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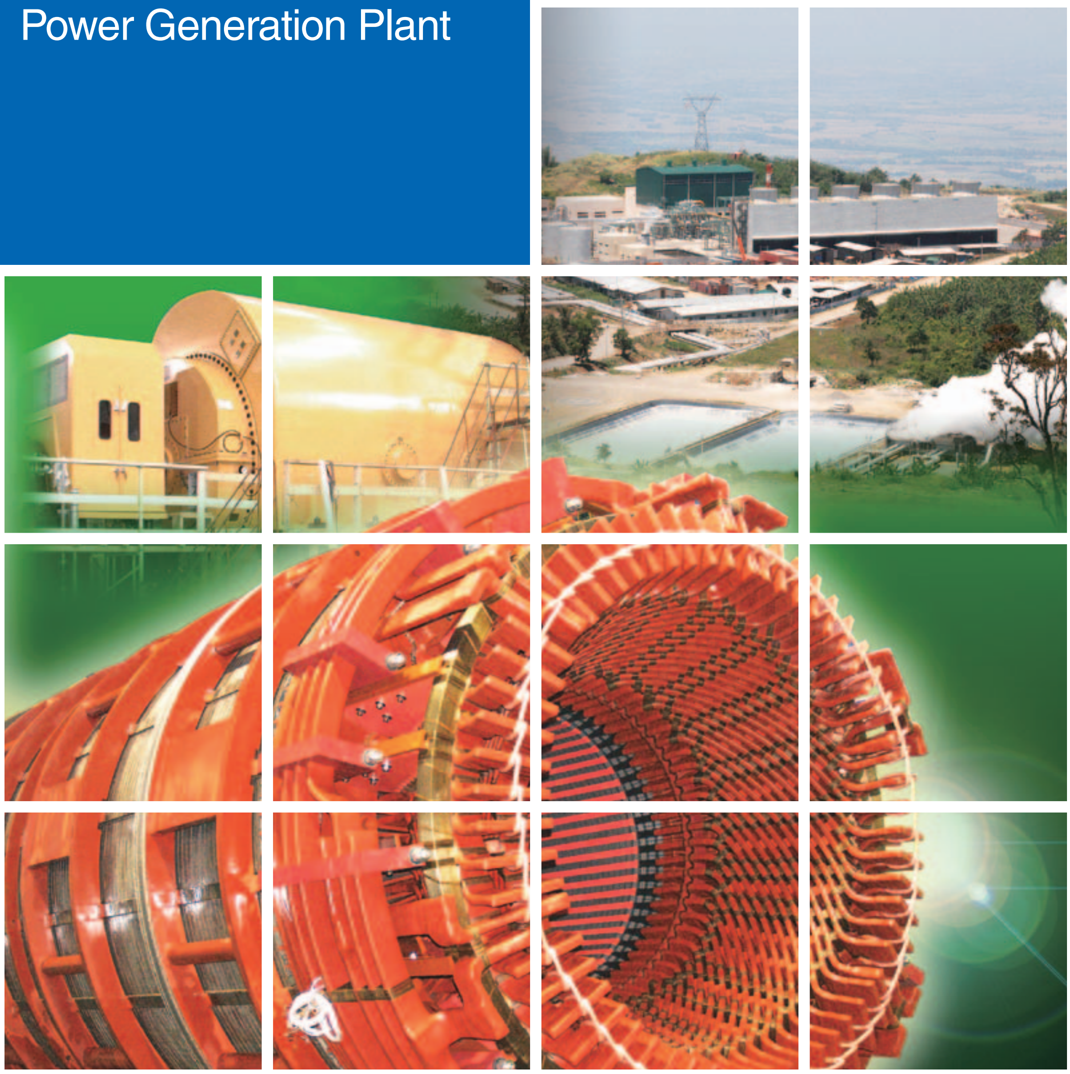
FUJI ELECTRIC REVIEW

3
2009 VOL.55

Power Generation Plant



Fuji Electric Group

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CONTENTS

Cover photo:

The worldwide demand for energy, and especially the demand for electric energy, is increasing dramatically with increasing population and economic development. On the other hand, the preservation of the global environment, and especially the prevention of global warming, are worldwide challenges and efforts to curtail CO_2 emissions and utilize natural resources and energy more efficiently must be strengthened.

Fuji Electric's Electric Power Division has applied its distinctive technology to advance the fields of thermal-electric power, hydroelectric power and nuclear power generation and to benefit society.

The cover photo shows a global vacuum pressure impregnation insulation generator which has the world's largest size power generator stator and is a record for Fuji Electric. The global vacuum pressure impregnation insulation generator is a world-class generator having excellent cost, insulation quality and production characteristics and can satisfy the recent needs for economic efficiency and maintainability of thermo-electric power equipment.

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Present Conditions and Prospects of Power Generation Technology

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1. Introduction

The worldwide demand for energy, and especially the demand for electric energy, is increasing dramatically with increasing population and economic development. Particularly in China and India, the increased demand for electric power has been significant, and has accelerated efforts to develop new power sources. Elsewhere in Asia and in the Middle East, the development of new power sources is also being advanced at a brisk rate.

On the other hand, the preservation of the global environment, and especially the prevention of global warming, are worldwide challenges, and are top priority issues that must be addressed for the future survival of our society. The prevention of global warming was a main theme of the G8 Hokkaido Toyako Summit held in July 2008 where a basic agreement was reached "to establish the long-term goal of reducing emissions of greenhouse effect gases worldwide by at least 50% by the year 2050." Companies must also participate by strengthening their efforts to reduce CO_2 emissions, conserve resources, and utilize energy more efficiently.

By focusing on the keywords of "environment" and "energy," Fuji Electric aims to contribute to the creation of a self-sustaining society. Fuji Electric is helping to preserve the environment through its water treatment technology, lead-free initiative, and so on, and is also contributing to energy saving technology with its inverters and other devices that are driven by power electronics technology. In the field of electric power generation, Fuji Electric has stepped up its efforts in geothermal power generation which is a natural and circulating energy, and has become a global leader. Fuji Electric is also contributing to nuclear power generation technology with which there is no emission of CO_2. For clean energy, Fuji Electric is also strengthening its efforts for fuel cells and solar cells, which can be used as distributed energy sources.

Fuji Electric's Electric Power Division has advanced technical development focused mainly on intermediate capacity thermal power and geothermal power in the thermal power field, and fuel handling equipment and waste disposal facilities in the nuclear power field. Fuji Electric has also advanced technical development for repowering and rehabilitation to increase the performance and reliability of existing electric power generating facilities and devices. This paper introduces a portion of this distinctive power generation technology.

