class hydrogen-cooled generators, the coils are longer, the insulation is thicker and the withstand voltage is higher than in previous stator coil. Thus, Fuji Electric developed this technology by focusing on the taping characteristics and impregnation characteristics of the main insulation layer and the reliability of the end corona shield, and by evaluating the reliability of the Global VPI insulation.

#### 4.2.1 Analysis of the main insulation taping

The stator coil is insulated by winding a main insulation tape of mica paper several times around the coil. The insulation characteristics of this stator coil are influenced by the taping method and the thickness and width of the tape. For an example, overlapping state of the main insulation tape affects the break down voltage (BDV) value, so that it is required to study the taping method in order to achieve the maximum BVD value with the same layer numbers. In order to obtain the optimum condition for taping, an analytical software program had been developed and applied. In the operating voltage and withstand voltage, the electric field was observed to concentrate at the corners of the cross-section of the stator coil insulation. While taping, the number of overlapping layers must not decrease at these locations. Figure 7 shows the analysis results of taping with 22 kV-class insulation. The number of overlapped tape layers increases at the coil corners, and it was verified that the taping is regular. This result is reflected in the taping process of the 22 kV coil.

#### 4.2.2 Temperature distribution of end corona shields

End corona shield zones are provided at the end of the stator to relieve the potential gradient from the end of the coil. The temperature distribution of the end corona shield zones was quantified with this 22 kV-class insulation. Figure 8 shows the temperature distribution of the end corona shield zone while the nominal operating voltage is applied. The maximum temperature occurs near the edge of the slot corona shield, and this is in agreement with the results of surface potential measurements. The maximum temperature rise of 1.6 K was a small value, however. Even in withstand voltage tests, ($2E+1$, where $E$ is the rated voltage [kV]), no abnormalities such as flashover or surface discharge were observed. Thus, it has been verified that the end corona shield zones with 22 kV-class insulation provide sufficient functionality.

#### 4.2.3 Evaluation of insulation reliability

A straight bar model and full-scale model were manufactured for the evaluation of insulation reliability. A heat cycle test and $V$-$t$ test were performed with the straight bar model, verifying that that insulation provided stable performance in response to heat stress and a sufficient voltage endurance lifetime. Moreover,

Fig.7 Isolayer distribution over coil surface in 22 kV model with taping in both directions

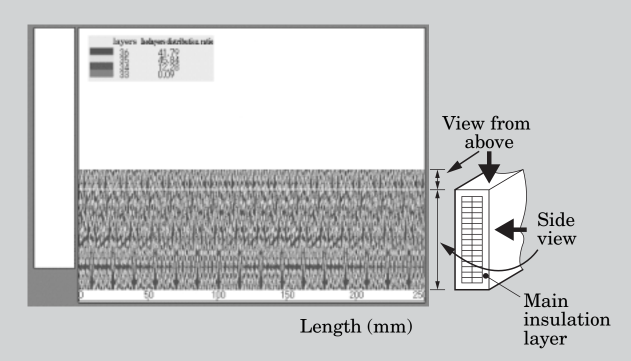



Fig.8 Surface temperature distribution on end corona shield in 22 kV model

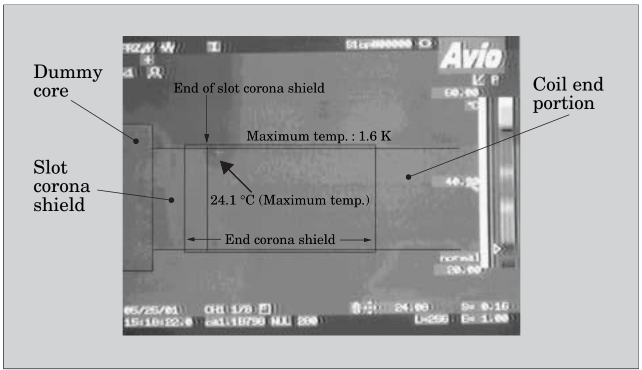



Fig.9 Appearance of 22 kV full-scale model

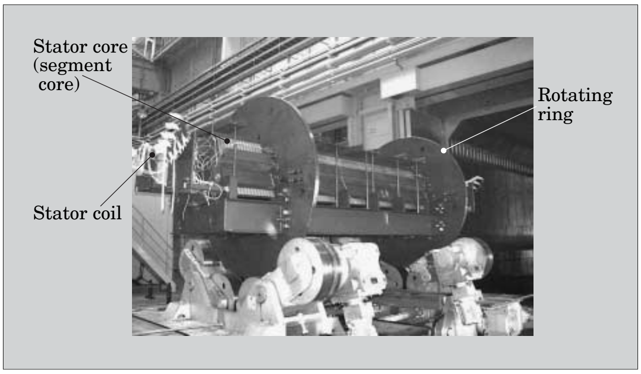
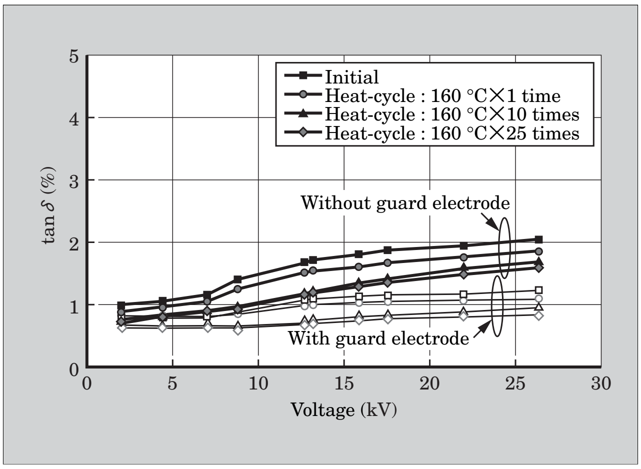



Fig.10 Tan$\delta$ - V characteristics of full-scale model during thermal cycle testing




the full-scale model shown in Fig. 9 was also manufactured in order to verify reliability of the insulation, including its method of manufacture. The full-scale model assumes a 450 MVA indirectly hydrogen-cooled turbine generator. The model core is 4.5 m in length and has 5 slots. The full-scale model is built with the same configuration as an actual generator, i.e. with an inserted stator coil, a fastened coil end and Global VPI processing, and therefore a coil end support and support ring are attached to the stator core of the full-scale model so that after the vacuum pressure impregnation procedure, the stator coils and core can be cured while rotating.

After the initial withstand voltage ($2E+1$) test, 25 iterations of a heat cycle test are then carried out with the full-scale model. The tan $\delta$ vs. voltage characteristics during the heat cycle testing are shown in Fig. 10. Since the tan $\delta$ characteristics do not exhibit much change from their initial value to their value at the 25th iteration of the thermal cycle test, the stability of the insulation performance was verified. Moreover, after the 25th heat cycle, an insulation breakdown voltage test of the full-scale model was performed in an atmosphere of air, and the breakdown voltage was verified to be at least three times greater than the rated voltage (in air).

## 5. Manufacturing Automation Technology

The market place demands turbine generators to have short delivery times, low price and stable quality. In order to meet with these demands, Fuji Electric has developed and applied technology for the automation and mechanization of manufacturing processes. A portion of this technology is introduced below. Previously, generator manufacturing technology depended largely upon the skill of the manufacturing workers, but the introduction of automated and mechanized manufacturing processes has made if possible to achieve stable quality.

### 5.1 Automatic brazing equipment for the rotor coil

Until now, the process of manufacturing a rotor coil involved the manual brazing of a copper bar. Automatic brazing equipment has been newly developed, however, and is shown in Fig. 11. This automatic brazing equipment continuously brazes copper bars with a high-frequency brazing machine, and then finishes the copper bars to form spiral-shaped rotor coils. In changing over the brazing work from a manual to an automated operation, the temperature during high-frequency heating and the timing for

Fig.11 Automatic brazing equipment

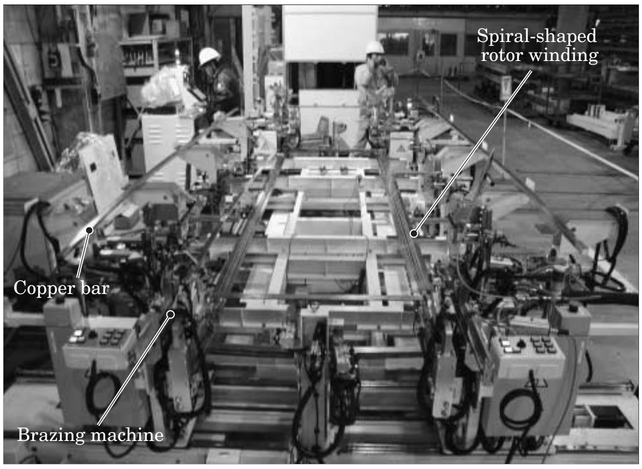
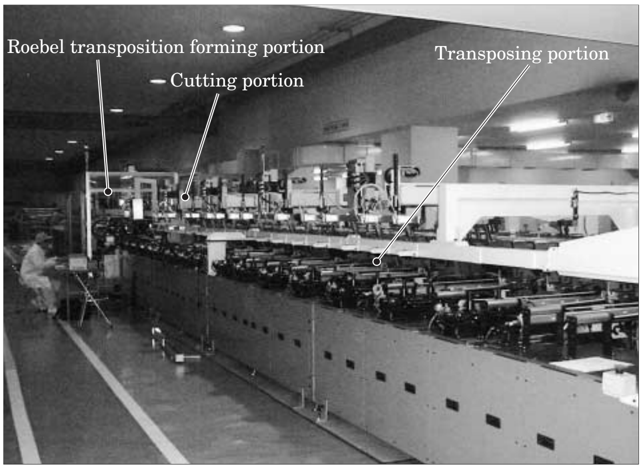



Fig.12 Automatic transposing equipment

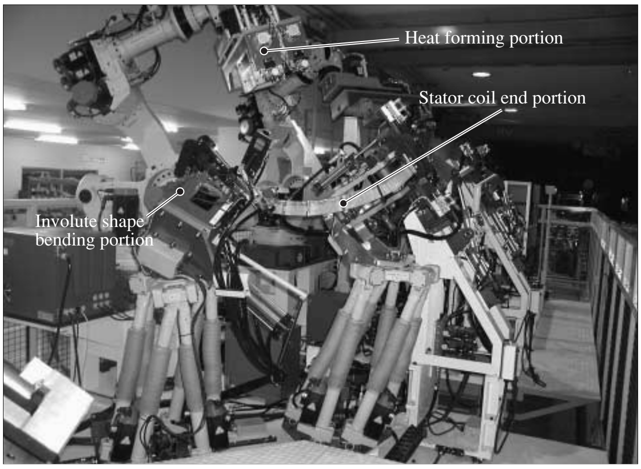



inserting the brazing filler metal were computed, and conditional settings for the automated machinery were determined based on such relationships as the material strength and cross-sectional analysis of the brazed portion. Moreover, in the case of a rotor coil copper bar of different dimensions, prior to manufacturing an actual generator, a brazed sample is fabricated and a strength test performed to verify whether the conditional settings are appropriate and to ensure good quality.

### 5.2 Auto-transposing machine

In order to reduce loss in the stator coil, Roebel transposition, in other words, strand transposition, is utilized. Previously, the tasks of strand cutting, forming, and transposing were performed manually for each work process. An auto-transposing machine has been newly developed, however, and is shown in Fig. 12. This auto-transposing machine automates the series of work processes from strand cutting, stripping of insulation from the strand ends, strand forming, transposing, and inserting of insulation material, to strand bundling. When strand wire and insulating material are input into the auto-transposing machine, the machine transposes the strands and outputs a coil. The auto-transposing machine is designed with a proprietary transposing mechanism to realize homogeneity of the transposing.