† Fuji Electric Systems Co., Ltd.

2. Thermal Power Plants

2.1 Market trends of thermal power plants

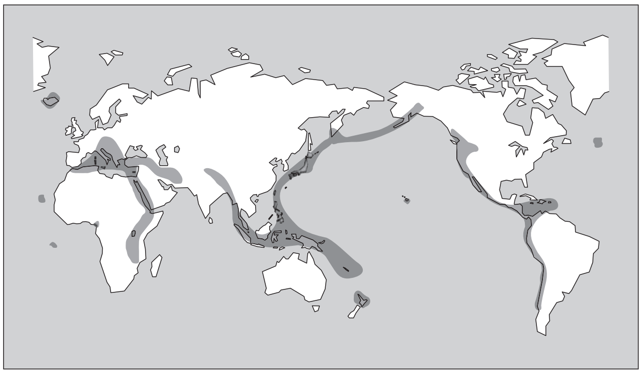
In the first half of 2008, the worldwide market for thermal power plants maintained the robustness of the 2007 market, but after the effect of the worldwide recession began to be felt, there was a sudden drop in the second half of 2008 as new orders decreased significantly. Orders for gas turbines increased dramatically in the USA, but fell overall by 4% from the prior year to 69.3 GW. Orders for steam turbines decreased in all regions of the world, without exception, by 8% from the prior year to 209.6 GW.

In the Japanese market, due to sluggish demand for electric power and large fluctuations in the price of oil, coal and natural gas, the development of new electric power sources was at a standstill as usual. Implementation of the "Renewables Portfolio Standard" and reduction of CO_2 emissions will have a beneficial effect on the market, but a turnaround is not expected.

In overseas markets, as described above, the outlook is uncertain, but pent-up need remains at a high level. Because circumstances and policies differ by country and region, many different plans exist for developing new power sources and replacing aging facilities. These plans are expected to be realized in the near future. Fuji Electric received 13 orders for steam turbine power generating facilities in 2008. These orders are all to be delivered overseas, mostly to destinations in the Far East and South East Asia, but also to North America and Europe.

The development of geothermal power is being advanced throughout the world in order to help prevent global warming and to efficiently utilize natural energy. Geothermal power is limited to regions in volca-

Fig.1 Geothermal zones worldwide



nic geothermal zones, but promising sites also exist in geothermal fields in the Pacific Rim and in regions in Africa and Northern and Southern Europe (See Fig. 1).

At present, robust development is progressing mainly at sites in Indonesia, Philippines, New Zealand and Iceland. Development of geothermal regions in South America and Africa is anticipated in the near future.

Fuji Electric's share of geothermal power facilities delivered over the past 10 years is approximately 40%, and Fuji has contributed greatly to the development of geothermal power throughout the world. At a geothermal plant in New Zealand, Fuji Electric is working to develop a steam separation system that produces steam for electric power generation from the geothermal fluid extracted from a geothermal well, and is also working to construct a turnkey geothermal plant.

Moreover, Fuji Electric is also promoting the commercialization of binary cycle power generating equipment as intermediate- and small-capacity geothermal power generating equipment. Demonstration equipment that has been installed and that continues to run at the Kirishima Kokusai Hotel is providing results as expected.

2.2 Technical development for thermal power plants

Fuji Electric is developing various technologies in response to recent market needs. A simplified overview of a portion of this technical development is presented below.

(1) Technical development of general thermal power devices

(a) Single-casing reheat steam turbine

To realize a 100 to 150 MW reheat steam turbine in a more compact size than the two-casing type that had been used previously, a single-casing type was developed, achieving a reduction in the required installation area, shorter delivery time, and improved economic efficiency and maintainability.

(b) Welded shaft for single-casing steam turbine

Technology was developed to integrate the high pressure and low pressure parts of a turbine by welding heterogeneous materials, each having the required characteristics for their respective part. As a result, lead times were reduced and economic efficiency was improved.

(c) Steam turbine for desalination plant

A large capacity single-casing non-reheat steam turbine suitable for desalination plants, which are actively being constructed in Middle Eastern countries, was developed, and Fuji Electric aims to enter this new market.

(d) Global vacuum pressure impregnation insulation system

The application of a global vacuum pressure impregnation insulation system to a 400 MVA-class large capacity hydrogen-cooled generator resulted in improved reliability, maintainability and economic efficiency.

(2) Technical development for geothermal power plants

(a) High corrosion-resistant geothermal steam turbine

Technology for improving the corrosion resistance of critical internal components of a steam turbine at a geothermal power plant has been developed, enabling an improvement in device reliability and maintainability.

(b) Steam purity monitoring system

A monitoring system that automatically measures the properties of geothermal steam at regular intervals and promptly detects any deterioration in those properties has been developed. By proactively preventing corrosion and scaling, reliability and maintainability are improved.

(c) Geothermal binary cycle power generation

Geothermal binary cycle power generation capable of generating electric power at a lower temperature than flash cycle power generation has been developed. This technology is applied to intermediate- and small-scale geothermal energy generation, and an expanded range of usage and more efficient utilization of geothermal energy are anticipated.

(3) Technical development for improved maintenance

(a) Leak buster

The vacuum region surrounding the condenser deteriorates with age, and the intake of air leads to decreased plant performance. A device has been developed that improves the maintainability and economic efficiency of a plant by accurately locating air leaks and measuring the amount of leakage without shutting down the plant.

(b) Remote monitoring system

A remote monitoring system capable of monitoring the status of an operating plant from a remote location at a Fuji Electric factory has been constructed, enabling a specialist to provide the customer with timely and suitable advice.

3. Nuclear Power Plants

3.1 Market trends of nuclear power plants

The environment surrounding nuclear power differs from the sluggishness that had existed since the late 1990s, and nuclear power is recently being reconsidered by all countries as a power generating system that helps to meet the increase in energy demand and reduce CO_2 emissions. Construction plans for nuclear power plants are putting into practice in such countries as United State, China and India. Only France and Japan have continued to construct and commission nuclear power facilities. Consequently, as construction plans materialize, highly reliable Japanese technology is again attracting attention.

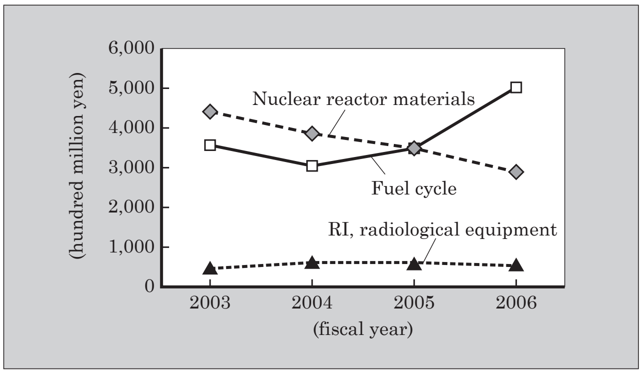
Meanwhile, in relation to environmental issues and targeting the G8 Hokkaido Toyako Summit in Japan, a report of the Nuclear Safety and Security Group was assembled under the auspices of the Japan Atomic Energy Commission (JAEC), and subsequently, a systematic promotion of nuclear power was incorporated.

In 2007, Tokyo Electric Power Company Inc.'s Kashiwazaki-Kariwa Nuclear Power Plant shut down operation because of the Niigata-Chuetsu-Oki Earthquake. This attracted the attention of the nation via reports from various media outlets. This time, however, the public opinion was different from that of several years earlier and a calm attitude was adopted toward the problem of aseismic design of nuclear power facilities. Therefore, other plans are progressing without significantly delays or suspensions. In particular, the Ohma Nuclear Power Plant of the Electric Power Development Co., Ltd. has a plan to load MOX (uranium-plutonium mixed oxide) fuel into the full core for which a safety review had been cancelled in the aseismic performance evaluation, and the Ohma Nuclear Power Plant's application for a nuclear power reactor plant license has been approved by the Ministry of Economy, Trade and Industry.

To complete the nuclear fuel cycle, which is important for providing a steady supply of nuclear fuel, Japan Nuclear Fuel, Ltd.'s reprocessing plant has been constructed in Rokkasho-mura, Aomori Prefecture, Japan, and testing has been performed. The final commissioning test stage is completed, and testing for startup operation has entered the final stage. For the "Monju" fast-breeder reactor, a highly anticipated successor to the light-water-reactor era, sodium leakage preventative measures have been completed and a secondary safety review concerning the loading of fuel to cause the reactor core to reach a critical state has been completed.

Japan's total nuclear power-related expenditures per sector are shown in Fig. 2. The portion for construction of nuclear power-related facilities is for projects involving the major plant manufacturers in Japan. With remote handling technology for nuclear fuel and high dose rate waste material containers, Fuji Electric has made contributions from the design stage, to the construction and modification/renewal stages for each facility. Making full use of these technologies, research and development efforts are being advanced for applications ranging from nuclear power plants to nuclear fuel cycle facilities, and also to devices for other large-scale research facilities.

Fig.2 Total nuclear power-related expenditures per sector in Japan



3.2 Technical development for nuclear power plants

(1) Development of remote handling an auxiliary system

A remote handling auxiliary system was developed after observing an increase in operations involving the handling of solid matter in a radioactive environment. At these types of facilities, many radiation tolerant cameras are installed, and skilled operators use the limited video information from these cameras to operate remote control equipment.

Fuji Electric has developed a remote handling auxiliary system that applies 3-dimensional shape recognition technology to identify the position and orientation of a handling object (target) virtually. With this system, multiple virtual screens can be set in arbitrary directions, without using a large number of radiation tolerant cameras, and remote control equipment can be operated easily, regardless of the skill level of the operator. In the development of this system, the development work had concentrated on shape recognition technology, and initial goals have been achieved. In the future, a simple and easy-to-use human-machine interface will be developed in consideration of a more realistic work environment. The remote handling auxiliary system is also expected to be used in fields other than nuclear power where dangerous substances and large heavy loads are also handled.

(2) Development of devices for J-PARC Material and Life Science Facility

Devices for the J-PARC Material and Life Science Facility are devices that have been remotely handled and delivered to the Japan Proton Accelerator Research Complex (J-PARC) which is being constructed by the Japan Atomic Energy Agency, an independent administrative agency. At this facility, neutrons and other secondary particles (mesons, neutrinos, muons, etc.), generated when the world's largest-class high intensity proton beam is aimed at a target are used to conduct research in various fields such as life science, materials science, atomic nuclei and elementary particles, astrophysics and energy research. Leveraging its remote handling technology which has been acquired over many years, from 2002 to 2007 Fuji Electric designed, manufactured and installed the following three devices: a target trolley (having a total length of approximately 14 m and mass of approximately 300 t) for setting up and moving a mercury target, moderator-reflector remote handling devices for replacing moderator pipes and the like, and irradiated component storage facilities for storing the mercury target and moderator pipes after having been replaced and that also include a cutting device for cutting 90 mm-diameter multi-layered pipes.

Because these equipment are required to provide remote operation and remote maintenance, and are also related with another equipment both structurally and operatively, coordinated tests were carried out at the factory test stage and onsite installation test stage, and the design and performance of each device were verified to be adequate for the entire facility. All of these activities were completed by March 2008.

(3) Other research and development

Fuji Electric's efforts in the field of nuclear power, not limited to remote handling devices for such types of large equipment, also include devices that handle small objects in a glove box such as the MOX fuel manufacturing process. In Japan, the construction, expansion and renewal of facilities are planned for both front-end (such as a "MOX fuel plant" that processes reprocessed uranium-plutonium into nuclear fuel) and back-end (decommissioning, the treatment and disposal of radioactive waste, and so on) fields relating to nuclear power generation, and technical development is being advanced according to those needs to provide highly reliable device systems.

Moreover, as a next-generation nuclear power generation system, research and development continues into a high-temperature gas-cooled reactor capable of supplying a high-temperature heat source that can be used for power generation and hydrogen production at the same time.

4. Postscript

The worldwide demand for energy continues to increase, and the positioning of electric energy relative to other forms of energy will obviously become a critical factor. Meanwhile, to safeguard the earth's environment, measures for reducing the environmental load must be addressed as a top priority issue. Continuing to pursue higher efficiency and economic performance for power generating devices, Fuji Electric intends to contribute to the creation of a self-sustaining society by advancing the research and development of geothermal power that effectively utilizes natural energy, and by actively promoting research and development in the field of nuclear power, which is a clean form of energy.

Reference

(1) McCoy Power Reports. 2008.

Kawerau and Nga Awa Purua Geothermal Power Station Projects, New Zealand

Tadao Horie †

1. Summary

Mighty River Power's nominal 90 MW Kawerau Geothermal Power Station has been the largest geothermal project in New Zealand for more than 20 years. Fuji Electric has played a major role in this project for which Sumitomo Corporation was the turnkey EPC Contractor. Fuji Electric has engineered and manufactured principal equipment such as the steam turbine, generator, condenser, MV & LV electrical switchgear, etc., procured balance of plant equipment and materials, supervised construction and commissioned the project. The project has successfully satisfied its contractual performance criteria, construction work and commissioning have achieved the required quality standards, and the plant was put into commercial operation on August 30, 2008, more than one month ahead of contractual time limit. Success of the Kawerau project has led Fuji Electric to work on a next project, the 132 MW Nga Awa Purua Geothermal Power Station at Rotokawa, New Zealand, where construction is underway and commercial operation is expected to start in 2010. The Nga Awa Purua Geothermal Power Station is a joint venture between Mighty River Power and the Tanhara North No.2 Trust.