Fig.13 Automatic bending machine




### 5.3 Automatic bending machine

Previously, the end portion of the stator coil has been formed by manually bending the coil, placing it in a shape, and then hardening it. An automatic bending machine has been newly developed, however, and is shown in Fig. 13. The automatic bending machine uses robotic technology to automate all processes from bending the coil end portion into an involute shape and heat forming, to cutting the conductor at the coil end. Use of this automatic bending machine achieves uniformity of the involute shape of the coil end and shorter lead-times.

### 5.4 Automatic process control for the Global VPI system

Moreover, in the Global VPI process, which is the most important manufacturing technique, the impregnating resin used is controlled strictly and the impregnation and rotational hardening processes are regulated automatically. Also, during the impregnation process, an impregnation monitoring system is utilized to ensure that the resin has impregnated the insulation layer of the coil. Thus, the Global VPI process is implemented under strict manufacturing process control, aiming to realize automation and good stability of the quality.

## 6. Conclusion

The present status of Fuji Electric's development of turbine generators has been described.

Fuji Electric intends to continue to develop technology to produce high quality and highly reliable turbine generators in response to market needs.

# Small Capacity Geothermal Binary Power Generation System

**Shigeto Yamada**
**Hiroshi Oyama**

## 1. Introduction

Japan is a volcanic country having abundant geothermal resources. To date, Japan has 20 geothermal power generation facilities, with a total installed capacity of 550 MW. Most of these facilities are large capacity geothermal power plants constructed by utility power companies, but due to various circumstances, there are no further plans to build large capacity plants in the near future. The New Energy and Industrial Technology Development Organization (NEDO) is continuing its program of Geothermal Development Promotion Surveys, which since 2003 have targeted the development of small and medium capacity resources. There are many high temperature wells and steam discharge sites in Japan which are not utilized. Various studies are being carried out to expand the usage of such geothermal energy sources that are not currently utilized for domestic energy generation. Efforts are underway to promote the use of natural resource-based energy systems, including geothermal energy, and this initiative is known as EIMY (energy in my yard).

In addition, RPS (renewable portfolio standard) legislation mandating the utilization of electricity generated from renewable energy has been enacted in many countries. In Japan, the RPS became effective in April 2003. The renewable energy required for use in accordance with the RPS includes geothermal energy. Consequently, utilization of low temperature geothermal resources for electricity generation, which was not considered previously, is now being planned.

For small scale or low temperature geothermal resources, it is sometimes more economical to use a binary power generation system having a lower boiling point medium than that of conventional geothermal steam turbines.

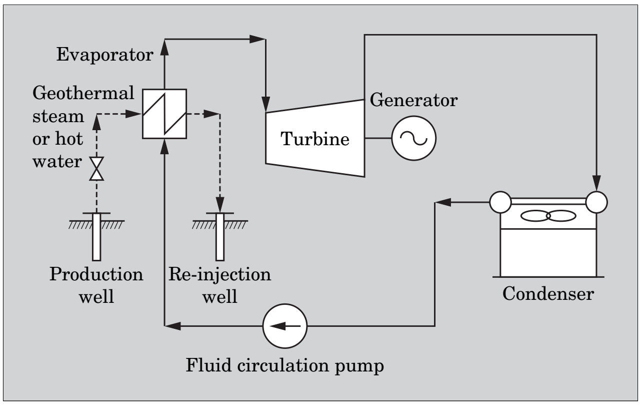
In consideration of these circumstances, Fuji Electric is developing a small capacity geothermal binary power generation system.

## 2. Binary Power Generation System

Geothermal binary power generation systems utilize a geothermal resource (steam or hot water) as a heating source to evaporate a low boiling point fluid, which drives a turbine. Such a system is called a "binary power generation system" because it uses two different kinds of fluids, geothermal fluid and low boiling point fluid. Figure 1 shows a conceptual schematic diagram of a geothermal binary power generation system. In Japan, binary systems were experimentally operated for 5 years beginning in 1993 by NEDO (new energy and industrial technology development organization). During that experimental operation, hydrochlorofluorocarbon (HCFC) was used as the low boiling point fluid, however, HCFC use must be abolished by 2020. There is a manufacturer abroad who has commercialized a binary power generation system that uses hydrocarbons such as butane or pentane. Another system is the so-called "Kalina cycle" which uses a mixture of ammonia and water.

In countries such as the USA, Philippines, New Zealand and Iceland, binary power generation systems are widely utilized for geothermal power generation at facilities ranging in capacity from several hundreds of kW to tens of thousands of kW. The binary power generation system by Ormat Industry, Inc. that uses pentane is especially well known and has been delivered to many geothermal countries. One of those systems has been delivered to Japan at the Hachobaru Geothermal Power Station of Kyushu Electric Power Co., Inc. as a pilot machine. Several published papers

Fig.1 Schematic diagram of binary power generation system



describe small capacity geothermal binary power generation systems of other manufacturers that are being operated in Europe. In Japan, there are no manufacturers supplying geothermal binary power generating systems as commercial products, although there have been instances of experimental operation. When importing a power generation system from overseas, the owners of the small capacity geothermal binary power generation system may require technical support from Japanese engineers to comply with Japan's various requirements such as documentation and inspections in accordance with the Electricity Utilities Industry Law. There might also be some concerns regarding the after sales service of the imported system. In this regard, we consider it quite important that small scale geothermal binary power generation systems be supplied by Japanese manufacturers.

The first geothermal power generation experiment was successfully carried out in Italy in 1904(1), and the experimental system reportedly used a steam engine driven by steam obtained from pure water evaporated by the geothermal steam. This system is one type of a binary power generation system.

A binary power generation system is driven by the vapor of fluid different from the heat source, and such heat source is not necessarily a geothermal resource. In Minakami, Gunma, a binary power generation system has been constructed and operated utilizing steam generated by an RDF (refuse derived fuel) boiler. A binary power generation system can be used to generate electricity from various heat sources such as industrial waste heat.

## 3. Development Through Experimental Operation

Fuji Electric is proceeding with the development of a geothermal binary power generation system, aiming at the Japanese market of small scale low temperature geothermal resources as well as geothermal resources throughout the world which may be suitable for a binary system.

Binary power generation systems use the Rankine cycle and basically apply the technologies associated with thermal power generation systems. One of the most important issues is the selection of the most appropriate and economical low boiling fluid, which effectively functions between the high heat source (geothermal resource) and the low heat source (atmosphere). Once a fluid is selected, the heat cycle can be planned with a simpler heat balance calculation than for a conventional thermal power plant.

The other important issue is the selection of optimum design conditions so that the design is both efficient and economical. It is also important to apply appropriate measures to prevent leakage of the fluid. Economical design is quite important for a small capacity system.

Fuji Electric plans the experimental operation of a prototype binary power generation system and intends to develop a product series based on the results of study and evaluation of the experimental operation.

## 4. Prototype System

### 4.1 Overview of prototype system

In consideration of the targeted heat source (low temperature geothermal resources) Fuji Electric decided to use iso-pentane which effectively evaporates with such heat sources and condenses at atmospheric conditions. Although iso-pentane is a flammable gas, it can be safely used with proper design and handling. Moreover, since the similar hydrocarbon of butane is recently being used as a cooling medium for home-use refrigerators, it is likely that the usage of hydrocarbon will be easily accepted by future owners.

In order to facilitate proper evaluation of the results from the experimental operation, the prototype system has been designed in consideration of the geothermal resource temperature at the actual well site. It is expected that a mixture of geothermal steam and hot water will be used, and that the separated hot water will be used for pre-heating and the separated steam will be used for evaporating at the pre-heater and the evaporator respectively. Also, an air-cooled type condenser is used because large amounts of cooling water will not always be available at sites where the binary power generation system will be installed. The prototype system is designed with a simple cycle, that is, the pentane vapor evaporated through the pre-heater and the evaporator drives the turbine, pentane vapor exhausted from the turbine is condensed at the condenser, and the condensed pentane is pumped back to the pre-heater.

Figure 2 shows the main flow diagram of the prototype system, and Fig. 3 shows an overview of the prototype system.

In order to realize an economical system, the prototype system is designed with general products and technologies, and does not require the development of any new equipment or materials.

### 4.2 Pre-heater and evaporator

Both the pre-heater and evaporator use the geothermal fluid as their heat source. In general, the geothermal fluid contains calcium carbonate or silica which causes scaling, and therefore, the pre-heater and the evaporator should be designed with a construction that enables easy periodic cleaning of the internal works. For the prototype system, shell-and-tube type heat exchangers are utilized, and the geothermal fluid flows on the tube side. Table 1 lists major features of the pre-heater and the evaporator.