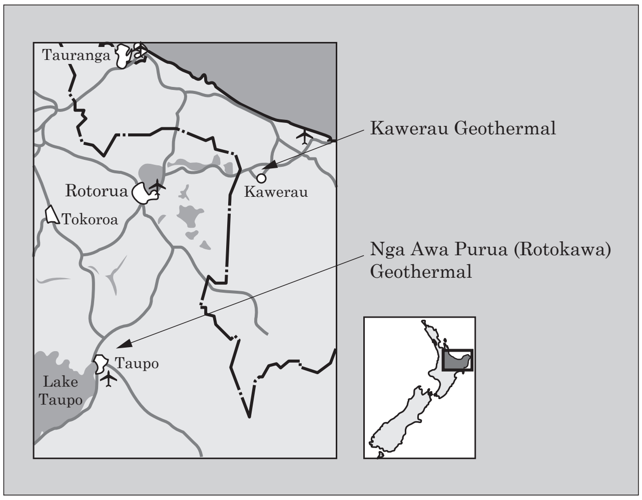
This paper introduces and presents an overview of the Kawerau and Nga Awa Purua geothermal projects, technical features of the plant systems and components, and our experiences in supervising the construction and commissioning the projects. Technical features of the plant systems are divided into the Steam Separation System (SSS) which separates and produces purified steam from geothermal two-phase fluid, and the Power Generation Facility (PGF) which converts steam energy to electricity, as in boiler-based steam power plants.

2. Project Overview

2.1 Project location

The Kawerau project is located approximately 3 km east of Kawerau Township near the east coast of the North Island of New Zealand. The Nga Awa Purua site is located 10 km north of Taupo, close to the Waikato River downstream of the Aratiatia Hydro Power Station and on the Tauhara North No. 2 Trust land adjacent to the existing Rotokawa Geothermal Power Station. These plants are located at the southern and northern ends of the Taupo volcanic zone of New Zealand (Fig. 1), where significant potential exists for further geothermal development.

Fig.1 Location map of Kawerau and Nga Awa Purua projects



The Steam Separation System as well as the Power Generation Facility is situated within the power station boundary. The equipment, buildings and ponds are suitably arranged in the available space to provide easy access for operation and maintenance, as shown in Fig. 2 for Kawerau and in Fig. 3 for Nga Awa Purua.

2.2 Project scope and major parties involved

For both projects, the scope of work and services to be supplied within the context of the EPC contract comprise the planning, design, manufacture, procurement, transportation, construction, installation and commissioning of all facilities within the boundary of the power station. Fuji Electric was responsible for the conceptual and detail engineering, overall project management, installation supervision and commissioning & start-up of the power station including both SSS

† Fuji Electric Systems Co., Ltd.