### 4.3 Turbine and generator

Iso-pentane is non-corrosive to metals, and there-

Fig.2 Main flow diagram of prototype system

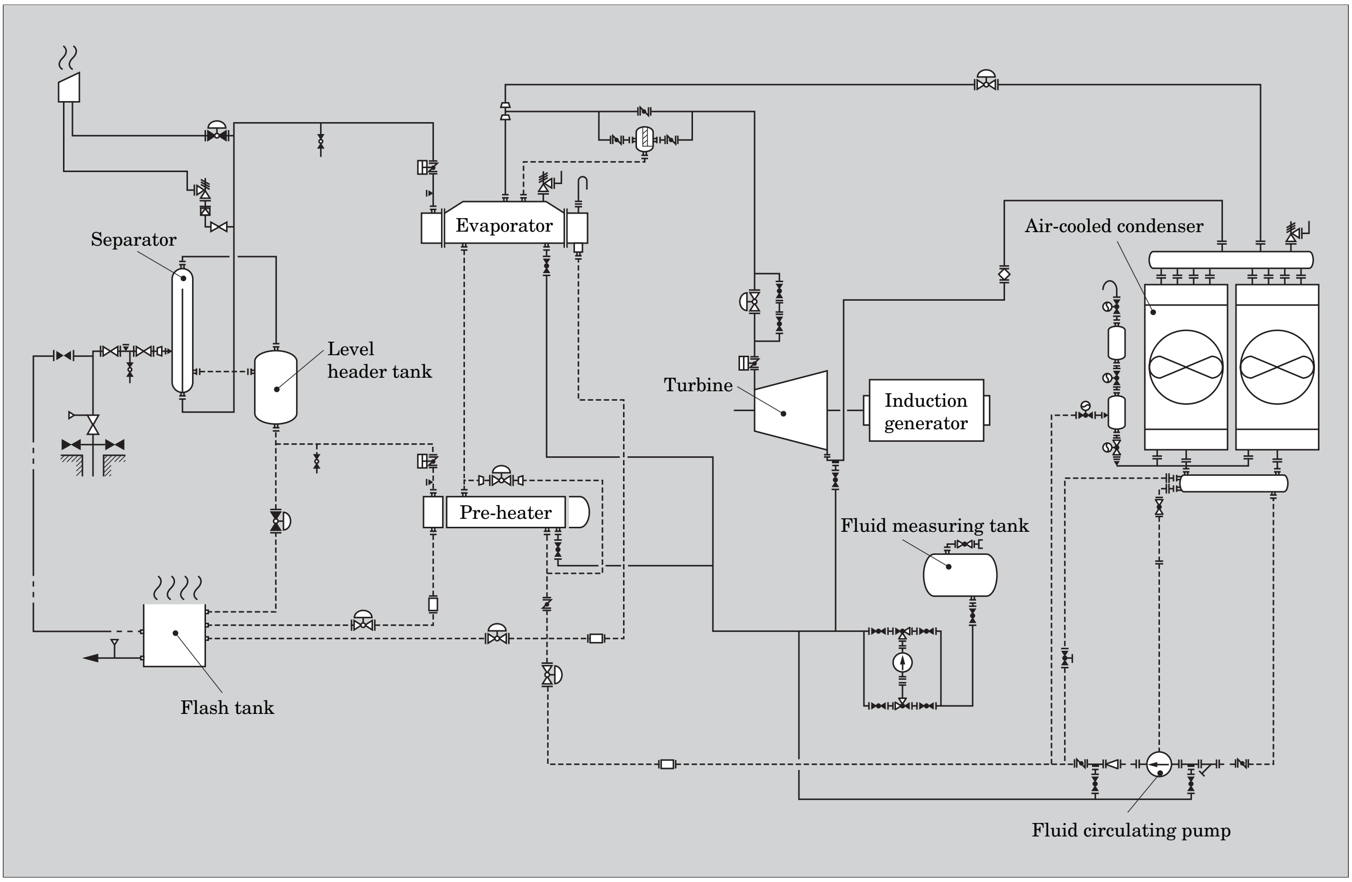
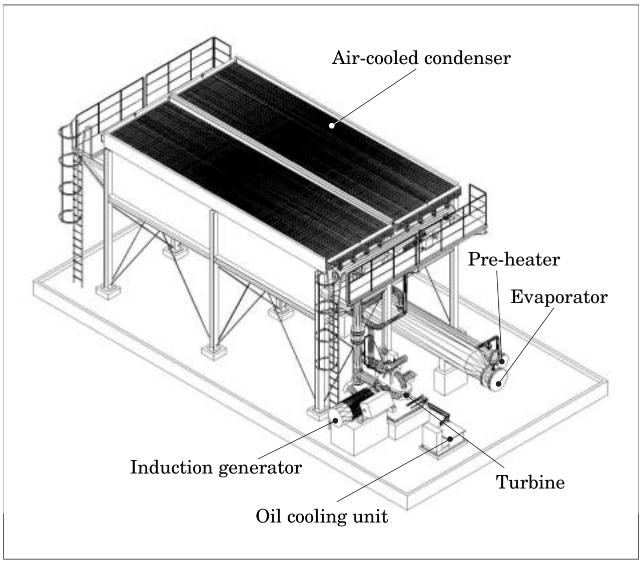



Fig.3 Overview of prototype system




fore, a standard single-stage steam turbine is utilized. However, a dual mechanical seal system is applied at the shaft seals to eliminate any leakage of iso-pentane from the shaft ends.

Because a standard induction generator is utilized, a speed governor is not provided for the turbine. Therefore, the use of a standard turbine stop valve and governing valve is unnecessary, and instead, a standard process stop valve and control valve which have no fluid leakage can be used. The control valve is used

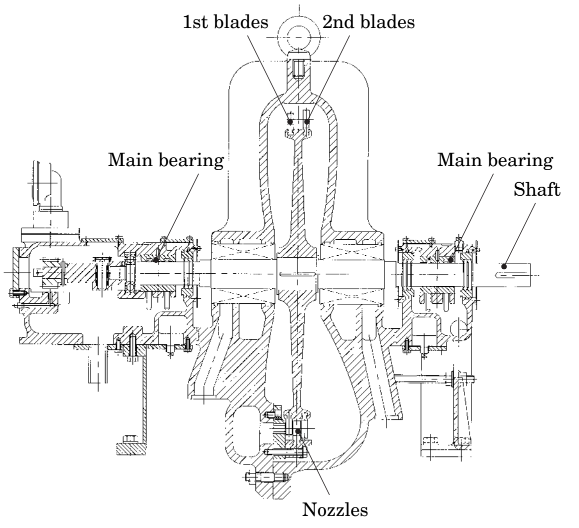
Table 1 Features of pre-heater and evaporator

| | Item | | Major features |
|---|---|---|---|
| Pre-heater | Type | | Horizontal shell-and-tube type |
| | Capacity | | 720 kW |
| | Temperature Inlet / outlet | | Iso-pentane : 36 / 84°C |
| | | | Geothermal hot water : 130 / 100°C |
| Evaporator | Type | | Horizontal shell-and-tube type |
| | Capacity | | 1,990 kW |
| | Temperature Inlet / outlet | | Iso-pentane : 84 / 105°C |
| | | | Geothermal hot water : 130 / 130°C |

Table 2 Features of turbine and generator

| | Item | Major features |
|---|---|---|
| Turbine | Type | Horizontal, single stage, impulse type |
| | Output | 220 kW (maximum) |
| | Speed | 1,800 $min^{-1}$ |
| | Type of shaft seal | Dual mechanical seal |
| Generator | Type | Three phase induction type |
| | Output | 250 kW |
| | Speed | 1,800 $min^{-1}$ |

Fig.4 Section of turbine




to regulate the inlet pressure so as to maintain the evaporator outlet vapor pressure. The stop valve closes immediately at the occurrence of an emergency and stops the turbine and the generator.

Table 2 lists major features of the turbine and the generator. Figure 4 shows a cross-sectional view of the turbine.

#### 4.4 Air-cooled condenser

As described above, the air-cooled condenser is considered as the primary option, and the prototype system also employs air-cooling with fin-tubes. The air-cooled condenser is the largest component in the system and determines the dimensions of the system. When large amounts of water can be used for the purpose of cooling, a water-cooled condenser may be used to achieve a smaller sized system.

## 5. Conclusion

The prototype system will be constructed within the fiscal year of 2005, and experimental operation will be commenced thereafter. Fuji Electric intends to expand the utilization of low temperature geothermal energy in Japan and throughout the world by providing economical and easy-to-operate binary power generation systems, and anticipates that all forms of renewable energy and natural energy will be recognized as important energy sources. Furthermore, Fuji Electric hopes that the expanded utilization of renewable and clean geothermal energy will contribute to preservation of the global environment and will enable society to leave natural resources for our future generations.

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# Recent Technologies for Geothermal Steam Turbines

Yoshihiro Sakai
Kenji Nakamura
Kunio Shiokawa

## 1. Introduction

Geothermal energy differs from fossil fuels such as oil, coal and natural gas in that it is a clean energy, having little impact on the environment and emits almost no carbon dioxide ($CO_2$), nitrogen oxides ($NO_x$) or sulfur oxides ($SO_x$). Fuji Electric delivered Japan's first practical geothermal power plant to the Fujita Tourist Enterprises Co. at Hakone Kowaki-en, since then has gone on to deliver more than 50 geothermal plants in Japan and around the world. Fuji Electric is counted as one of the leading manufacturers of geothermal power plants in the world.

Because geothermal steam is highly corrosive, when designing steam turbines for geothermal power generation, it is extremely important to realize and give due consideration to the corrosion of materials. For this reason, Fuji Electric has carried out continuous corrosion testing onsite at the location of geothermal power generation, and materials testing in a laboratory. The valuable data thus acquired was reflected in the turbine design in order to realize high reliability. Moreover, Fuji Electric has also actively worked to enhance the efficiency of geothermal steam turbines by applying recent blade row technology.

This paper introduces Fuji Electric's recent technologies for geothermal steam turbines.

## 2. Recent Materials Technology for Geothermal Steam Turbines

### 2.1 Corrosion testing in a modeled geothermal environment

In order to increase the reliability of geothermal steam turbines, it is important to assess the life of materials under the conditions of the geothermal environment. Fuji Electric tests the corrosiveness of geothermal steam turbine materials and evaluates their applicability to even more severe environmental conditions.

Assuming harsh conditions as the environment to which a turbine is exposed, environmental conditions were established for a concentrated corrosion test so that the long-term usage condition of a turbine could be modeled quickly. Table 1 lists the standard corrosion test environment, Table 2 lists the various corrosion tests performed in order to assess various stress conditions, and Fig. 1 shows the external appearance of the corrosion test equipment.

Table 1 Standard environment for corrosion tests

| Cl | $H_2S$ | $SO_4^{2-}$ | pH | Temp. |
|---|---|---|---|---|
| 10,000 ppm | 300 ppm | 50 ppm | 3.5 to 4.0 | 60°C |
| (1.8 %, as NaCl) | ($H_2S$ gas sealed at 0.2 L/min) | (Mixed as $Na_2SO_4$) | | |

Table 2 Contents of the corrosion test

| Test | Description |
|---|---|
| Corrosion test | Immersed in a corrosive solution. Weight reduction is measured and corrosiveness is assessed. |
| Stress corrosion cracking (SCC) test | While applying a static stress, immersed in a corrosive solution and the time to failure is evaluated. |
| Corrosion fatigue test | Repeatedly applied bending load while immersed in a corrosive solution, and number of ruptures are evaluated. |
| Corrosion fatigue test (mean stress loading) | Static mean stress and dynamic cyclic load are applied simultaneously, and the fatigue limit is obtained. |
| Blunt notched compact tension (BNCT) test | Static stress is loaded, and the amount of generated SCC cracking propagation is evaluated. |
| Double cantilever beam (DCB) test and Stress corrosion crack propagation (K1SCC) test | Pre-cracking is formed, and the susceptibility of propagation due to the concentration of stress at the tip of the cracking is evaluated (2 types of test are performed with different shaped test specimens) |

### 2.2 Use of new turbine materials

In existing geothermal steam turbines, 13 % Cr steel is used as the blade material and 1 % Cr steel is used as the rotor material. These materials are used widely and have a successful track record. However, we had developed and selected materials for both the blade and rotor in order to obtain even higher corrosion resistance and reliability. Table 3 lists the chemical compositions of the developed and selected

Table 3 Chemical composition of blade and rotor material that has been developed and selected

| | Material | Chemical composition (%) | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | C | Si | Mn | P | S | Cr | Ni | Cu | Nb | Mo | V | W | Al |
| Blade material | Existing material (13 % Cr steel) | 0.17 to 0.22 | 0.10 to 0.50 | 0.30 to 0.80 | ≦0.030 | ≦0.020 | 13.0 to 14.0 | 0.30 to 0.80 | — | — | — | — | — | — |
| | Developed material (16 % Cr 4 % Ni steel) | ≦0.05 | 0.10 to 0.35 | 0.30 to 0.60 | ≦0.025 | ≦0.005 | 15.0 to 16.0 | 4.2 to 5.0 | 3.0 to 3.7 | 0.20 to 0.35 | — | — | — | — |
| Rotor material | Existing material (1 % Cr steel) | 0.24 to 0.34 | ≦0.10 | 0.30 to 1.00 | ≦0.007 | ≦0.007 | 1.10 to 1.40 | 0.50 to 1.00 | — | — | 1.00 to 1.50 | 0.20 to 0.35 | — | ≦0.008 |
| | Selected material (2 % Cr steel) | 0.21 to 0.23 | ≦0.10 | 0.65 to 0.75 | ≦0.007 | ≦0.007 | 2.05 to 2.15 | 0.70 to 0.80 | — | — | 0.80 to 0.90 | 0.25 to 0.35 | 0.60 to 0.70 | — |
| | Selected material (3.5 % Ni steel) | 0.26 to 0.32 | ≦0.07 | ≦0.04 | ≦0.007 | ≦0.007 | 1.40 to 1.70 | 3.40 to 3.60 | — | — | 0.30 to 0.45 | ≦0.15 | — | ≦0.010 |