Fig.2 Kawerau plot plan

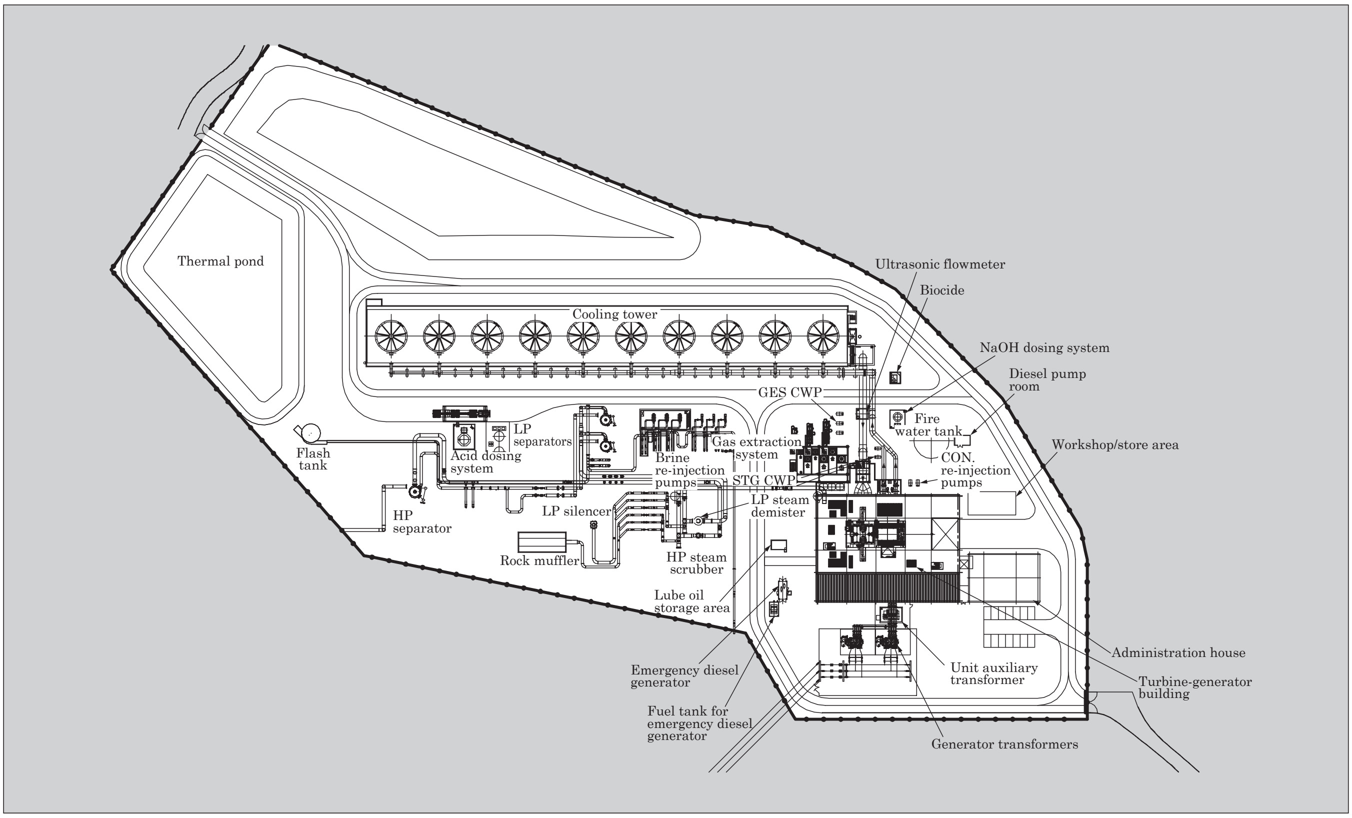
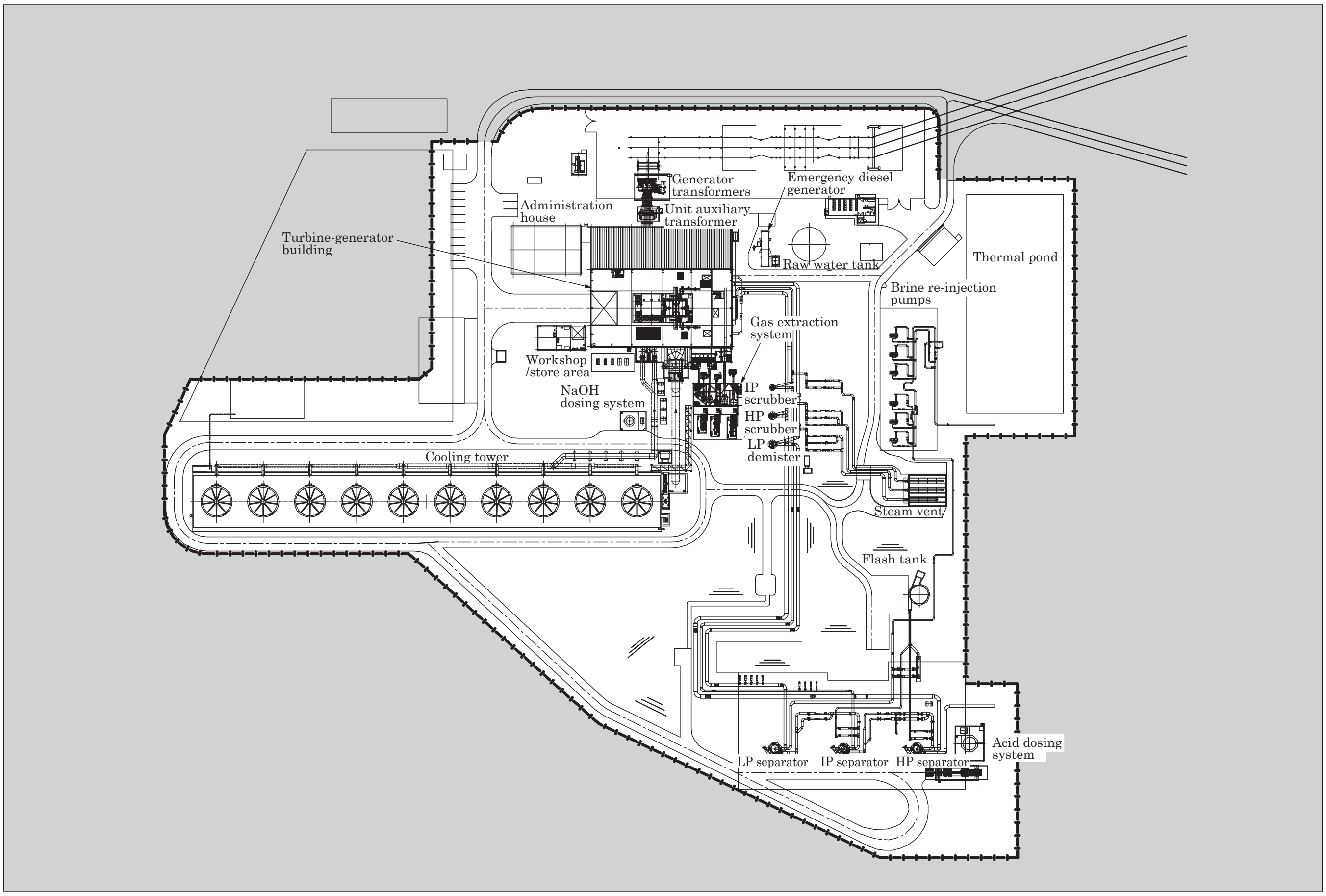


Fig.3 Nga Awa Purua plot plan



and PGF. Fuji Electric has also signed an agreement with a major NZ civil construction company, Hawkins Construction Limited, who assumed a partnership role in civil, structural, architectural and building services works. The agreement between Fuji Electric and Hawkins aimed to maintain a close and collaborative working relationship in order to complete this fast-track project within the targeted program without jeopardizing the quality of the work.

There were following three major process interfaces in the scope boundary of the EPC contract;

(a) TP-01: Two-Phase Geothermal Fluid Supply
(b) TP-02: Geothermal Brine Reinjection
(c) TP-03: Geothermal Condensate Reinjection

3. Overall Project Program

The overall programs for both projects are summarized as shown in Table 1.

For Kawerau, the power station commenced commercial operational more than one month ahead of schedule in compliance with the contractual performance guarantees. This outcome is the result of the high technical performances and great contributions from all related parties, i.e., the owner, civil partner, regulatory agencies, construction contractors, manufacturers, and designers and their staff.

4. Description of Technical Features

4.1 Power station

The process interface between the steam field and the power station is incoming geothermal two-phase fluid and the return of brine and condensate for reinjection, each at the power station perimeter fence. The Kawerau plant is designed for a rated two-phase fluid flow of 45,000 tons per day and a maximum of 55,000 tons per day. The Nga Awa Purua plant is designed for a rated two-phase fluid flow of 45,000 tons per day and a maximum of 48,000 tons per day. For Kawerau, six production wells ranging from 1,900 to 2,100 m depth, supply two-phase fluid with an enthalpy of approx. 1,300 kJ/kg, and for Nga Awa Purua, nine production wells will supply two-phase fluid with an enthalpy of approx. 1,560 kJ/kg. To provide flexibility to changing reservoir conditions, the plant is designed to cover a range of enthalpy, non-condensable gas (NCG) content and chemistry.

Table 1 The overall programs of Kawerau and Nga Awa Purua projects

Milestone Event	Kawerau (Completed)	Nga Awa Purua (Under Construction)
Resource consent granted	August 2006	January 2008
EPC project commencement	November 2006	May 2008
Delivery of generation equipment	October 2007	April 2009
First geothermal fluid admission	April 2008	November 2009 (Planned)
Power station operational	August 2008	May 2010 (Planned)

The Kawerau and Nga Awa Purua Power Stations are typical dual and triple flash plants respectively, so as to maximize electricity generation from the geothermal fluid. Kawerau is the largest dual flash geothermal single unit in the world when it started operation, and Nga Awa Purua will be the largest triple flash geothermal single unit in the world.

4.2 Steam Separation System (SSS)

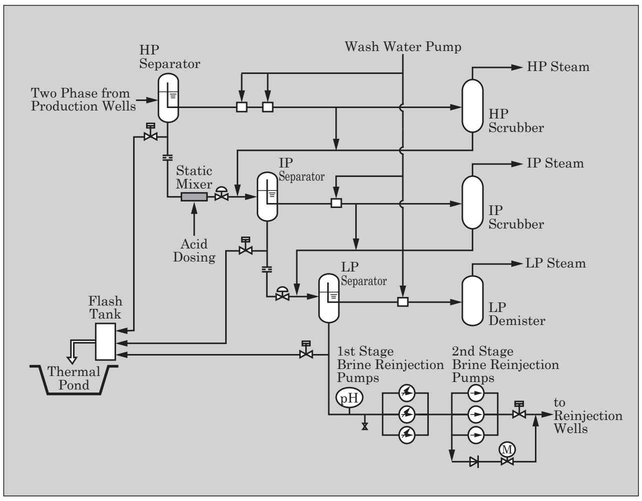
SSS receives the two-phase fluid from the production wells, separates the steam and brine, removes impurities in the steam and then delivers the purified steam to the steam turbine.

Figure 4 shows an overview of the Steam Separation System of the Nga Awa Purua project. Other than the fact that Kawerau has HP and LP systems only, there are no basic differences in the SSS between Kawerau and Nga Awa Purua.

At first, a high pressure (HP) separator receives the geothermal fluid from the production wells and separates it at approximately 12 bar abs (24.5 bar abs for Nga Awa Purua). The separator is a vertical, Webretype cyclone with a spiral two-phase inlet, internal steam pipe with side outlet and a tangential brine outlet from the steam drum. Brine flows from the steam drum to the brine drum through a loop seal.

The separated steam may carry minor quantity of impurities such as brine and volatile silica. The operating regime envisages that the steam turbine will be able to achieve four years operation between major outage, when the turbine will be opened up for internal inspection and cleaning. This resulted in a strong focus to achieve high steam purity at the steam turbine inlet. Particular attention was paid to the design of three key elements, namely: separa-

Fig.4 Nga Awa Purua Steam Separation System overview



tor, purifier and steam-line scrubbing system. The two-phase fluid gathering system results in relatively short steam piping compared to plants using well-head separators. That is whole separators are located near production wells some distance from the power station, and natural condensation can be used to facilitate steam scrubbing. Therefore, to capture impurities carried over from the separator, steam wash water is injected downstream of the HP separator. The wash water spray provides nucleation sites for condensation of steam and agglomeration of the droplets which have been carried over from the separator. Impurities fall down to the bottom of the pipe and are collected at condensate pots. To enhance the scrubbing effect, the steam scrubbing piping is designed so as the length is at least 100 m for Kawerau and 200 m for Nga Awa Purua, and the steam velocity is no more than 20 m/s. The remaining liquid in the steam is removed at the recycling type HP steam scrubber. The drains from the HP condensate pots and the scrubber are directed to the low pressure (LP) separators (IP separator for Nga Awa Purua) to utilize the available energy and minimize the discharge to the surface drains.

The brine from the HP separator flashes at the level control valves and it becomes two-phase LP (IP for Nga Awa Purua) fluid at approx. 1.8 bar abs (IP fluid at approx. 8.9 bar abs for Nga Awa Purua).

High purity (IP and) LP steam is achieved in a similar manner to the HP steam, with Webre-type cyclone separators, water washer steam-line scrubbing and a vane-type LP steam demister.

The LP separator levels are usually controlled by variable speed brine reinjection pumps. The separated LP brine is pumped-up and returned to the steam field for reinjection. The brine reinjection pumps are tandem configuration; the first stage utilizes the variable speed pump and the second stage pumps utilize the fixed speed pumps. The second stage pumps provide flexibility to address changes of the reinjectivity of the wells during start-up and long-term operation. The second stage pumps also provide sufficient pressure to enable the plant to operate with one well out-of-service. In normal operation, with all reinjection wells in service, the first stage pumps are sufficient and the second stage pumps are stand-by.

After removing the steam and reducing the temperature by flashing to approx. 1.8 bar abs (2.6 bar abs for Nga Awa Purua), the silica in the residual LP brine becomes supersaturated. To prevent the consequent polymerization and deposition of silica in the brine system, the pH of the brine is controlled by dosing the HP brine with sulfuric acid. The acid injection rate is precisely adjusted by the variable speed dosing pump to maintain the LP brine to the reinjection system at a target value of pH 5.0. The acid titration curve is quite steep which makes the control loop very sensitive to changes in acid dosing rate. The pH control logic is designed with the acid dosing rate being proportional to the HP brine flow rate. The set point for this control loop is trimmed with the measured LP brine pH. The acid dosing rate depends on the brine composition, which changes when the production well flows are adjusted.

The HP (IP) and LP brine systems have 2 x 100% emergency dump valves downstream of the separators. Excess brine is discharged to the thermal pond, which has a design capacity of 3 hour discharging brine.

4.3 Power Generation Facility (PGF)

Figure 5 shows an overview of the PGF system overview at Nga Awa Purua.

HP (IP) and LP steam from SSS are brought to the steam turbine, which produce electricity at the generator.

The steam turbine for Kawerau is of dual pressure inlet, single-casing, single-shaft, single-flow HP section and double-flow LP section, bottom exhaust and its nominal output is 95 MW. The steam turbine for Nga Awa Purua is of triple pressure inlet, single-casing, single-shaft, double-flow HP, IP and LP sections, bottom exhaust, and its nominal output is 139 MW. Both steam turbines utilize 31.4-inch-long last-stage blades, which are the largest in any geothermal application. This makes it feasible to build the largest singlecasing geothermal power station utilizing multi-flash cycle technology.

The generator is totally enclosed water to air-cooled (TEWAC) type with brushless exciter. Design features to mitigate the risk of corrosion from H_2S gas include: global vacuum pressurized impregnated stator coil, tin-plated rotor coil and slot wedges, and catalytic filters for circulating and make-up air.

Table 2 shows the major design parameters of the steam turbine and generator of each project and Fig. 6 shows a view of the steam turbine and the generator for Kawerau.

Turbine exhaust steam is condensed at approximately 0.08 bar abs in a direct-contact, spray-type condenser with cooling water from the forced draft cooling tower. The NCG is removed from the condenser with a hybrid gas extraction system (GES).