Fig.1 Corrosion cracking and corrosion fatigue test equipment

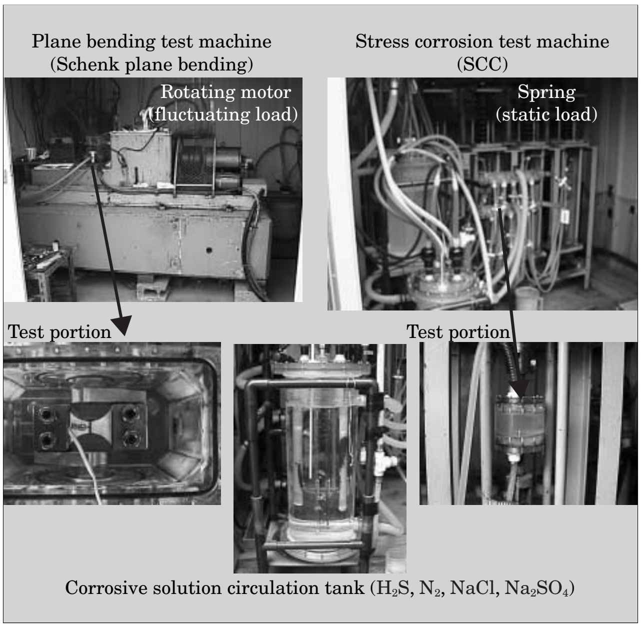



Fig.2 Fatigue limit diagram of existing and new materials

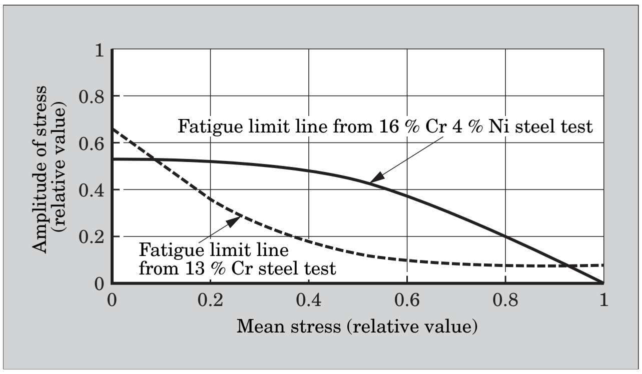
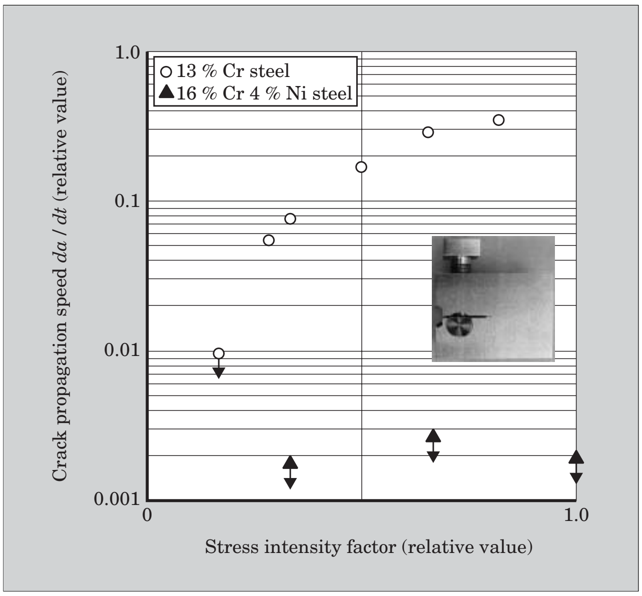



Fig.3 K1SCC test results




blade and rotor materials. New materials have higher chromium content than the existing materials, and this contributes to their better resistance to corrosion. The new blade materials are also heat treated appropriately in order to lower their susceptibility to corrosion and cracking.

The corrosion test described in section 2.1 was implemented for the existing blade material and for the new blade material, and the fatigue limit diagram obtained from the result of this testing is shown in Fig. 2. The results verified that under the operational stress conditions of the turbine, the new blade materials tolerated a higher stress amplitude, and exhibited higher corrosion resistance and reliability. This improvement is believed to be due to the increased chromium additive, which has the effect of suppressing the formation of corrosion pitting that has a large impact on corrosion resistance and reliability.

Figure 3 shows the results of a stress corrosion cracking propagation test (K1SCC test) that was used to evaluate the propagation of cracking at areas of concentrated stress in both the existing material and the new blade material. The crack propagation threshold of the stress intensity factor (in units of MPa $\sqrt{m}$) was 10 MPa $\sqrt{m}$ (relative value of 0.17) for the existing blade material and 60 MPa $\sqrt{m}$ (relative value of 1.0) for the new material, thus demonstrating the superiority of this new material. On the other hand, Fig. 4 shows the results of corrosion fatigue testing

Fig.4 Results of rotor corrosion test

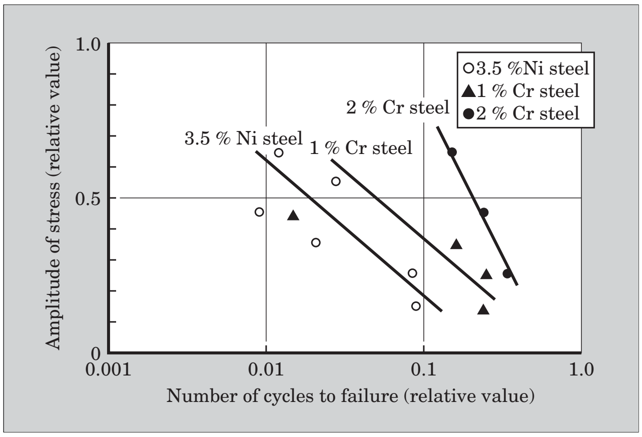
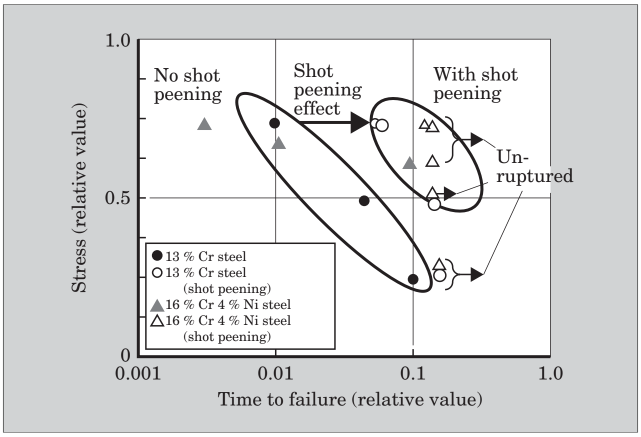



Fig.5 SCC test results (with and without shot peening)




performed on the rotor material. As in the case of the blade material, it can be seen that the application of the selected material (2 % Cr steel) resulted in higher resistance to corrosion.

### 2.3 Shot peening technology

As described above, the application of newly developed materials was confirmed to achieve higher resistance to corrosion, but in order to support operation in an even more severe corrosive environment and under higher stress, shot peening technology is also being studied and utilized. Shot peening generates compressive residual stress by impacting a blade or rotor area in which the generated stress is severe with a steel ball having a certain amount of energy.

Stress corrosion cracking tests were performed on the shot-peened blade and rotor material, and Fig. 5 shows results that verify their longer life. It can be seen that the time to failure is at least twice as long for shot-peened material compared to material that is not shot-peened. Based on these results, Fuji Electric began using shot peening as an effective measure to increase the corrosion life of steam turbines.

### 2.4 Coating technology

Blade material is required to be resistant to both corrosion and to erosion. Increasing the corrosion resistance generally requires that the material's hardness be increased. However, when the hardness is increased, the stress corrosion cracking characteristics become poorer. Flame spray coating is considered to be a method potentially capable of realizing resistance to both corrosion and erosion simultaneously. Seven types of materials were selected as candidates for the flame spray coating, their hardnesses were measured, and the corrosion test described in section 2.1 and a blast erosion test were performed for each. The results are listed in Table 4. These results show that the WC-CoCr material has excellent corrosion resistance and erosion resistance as a flame spray coating material. The flame spray coating conditions were optimized for this material and the flame spray coating material and

Table 4 Results of coating test

| Coating material | Stress corrosion cracking (SCC) | Fatigue | Corrosion weight reduction | Blast erosion (amount of average wear) | Hardness Hv |
|---|---|---|---|---|---|
| CoNiCrAlY+ $Al_2O_3 \cdot TiO_2$ | Poor | Poor | Excellent | Good | 790 |
| WC-10Co4Cr | Excellent | Excellent | Excellent | Excellent | 1,100 |
| CoCrMo | Poor | Fair | Excellent | Good | 650 |
| Al-Zn | Poor | — | — | — | — |
| Stellite No. 6B spraying | — | — | Poor | Good | 540 |
| 50 % $Cr_3C_2$-50 % NiCr | Excellent | Fair | Fair | Good | 770 |
| 75 % $Cr_3C_2$-25 % NiCr | — | — | Fair | Good | 810 |

— : Not tested

application method were verified to be at a level suitable for practical application to steam turbines.

### 2.5 Welding repair technology for the rotor

As described above, various technologies have been developed and selected in order to increase corrosion resistance. However, products that have already been delivered contain existing materials and their corrosion resistance is insufficient compared to the new products. In some geothermal steam turbines that have been in operation for a long time, corrosion has caused pitting and stress corrosion is causing cracks to appear. Accordingly, a repair technology was needed for these already-delivered products.

In the case of a rotor, stress corrosion cracking occurs at the bottom of the blade groove where the concentration of stress is highest. If cracks occur in this area, the propagation can be suppressed by shaving the area of occurrence so as to eliminate the crack. However, if the crack grows larger, it will be necessary to shave the entire blade groove. At such a time, technologies for overlay welding and for reusing the blade groove are required.

After welding conditions were selected for the plate material, welding was performed according to the dimensions of the turbine and then a mechanical property test and a corrosion test were implemented. 13 % Cr steel is used as the overlay material and the welding was implemented as multi-layer tungsten inert gas (TIG) welding.

A test specimen was sampled at the weld location, and the results of its corrosion fatigue testing are shown in Fig. 6 and the sample's overlay welding microstructure is shown in Fig. 7. The microstructure has zero defects. Excellent mechanical properties and corrosion resistance were verified for the rotor host material, and this welding repair technology was established for steam turbines.

As described above, a method has been established for assessing corrosion, which largely impacts the reliability of geothermal steam turbines, and new materials, shot peening technology, coating technology and repair technology have been developed and established. By using these materials and technologies appropriately according to the geothermal conditions and the generated stress, it is thought that higher reliability can be achieved.

In the future, Fuji Electric plans to advance the assessment and research of corrosion under geothermal conditions and intends to evaluate techniques for achieving even higher reliability and for assessing the residual life.