For both projects, the GES comprises of three in-

Fig.5 Nga Awa Purua Power Generation Facility overview

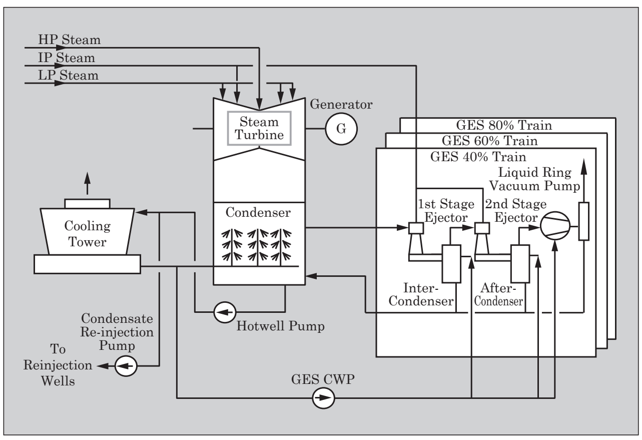


Table 2 Design parameters of steam turbine and generator for Kawerau and Nga Awa Purua

Steam Turbine	Kawerau	Nga Awa Purua
Type	Single cylinder, Double flow, Reaction, Condensing	
Output	Rated 95 MW Max 113 MW	Rated 139 MW Max 147 MW
Inlet steam pressure	HP 11.3 bar abs LP 1.8 bar abs	HP 23.5 bar abs IP 8.4 bar abs LP 2.3 bar abs
Inlet steam temperature	HP 185 °C LP 118 °C	HP 221 °C IP 172 °C LP 125 °C
Exhaust pressure	0.08 bar abs	0.085 bar abs
Steam flow	HP 465 t/h (including 2.3wt% NCG) LP 180 t/h	HP 617 t/h (including 2.3wt% NCG) IP 113 t/h LP 103 t/h
Rotation speed	3,000 r/min	3,000 r/min

Generator	Kawerau	Nga Awa Purua
Type	Totally Enclosed Water-to-Air Cooled (TEWAC)	
Capacity	130 MVA	173 MVA
Rated power factor	0.85	0.85
Voltage	11 kV	11 kV

Fig.6 Photo of steam turbine and generator at Kawerau

dependent trains sized for 40%, 60% and 80% of the design NCG flow. Each train is designed as a hybrid system, with two stages of ejectors followed by a liquid ring vacuum pump. (See Fig. 7.)

This configuration produces the seven combinations of GES trains, which handle 40 to 180% of NCG flow rate. This configuration provides flexibility to allow for uncertainty of NCG content. It should be noted that the GES is procured before all production wells are drilled and tested. During the commissioning period of Kawerau, all three trains were operated but after six months, of operation, only 40% and 80% trains are required in normal operation.

Fig.7 Photo of gas extraction system at Kawerau

For both projects, the cooling tower is a counterflow, mechanical draft-type and made of FRP. It consists of ten cells, arranged in a single line. Two cells are equipped with dual speed fans. Switching fans on or off and selection of half/full speed provides flexibility to adjust the operating configuration to the atmospheric conditions and save the auxiliary power consumption.

The steam flow into the system exceeds the cooling tower evaporation loss, which results in an excess of condensate. Condensate is reinjected to the well to maintain a constant level in the cooling tower basin.

4.4 Plant control

The plant control system provides overall control and supervision not only for SSS and PGF, but also for steamfield and switchyard. The control system matches the steamfield supply to the power demand and maintains safe operation of the plant under transients or equipment faults. The turbine governor controls the entire plant steam pressure and the production well control valves open or close in accordance with the required generator output. In the event of a fault or transient, when the steam vent valves open or a rupture disc burst, the production well control valve position is automatically locked to prevent the further discharge. For a turbine trip the fluid supply from the steamfield is reduced and shutdown automatically without operator intervention.

5. Engineering and Design

Mighty River Power had a dedicated contract management and design review team within their organization. During the detail design stage, periodical design review meetings were held between Mighty River Power and project engineering team members. At the freezing point of key engineering deliverables such as P&IDs, single line diagrams, functional descriptions, etc., a full project HAZOP review was conducted.

The review was facilitated by an external specialist and was attended by Mighty River Power design review staff, operating staff, external plant specialists and Fuji Electric engineering team members. After HAZOP, a detailed 3D-model review meeting was also conducted to review buildability, operability, maintainability, etc.

In the HAZOP review for Nga Awa Purua, systems and areas different from those of Kawerau were intensively reviewed.

6. Construction and Commissioning at Kawerau

Following the ground breaking ceremony of November 29, 2006, site establishment and temporary work commenced, and bulk earthwork started in January 2007. The erection of steel structures for the turbine building started in July 2007 and the final pour for the turbine generator pedestal was completed in September. From late October, major pieces of equipment started to arrive, at which time mechanical and electrical contractors began to mobilize onsite, and piping work for the steam separation system commenced in November. The load rejection, runback, houseload operation test etc. work was implemented by three subcontractors, i.e., mechanical works, electrical works, and cooling tower works. Despite its fast-track program and interference challenges, the overall site construction was generally well coordinated among the relevant parties. There were also ETF and Steam field Contractors, having been separately engaged by Mighty River Power. The work in some areas of the power station overlapped among the contractors, but work interface coordination was also well managed among the parties. For the mechanical work, the outdoor construction work was prioritized because commissioning of the SSS area had started earlier than for the PGF, and also in anticipation of being affected by rain, but the construction period fell during the summer season in NZ so such affect was minimal.

In early 2008, pre-commissioning began in February and the first commissioning milestone of power backfeed from the 110 kV grid was achieved on March 14th, followed by another milestone of the commencement of steam blowout, or in other words, the admission of two-phase geothermal fluid into the power station which was achieved on April 19th.

Commissioning works were planned and executed by Fuji Electric's commissioning managers and supervisors, with involvement of Mighty River Power operators.

Overall commissioning works were managed and executed in the following stages and work sequences.

a) Site acceptance test and commissioning of DCS
b) Electrical system commissioning to achieve power backfeed from 110 kV grid
c) Stationary commissioning of a Steam Separation System to bring geothermal fluid
d) Commissioning of a Steam Separation System, including HP/LP steam pressure control and steam venting, HP/LP separator level control and brine dumping, pH modification control for LP brine, steam scrubbing system to achieve targeted steam purity
e) Commissioning of circulating water system, including hotwell pumps, cooling towers, condenser level control, and other auxiliary cooling water circuits
f) Commissioning of Gas Extraction System including vacuuming of condenser
g) Steam admission to turbine and load testing
h) 30-day reliability run
i) Plant efficiency testing

During commissioning, it was revealed that the actual NCG content was greater than 100%, so all three trains of the GES system were run most of the time during commissioning and the reliability run. Also, to maintain the LP brine at a pH of 5.0, a higher than expected sulfuric acid dosing rate was required and the variable-speed drive for the acid dosing pump was readjusted to match the actual demand. At the condensate reinjection system, originally the condensate was flashed before reaching the plant outlet interface point, so an adjustment was made to maintain positive interface pressure by using the wellhead valve instead of the power station side.