Fig.6 Results of corrosion fatigue test of repair welded area

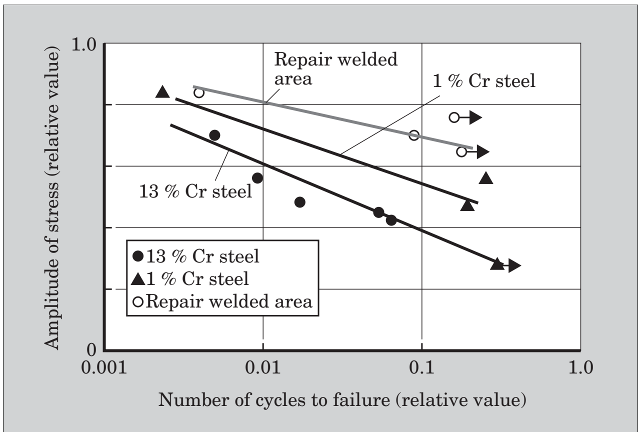
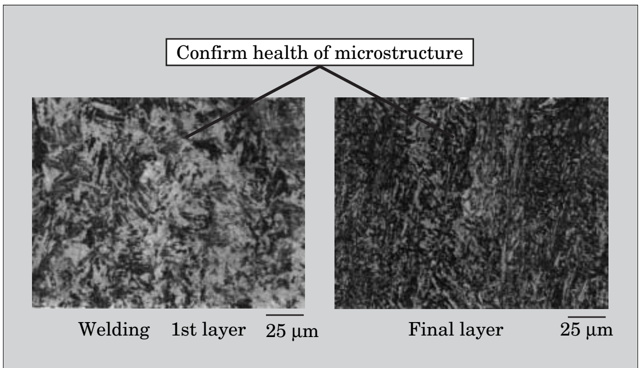



Fig.7 Microstructure of the overlay welding




## 3. New technologies of Improving the Efficiency of Geothermal Steam Turbines

As a measure to improve the efficiency of geothermal steam turbines, recent technologies based on expertise acquired from the development of steam turbines for conventional thermal power generation are applied mainly to blade rows in order to realize a significant improvement in efficiency.

### 3.1 Advanced reaction blades (high load and high efficiency reaction blades)

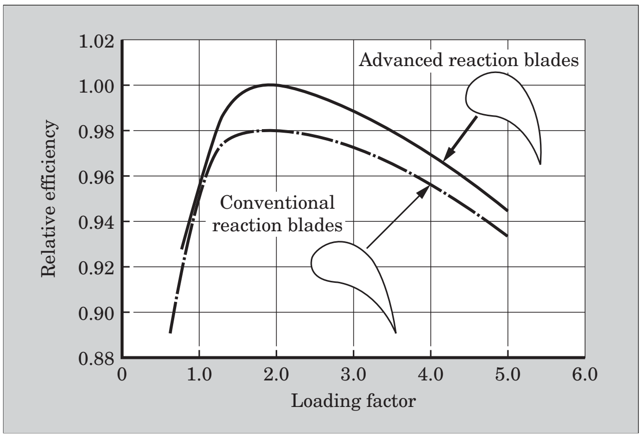
Utilizing recent blade row design technology, high-efficiency reaction blades capable of maintaining high efficiency while increasing the load per stage are used in blade rows, with the exception of low-pressure blade rows, in geothermal steam turbines. For the same number of stages, the use of these reaction blades increases the efficiency by at least 1 % compared to the conventional reaction blades (see Fig. 8).

### 3.2 Improving the performance of low-pressure blades

Because low-pressure blades in a geothermal steam turbine account for a larger proportion of the total turbine load than in a conventional steam turbine, improving the performance of these low-pressure blades will have a greater effect on improving the performance of the total turbine than in the case of a conventional steam turbine. Originally developed for use with conventional steam turbines, a new series of low-pressure blades having much higher performance are being adjusted for use in an environment of highly corrosive geothermal steam and are being applied to actual turbines.

Below, features of this new series of low-pressure blades will be described from the perspective of their efficiency and the status of the compact-size high-efficiency low-pressure blades currently being developed will also be discussed.

Fig.8 Efficiency of conventional and advanced reaction blades



(1) Transonic profiles

Recent advances in computational fluid dynamics have made it possible to simulate accurately the flow within a blade row, and by optimizing the velocity distribution within that blade row, a low-loss profile can be realized (see Fig. 9). The new profile shape is characterized by a convergent-divergent profile (a profile designed so that the flow path widens towards the end) that is adapted for transonic flow. The results of steam wind-tunnel testing confirmed that when the outlet Mach number is large, use of the new profile shape reduces profile loss to less than 1/2 of the prior value.

(2) Lean-radial stationary blades

Using a 3-dimensional time-marching method, various profile shapes were compared while varying the flow pattern, and from the results of this comparison it could be understood that a banana-shaped stationary blade which leans toward the circumferential direction at its root and toward the radial direction at its tip, as shown in Fig. 10, was the optimal shape. By using this type of lean-radial stationary blade, flow in the vicinity of the root, where separation is likely to occur, has been improved dramatically. The results of a model turbine test confirmed that stage efficiency was improved by at least 2 % compared to the conventional stationary blades.

Fig.9 Advanced low-pressure blade analysis example and steam wind-tunnel test results

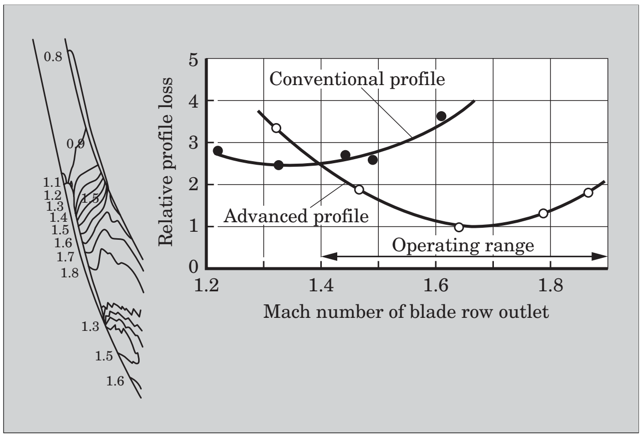
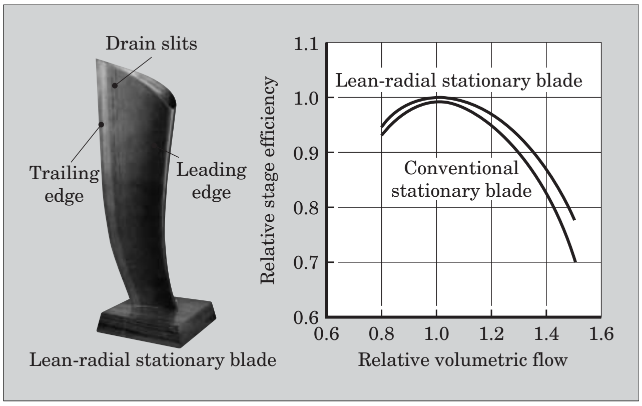



Fig.10 Results of efficiency test of lean-radial stationary blades in a model turbine




(3) Development of high efficiency, compact-size low-pressure blades

The technologies used to design the new series of low-pressure blades for conventional large steam turbines were also applied to the design of 500 mm-and-shorter low-pressure blades, and a high-efficiency compact-size low-pressure blade series that achieves dramatically higher performance is presently being developed (see Table 5).

This series is designed originally under consideration with use in geothermal steam turbines, and will also be provided the following features as well as the items adopted to enhance efficiency by using this new series of low-pressure blades.

(1) Highly reliable, rugged design for operation in a corrosive environment
(2) The blade root mounting area in all stages uses a simple inverted T-shape
(3) Redusing leakage loss from the blade tip with shroud is in all stages

Figure 11 shows the blading plan for the largest size blades (490 mm) in this series.

## 4. Example Applications of the Recent Technologies

Introduced below are examples of actual geothermal steam turbines to which the above-described recent technologies have been applied.

Table 5 Development of high efficiency compact-size low-pressure blades

| 50 Hz-use (nominal exhaust area) | 60 Hz-use (nominal exhaust area) |
|---|---|
| 490 mm blade (2.5 m$^2$) | 410 mm blade (1.7 m$^2$) |
| 350 mm blade (1.6 m$^2$) | 290 mm blade (1.1 m$^2$) |
| 290 mm blade (1.3 m$^2$) | 240 mm blade (0.9 m$^2$) |

Fig.11 Blading plan for 490 mm low-pressure blades

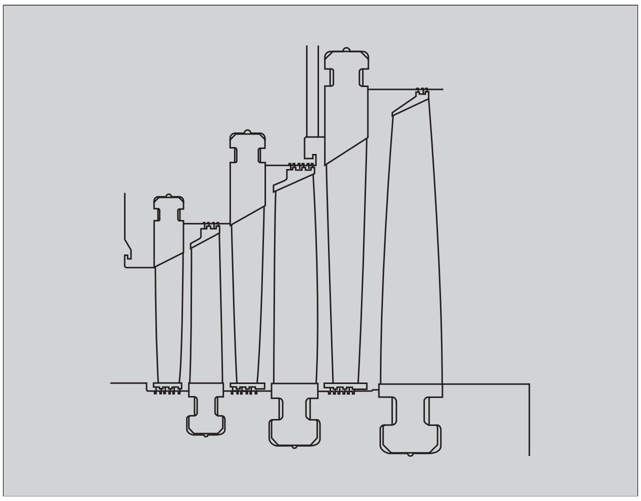


Fig.12 Cross-section of 64.7 MW geothermal steam turbine for Dixie Valley geothermal power plant

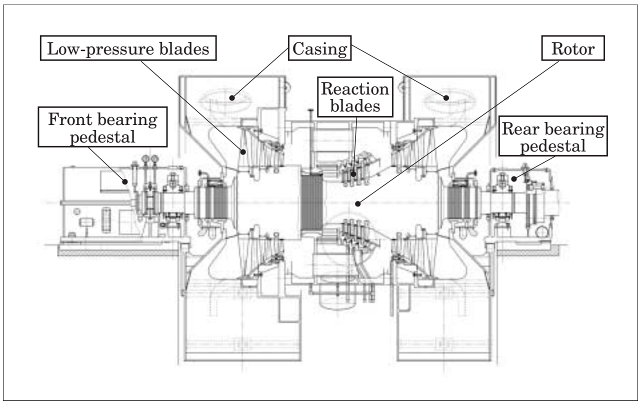
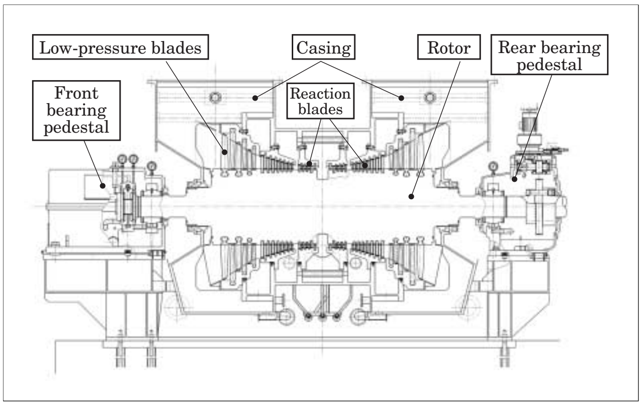



Fig.13 Cross-section of 55 MW geothermal steam turbine for Reykjanes geothermal power plant




### 4.1 64.7 MW geothermal steam turbine for the Dixie Valley Geothermal Power Plant

Figure 12 shows a cross-sectional view of the steam turbine whose efficiency was upgraded at the Dixie Valley Geothermal Power Plant in the United States. This turbine was placed into service in 1988, and 15 years later its internal components (rotor, blades, stationary blade holder, stationary blade rings, etc.) were upgraded using the latest technology in order to increase efficiency of the turbine. The major recent technologies applied to this turbine are listed below.

(1) New blade material is used in moving blades, except in the last 2 stages
(2) New series of high-efficiency 665 mm low-pressure blades are used for the low-pressure blades (in the last 3 stages)
(3) To increase reliability, shot peening is implemented in areas of concentrated stress at the blade root and blade groove of low-pressure blades (in the last 3 stages)

The efficiency upgrade enabled this plant to increase its maximum load significantly from the previous value of 60.5 MW to 64.7 MW. After the upgrade, stable operation continued as before.

### 4.2 55 MW geothermal steam turbine for the Reykjanes Geothermal Power Plant

Figure 13 shows a cross-sectional view of the steam turbine currently being manufactured for the Reykjanes Geothermal Power Plant in Iceland. The characteristic features of this turbine are a high inlet steam pressure of 19 bar abs., and 2 × 14 blade stages, which are more stages than in a normal geothermal steam turbine.

The major recent technologies applied to this turbine are listed below.

(1) High-efficiency high-load reaction blades are used in blade rows, except for the low-pressure blades (last 3 stages)
(2) 490 mm high-efficiency compact-size low-pressure blades are used for the low-pressure blades (in the last 3 stages)
(3) 2 % Cr rotor material, which has excellent corrosion resistance, is used in the rotor
(4) New blade material is used in the moving blades at the steam inlets (main steam, admission steam)
(5) To increase reliability, shot peening is implemented in areas of concentrated stress at the blade root and blade groove of low-pressure blades (last 3 stages)

This plant is scheduled to commence operation in 2006.

## 5. Conclusion

Japan is a volcanic country with abundant geothermal energy resources, but at present, geothermal power generation only accounts for 0.2 % of Japan's total power generating capacity. Meanwhile, there are other countries such as the Philippines and Iceland where thermal power generation accounts for approximately 15 % of their total power generating capacity. It is hoped that geothermal power generation using domestically produced geothermal energy will continue to be developed in the future. As a leading manufacturer of geothermal power plants, Fuji Electric intends to continue to work to increase the reliability and performance of geothermal steam turbines.

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# Recent Technology for Reusing Aged Thermal Power Generating Units

**Masaki Kato**
**Seiichi Asano**
**Shousuke Fukuda**

## 1. Introduction

For the continuous operation in another 20 or more years from aged thermal power generating units that have already been operated for 30 years, Fuji Electric has replaced a two-cylinder reheat type turbine with sophisticated single-cylinder reheat type turbine, were reused the existing foundation and nearly all the auxiliary machinery as counter-measures of life prolongation of the plant.

By replacing a high-performance single-cylinder reheat type turbine in the limited space of an existing power plant, renewing the insulation of power generating equipment, renewing the high voltage power console and control monitoring equipment, utilizing a digital-electrical governor instead of a mechanical-hydraulic governor, and by adopting an automatic turbine start-up system (ATS) and CRT operation, operability, reliability and maintainability have been improved dramatically.

Because this renewal technology can be applied at low cost to aged thermal power generating units, which are comprised approximately 70 % of the total number of thermal power generating units supplied, this technology is expected to be in high demand as a way to provide new solutions to meet customer needs.

This paper introduces power generating unit renewal technology, which integrates sophisticated technology with mostly reused equipment from an aged thermal power generating unit to solve the issues concerned with that aged unit, and also presents an example application of the renewal technology. Fig. 1 shows the full appearance of a reused power generating unit.

Fig.1 View of reused thermal power generating unit

## 2. Serious Issues Concerning Aged Thermal Power Generating Units

With the development of residual life assessment technology, it has become possible to evaluate quantitatively the residual life of equipment, and statistical residual life and accident data have become publicly disclosed. On the other hand, users have the following concerns regarding the continuous operation and extension of regular overhaul and maintenance, inspection intervals for aged thermal power generating units, and we frequently hear about these serious below concerns.

(1) Concern about aging of the entire unit and the possible occurrence of trouble
(2) Apprehension about damage caused by deterioration of the high-pressure high-temperature steam turbine materials
(3) Wear, corrosion and erosion occurring throughout the steam turbine
(4) Concern about the occurrence of accidents due to piping wear, narrowing of the pipe wall thickness, and pipe rupture
(5) Insulation degradation and life of the generator and electrical equipment
(6) Incomplete maintenance due to a delay in discontinuing the use of obsolete equipment
(7) Deterioration in the reliability of control and protection devices
(8) Incorrect operation due to a delay in improving operability
(9) Concern about the tendency toward increased vibration with aging
(10) Loss due to a decrease in efficiency with aging
(11) Starting power loss due to start-up time delay

## 3. Counter-measures of Life Prolongation for the Power Generating Units

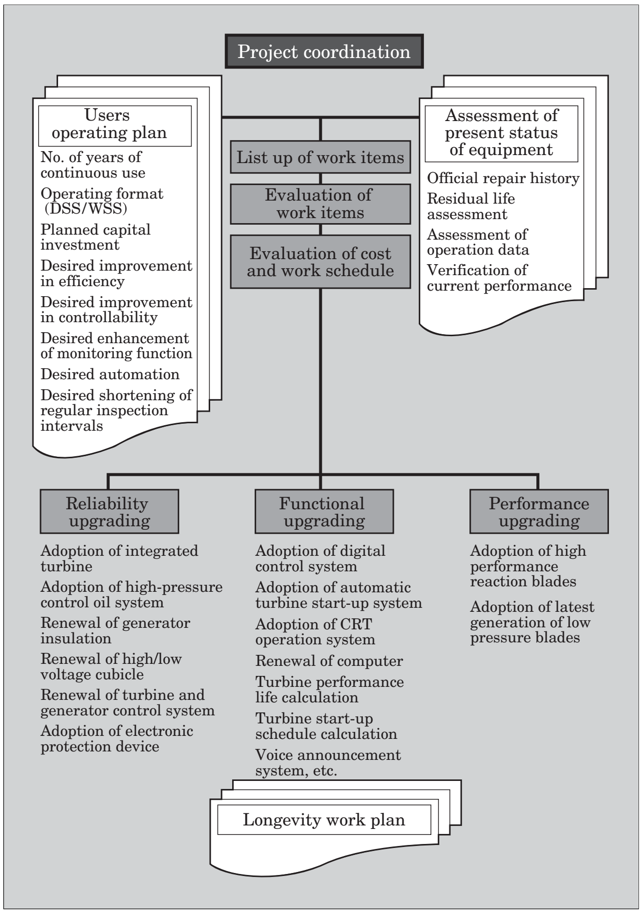
The purpose of the counter-measures of life prolongation, basically repair, replace or renew deficient parts of aging facilities in order to make possible the future long-term continuous operation of the facility and to eliminate user concerns. But it is also important to satisfy user needs by supporting their operating plans and to modernize the plants by applying a wide range of new technologies. Figure 2 shows an outline of the measures for plant longevity that were implemented.

## 4. Application of Sophisticated Steam Turbine Technology

In aged steam turbines that have been in operation for more than 20 years, due to the many years of operation, high temperature creep damage and fatigue damage to the materials can be observed. Such symptoms have typically been treated by replacing the affected parts with new components.

The counter-measures for plant longevity are not simply a return to the counter-measures against plant deterioration which have been practiced thus far, rather, these counter-measures employ the latest technology to modify the configuration of a two-cylinder reheat type turbine into a single-cylinder reheat type turbine while continuing to reuse the existing equipment to a large extent, in order to achieve a more compact size, higher efficiency, lower start-up loss, improved operability and much lower maintenance cost in a reused power generating unit.

Fig.2 Outline of work plan to increase plant longevity




### 4.1 Steam turbine specifications

Specifications of this steam turbine are listed below, and Fig. 3 shows a cross-sectional drawing of the steam turbine.

Type: Single-cylinder reheat
Output: 85,000 kW
Main steam pressure and temperature:
13.83 MPa/538°C
Reheat steam pressure and temperature:
3.13 MPa/538°C
Vacuum: 696 mmHg
Number of extraction stages: 5 stages
Rotating speed: 3,600 r/min

### 4.2 Adoption of single-cylinder reheat steam turbines

In recent years, steam turbine technology as progressed toward larger machine capacities and steam conditions of higher temperature and higher pressure. Turbines, which have conventionally been configured from multiple cylinders, have become much more compact by transitioning from three-cylinder to two-cylinder configurations, and then from two-cylinder to single-cylinder configurations. The steam turbine also achieves a dramatically more compact size by using the existing two-cylinder configuration as a high-medium-low integrated single-cylinder configuration, without any modification to the existing foundation.

Fig.3 Steam turbine cross-section

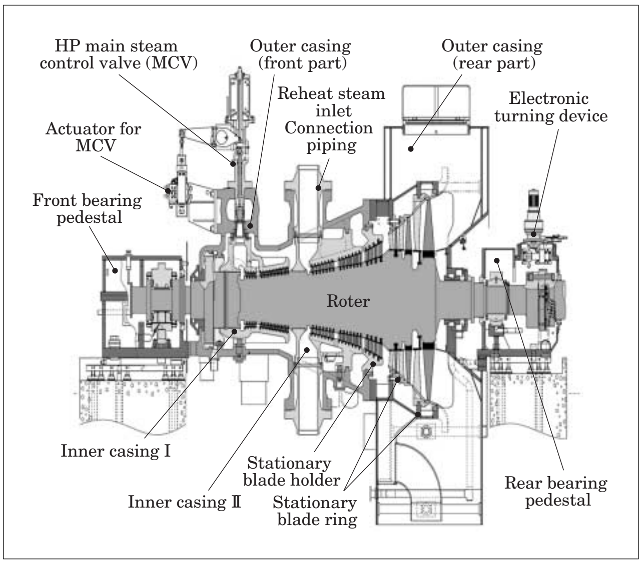


Table 1 Comparison of span and weight for reused and existing steam turbines

| Parameter | Single-cylinder type (reused) | Two-cylinder type (existing) |
|---|---|---|
| Axial span (mm) | 8,300 | 12,980 |
| Weight (t) | 160 | 210 |

Fig.4 Comparison of the reused and existing steam turbines

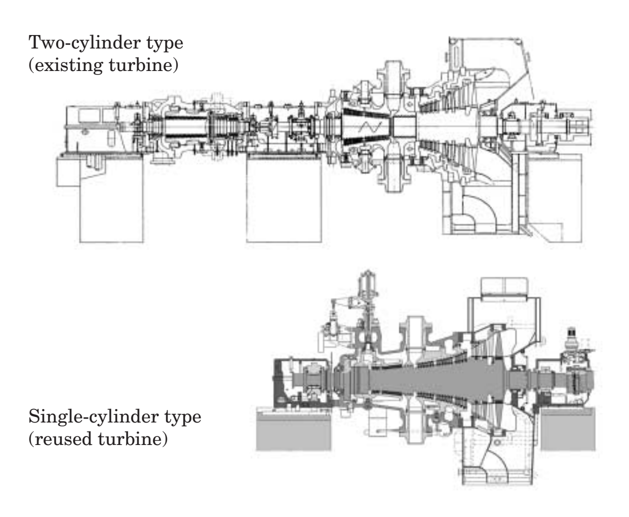



Table 1 and Fig. 4 compare the span and weight of the reused and existing steam turbines.

### 4.3 Characteristics of single-cylinder reheat steam turbines

(1) Reuse of the existing foundation and auxiliary equipment

One motivation for unit reuse is that the existing low-pressure steam turbine foundation could be used without any modification. The foundation concrete was assessed for deterioration and the strength of the turbine to be reused was analyzed, and the results showed that it was possible to avoid the cost and labor involved in modifying the foundation. Additionally, the specifications of auxiliary plant equipment such as the heater, de-aerator, condenser and turbine lubricating oil system were reexamined for the purpose of reusing the existing equipment.

(2) Adoption of a throttle governing double-shell structure

This plant is an oil-fired thermal power generating plant, and because it was designed for daily start-and-stop (DSS) operation, a throttle governing system was adopted, in which reaction blades were used in all stages, and without a control stage at the steam inlet. As a result of using this throttle governing system, the temperature fluctuation due to changes in the load at the cylinder under the most severe conditions has been reduced, enabling high-speed start-up and a larger range of allowable load changes. As a result, the start-up loss, an ongoing problem for existing plants, has been reduced dramatically.

Fig.5 Steam turbine rotor

(3) Analysis of shaft vibration and preventative measures

Along with the conversion to a single-cylinder configuration, we used a computer to analyze vibration over the length of the entire shaft coupled to the existing generator. The analysis results showed an increase in vibration of the exciter installed at the end of the generator. As a preventative measure, the field balance of the exciter was reconsidered to achieve the same level of vibration as was originally planned. Figure 5 shows the appearance of the steam turbine rotor.

(4) Temperature distribution and stress analysis of the entire turbine

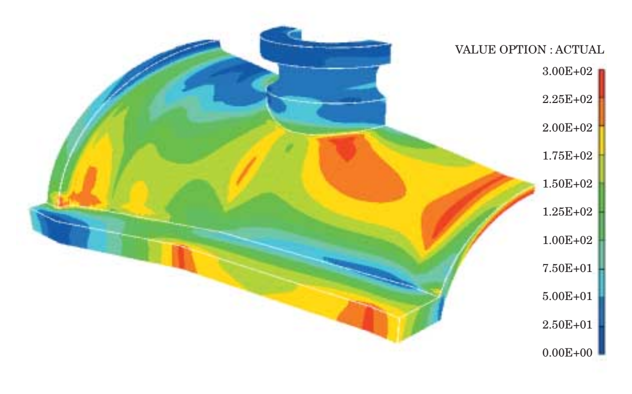
In the structural conversion to a single-cylinder reheat type turbine, the high pressure turbine steam outlet (low temperature reheat part) and medium pressure turbine steam inlet are combined within a single casing, and as a result, the temperature deviation of the casing largely influences such factors as thermal stress, fatigue life and local deformation. Consequently, analysis of this temperature deviation is important.

For this reason, the temperature distribution and stress (finite element method) at the middle of the interior of the reheat steam inlet were analyzed repeatedly and an optimum design (design of the casing and flange shape, wall thickness, etc.) for the single-cylinder reheat type turbine was achieved. Figure 6 shows the results of a temperature distribution analysis performed at the reheat steam inlet.

(5) Adoption of a separate-type oil system

The steam turbine was converted from a conventional common oil system (for both lubricating and control oil) to a separate-type oil system. This control oil system achieves higher valve operating force and improved controllability to realize a 14 MPa high pressure oil system, and is a new type of control system, using a plunger-type control oil pump for the operating oil, and using an electro-hydraulic actuator

Fig.6 Temperature analysis of reheat inlet steam part (finite element method)




for the valve operation. Moreover, the low-pressure lubricating oil system has changed from a turbine shaft-driven main oil pump to an AC drive main oil pump and has been designed to allow the continued use of existing lubricating oil system devices.

(6) Adoption of a digital governor and a fully electronic protection system

Labor savings, as typified by automatic start-up and remote automation capabilities, and improved controllability have been realized through the adoption of a digital governor and a fully electronic protection system.

Unlike the conventional protection system, the fully electronic protection system does not require oil pipes or mechanical apparatuses for detection, and thus realizes the advantages of a more compact detection sensor design and greater freedom in the selection of an installation site. Fuji Electric leverages these advantages by adopting this protection system as standard for all types of turbines, including the axial exhaust type turbine and the single-train type combined cycle generating plant.

## 5. Renewal Technology for Power Generating Equipment

The insulation for generator stator coil and others used for a long period of time deteriorates due to electrical stress, thermal stress, mechanical stress and contamination, and comes to the limit of dielectric strength (end point).

Accordingly, from the perspective of preventative maintenance of the equipment, before the insulation comes to the end point and causes a serious accident, it is important to renew that insulations systematically, based on the results of using methods such as non-destructive insulation diagnosis and physicochemical diagnosis to assess the level of degradation of the insulation.

The work plan implemented for plant longevity estimated quantitatively the limit of dielectric strength of the insulation from the statistically correlation between the generator stator coil breakdown voltage (BDV), calculated from non-destructive diagnosis data, and non-destructive data that had been accumulated over many years, and then assessed the exact timing and scope of the insulation renewal so that the equipment could be reused for another 20 years of continuous operation. This carried out example is described below.

### 5.1 Specifications of the generator

The generator has the following specifications.

Year of manufacture: 1972

Type: Horizontal-mount, cylindrical rotor, fully-enclosed rotating field, internally-cooled

Output: 100,000 kVA

Voltage: 13,800 V

Current: 4,184 A

Power factor: 0.85

Number of phases: 3

Number of poles: 2

Insulation class: B

### 5.2 Rewinding the generator stator

Based on the results of a residual life diagnosis which showed that the BDV value — an important parameter for safe operation — had decreased, we performed the renewal work of rewinding the coil. Since the insulation was class-B, we enhanced the insulating performance by using class-F epoxy resin and vacuum impregnation insulation material, and dramatically reduced the time required for onsite renewal work by upgrading the connecting method of conductor to block connections. Figure 7 shows the generator stator coil during this renewal work.

### 5.3 Renewal of the retaining ring for the generator rotor

As a measure to prevent stress corrosion cracking (SCC) of the retaining ring, we changed the material (18Mn18Cr) of the retaining ring. Additionally, we improved the dropout prevention of the coil end spacer and renewed insulation below the retaining ring to enhance reliability. Figure 8 shows the retaining ring of the generator rotor during this renewal work.

### 5.4 Renewal of the brushless exciter winding

Because cracking and other types of degradation were observed in the field winding lead, we rewound the rotor and stator coils of the exciter in order to improve reliability.

### 5.5 Renewal of the main terminal bushing

The existing main terminal bushing used insulation oil, but because we had previously experienced leakage of this insulation oil and had been repairing cracks in the mounting flange, we decided to change the main terminal bushing to an epoxy-molded type.

Fig.7 Rewinding of generator stator

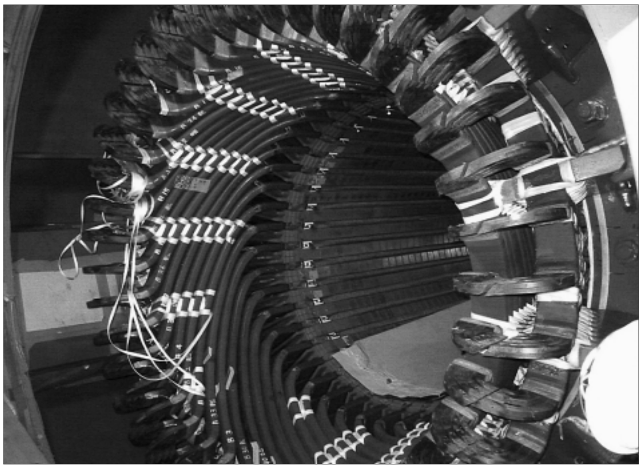
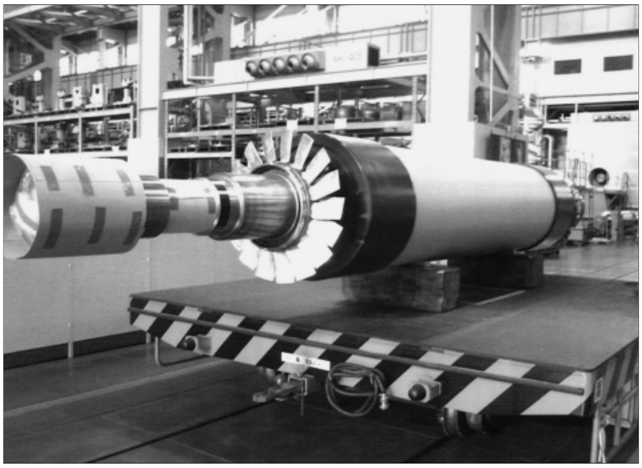


Fig.8 Renewal of retaining ring for generator rotor



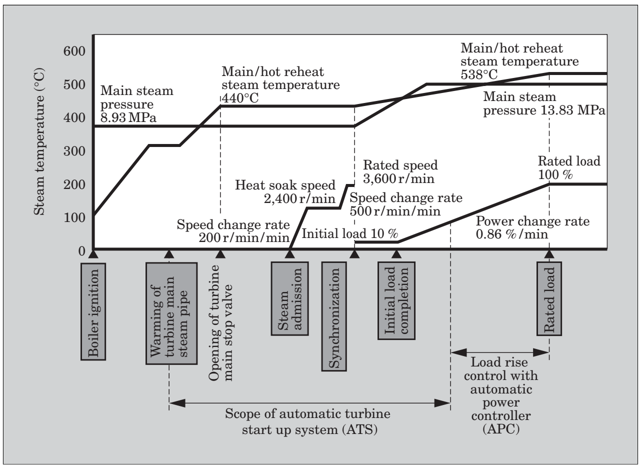
### 5.6 Other improvements

In addition, we improved the insulation to prevent current in the shaft bearing and renewed the generator stator pressurized through-terminal in order to enhance the reliability of all generator equipment.

## 6. Improvement with Electronic Control Equipment Technology

Among a power company's aged thermal power generating plants, the base plant is sometimes used as a load-adjusting plant and is operated to support daily and weekly start-and-stop (DSS and WSS) operation. For this purpose, higher reliability, shorter start-up time, and improved operability are required. In the work plan for plant longevity, in addition to implementing the previous measures for preventing degradation with age, it was also important to strengthen the turbine generator monitoring function, to add equipment and to configure an interface to the existing reused components, in order to satisfy customer needs for shorter start-up time and better operability of the turbine. The sophisticated digital control device and the integration with existing equipment in order to satisfy these needs are described below.

Fig.9 Scope of automatic turbine start up system (for cold start)




### 6.1 Configuration of automation and monitoring functions

By automating the various operations associated with turbine start-up, which had previously been performed manually, and by strengthening the plant monitoring function, the operator's workload has been reduced and start-up time shortened dramatically.

(1) Automatic turbine start-up system

As can be seen in Fig. 9, the scope of the automatic turbine start-up system (ATS) is confined to the range from the warming of the turbine main steam pipe until approximately 25 % of the rated output of the turbine, and thereafter, the load control switches to an automatic power control system (APC).

(2) Automation of auxiliary steam pressure control

The auxiliary steam pressure of the existing turbine is used for turbine shaft sealing and ejector driving, but such complicated switching operations required a considerable amount of time. Accordingly, the manual operation and admission conditions for the auxiliary steam are now implemented by an automatic control logic circuit, thereby achieving a drastic reduction in turbine start-up time.

(3) Automation of the existing turbine drain valve operation

The existing turbine drain valve is driven by an electric motor that operates automatically according to commands from the ATS.

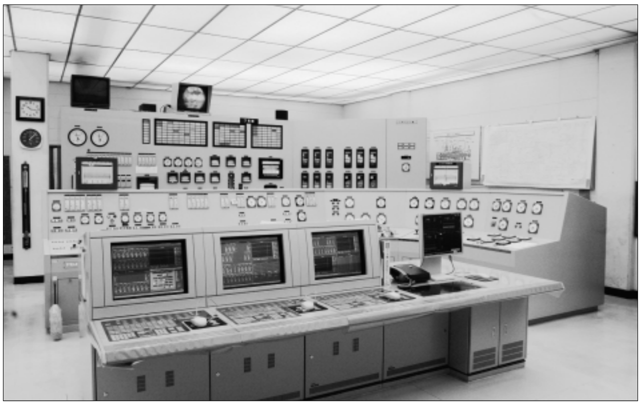
(4) Strengthening the plant monitoring function

CRT operation (see Fig. 10) was introduced in order to realize a comprehensive plant monitoring system and to reduce the number of operations involved. Consequently, the operator's workload decreased. Additionally, a voice announcement system enabled by the unit computer was added and the human-machine interface was improved.

## 6.2 Configuration of the digital control system

Figure 11 shows the automation and monitoring functions that were added and the interface to existing equipment. These added functions are configured with a digital controller. By using a digital controller that is the same model as the boiler controller, the operation monitoring system has been unified and replacement parts can now be shared. Additionally, all the main parts of controllers critical to plant control form a redundant system that instantaneously switches to a standby unit when an active control unit system goes down, so as to continue operation without tripping the plant. These digital controllers and their interface to existing equipment are described below.

Fig.10 Central operation room, after renewal



### 6.2.1 Addition of a digital electrical hydraulic governor (D-EHG)

The existing plant used a mechanical hydraulic governor (MHG), but in order to link to the newly designed ATS, APC and other digital control systems, addition of the D-EHG was required.

The D-EHG has the following advantages.

(a) Linear continuous control
(b) Easy setting of the speed change rate
(c) Turbine auto-accelerate and load-increase functions

### 6.2.2 Reconsideration and reconfiguration of existing functions

(1) Addition of a turbine auxiliary controller

The equipment for renewal includes a unit computer, and the system includes a computer I/O panel that inputs and outputs many field device signals. The body of the unit computer is an independent panel. By equipping the conventional computer I/O panel with a digital programmable controller for controlling turbine auxiliary equipment, a digital control system for both turbine automation functions and computer I/O functions was realized. By installing this turbine digital control system at the site from where the existing computer I/O panel has been removed, all computer-related external cables can be reused.

(2) Digitization of the turbine auxiliary closed loop control

Fig.11 System configuration, after renewal

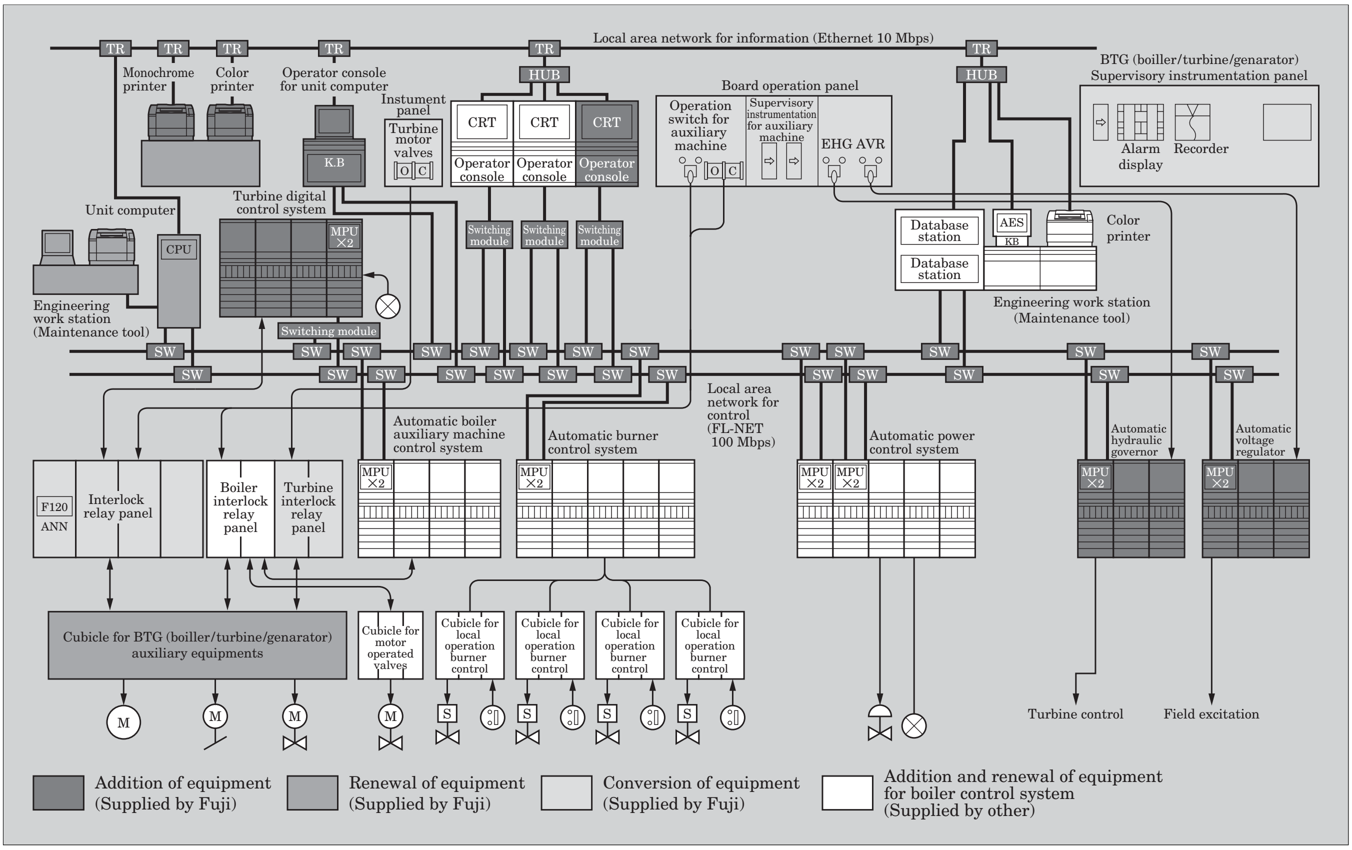
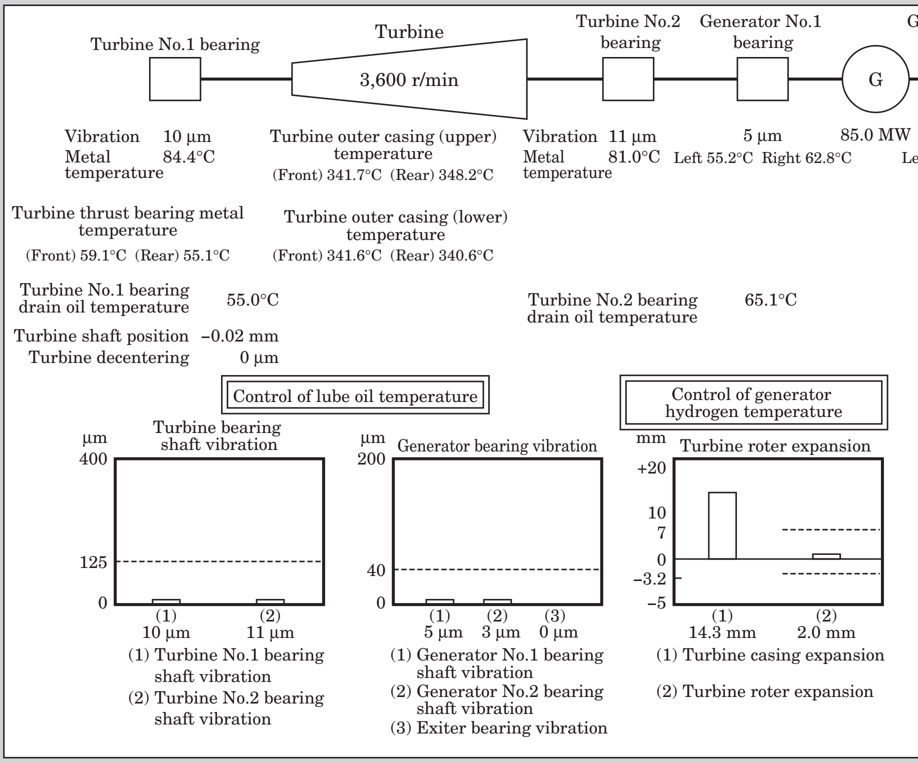


Fig.12 Turbine generator graphic




| | |
|---|---|
| Control fluid pressure | 14.88 MPa |
| Lube oil pressure | 0.195 MPa |
| Main steam inlet temperature | 535.3°C |
| Main steam inlet pressure | 13.83 MPa |
| Intermediate steam inlet temperature | 539.5°C |
| Intermediate steam inlet pressure | 3.375 MPa |
| Oil cooler inlet oil temperature | 56.2°C |
| Oil cooler outlet oil temperature | 45.0°C |
| Generator stator winding (U ph) temperature | 79.8°C |
| Generator stator winding (V ph) temperature | 80.2°C |
| Generator stator winding (W ph) temperature | 78.5°C |
| Generator hydrogen pressure | 0.19 MPa |
| Generator hydrogen purity | 97.8 % |
| Generator No.1 bearing drain oil temperature | 59.6°C |
| Generator No.2 bearing drain oil temperature | 53.7°C |
| Exciter bearing drain oil temperature | 44.5°C |

The existing turbine auxiliary closed loop control used an analog programmable controller for each loop, but all these control functions have now been configured with a turbine digital control system. Accordingly, what had been formerly board operations are now concentrated as CRT operations and the operator's workload has decreased. Due to the elimination of the analog programmable controls, maintenance has become more efficient.

#### 6.2.3 Introduction of CRT operation

Plant information from the turbine auxiliary controller and other control equipment is transmitted as digital signals to the CRT, and displayed. Figure 12 shows an example display of the CRT graphics.

With the introduction of CRT operation, the distinction between monitoring and operations with the existing board were reconsidered, and board operations were reduced. As an example, the necessary operations for start-up and stopping are implemented from the CRT, and individual auxiliary devices are controlled as a board operation. An auto-mode has been added to the board, and selecting the auto-mode enables board operations to be reduced.

#### 6.2.4 Addition of voice announcement system enabled by the unit computer

Linked to the automated operation, a voice announcement system that provides pre-announcements before a command is issued, post-announcements after an operation is completed, and warning announcements in the case of plant trouble has been provided. These voice announcements are linked to the information of CRT graphics.

#### 6.2.5 Improved reliability of data transmissions

A local area network (LAN) conforming to FL-net and connectable to an open loop dataway having high-speed transmission between digital controllers, high reliability, and a simple transmission interface was used. This LAN has a maximum transmission speed of 100 Mbps, is connected to both a digital automatic voltage regulator and a digital controller which had been delivered by the boiler manufacturer, and has a configuration that enables easy sharing of plant information. These communication networks are a mean of improving the reliability of the digital control system. The important control LAN relating to plant control is configured as a redundant system in order to improve reliability.

## 7. Conclusion

This paper introduced Fuji Electric's recently implemented technology for reusing aged thermal power generating units and examples thereof. In order to receive further continued use from these aged thermal power generating units, Fuji Electric intends to continue to supply reuse plans that combine existing units with sophisticated technology to transform those units into modern thermal power units having excellent reliability and operability.

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