On the other hand, than those, the steam purity rate for the originally targeted condition was achieved without major adjustment or modification of the original design, and commissioning was advanced in the fast-track mode. Before and after the 30 day reliability run, the plant was shut down for inspection and cleaning of vessels, drains, condensate drain pots, etc. and no particular erosion, corrosion or scaling was revealed. Cleanup of the system took some time, but that was not substantially different from other geothermal projects. During the reliability running test, the plant was operated not only at its rated condition but also at a maximum condition most of the time, without any trips, upsets or difficulties.

7. Construction at Nga Awa Purua

Our experience at Kawerau was reviewed by project participants, and in order to improve constructability but to maintain accessibility, several design changes have been implemented into the Nga Awa Purua project.

a) The Kawerau electrical annex has two stories. For Nga Awa Purua, the building was changed to a flat single-story building to improve construction and operational access.
b) At Kawerau, the project land site was flat so brine pumps were located in a 4 meter deep pit to retain suction head from the LP Separator. The Nga Awa Purua site natural terrain is hilly

compared to that of Kawerau, so separators were located at higher elevation and this brine pump pit was deleted.
c) At Kawerau, all the 1st and 2nd stage steam jet ejectors were arranged vertically to minimize the footprint area. For Nga Awa Purua, they are rearranged horizontally.

Photo of Nga Awa Purua construction site as of September 2009 is shown in Fig. 9a, as well as 3D model of the same view in Fig. 9b.

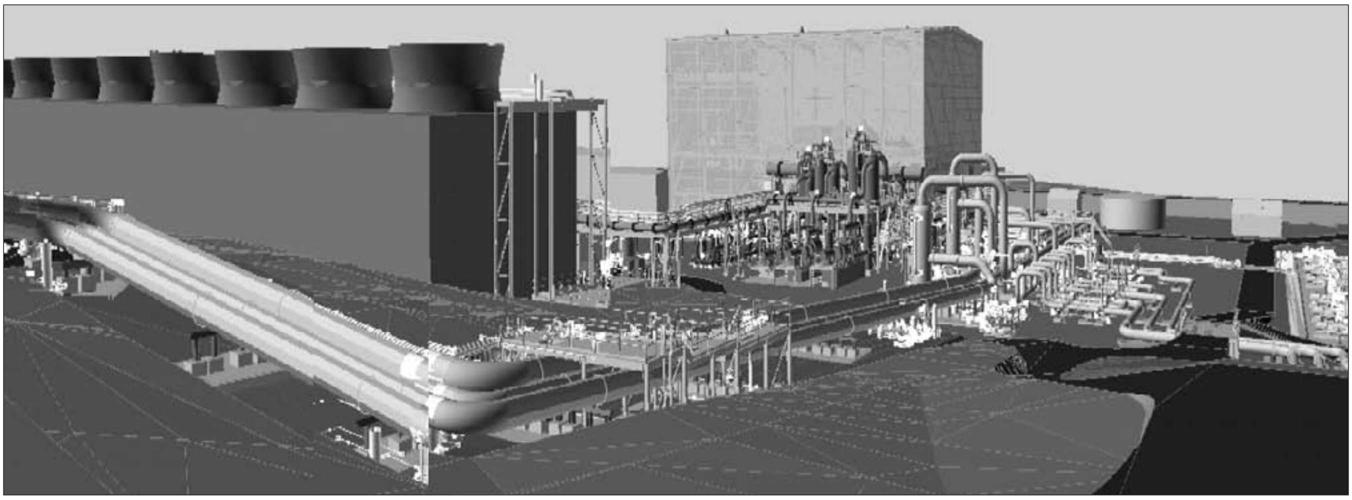
8. Postscript

The construction of the Kawerau and Nga Awa Purua geothermal power stations has taken advantage of the latest technologies. The design has maximized the power output for a given geothermal energy input and minimized the parasitic loads, under consideration of economic factors. Appropriate design margins have been included for the plant and equipment to provide operation flexibility and ensure that the plant can respond to foreseeable changes in the geothermal reservoir. These plants are aligned with the New Zealand government strategy and contributes to a reduction of NZ's carbon footprint from a global perspective.

Fig.8 Photo of Kawerau Geothermal Power Station

Fig.9a Photo of Nga Awa Purua construction site (As of September 2009)

Fig.9b 3D model of Nga Awa Purua (same view as Fig. 9a)



The Latest Geothermal Steam Turbines

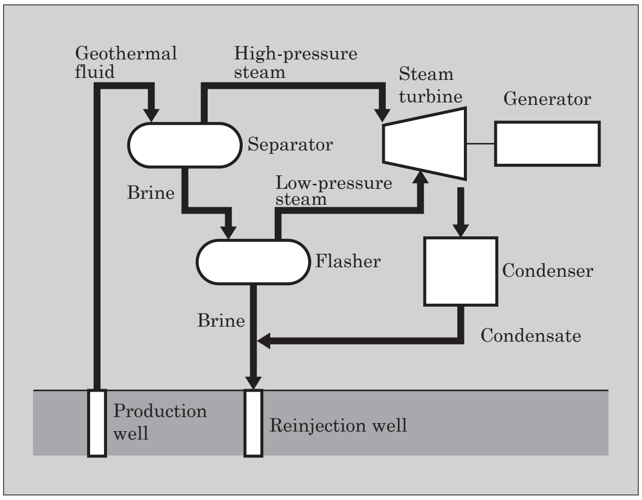
Yoshihiro Sakai †
Yoshiki Oka †
Hideo Kato †

1. Introduction

Geothermal power generation technology extracts a mixture of steam and brine (geothermal fluid) that has been heated by geothermal heat from a well dug deep underground, and then uses that thermal energy to generate power (Fig. 1). Since there is no need to burn fuels such as oil, coal and natural gas, there is almost no emission of such environmental pollutants as carbon dioxide (CO_2), nitrogen oxides (NO_x) and sulfur oxides (SO_x) which are a cause of global warming. Moreover, the steam, after having been used for power generation, can be fed to a condenser and converted into water and then reinjected underground and subsequently reused as geothermal steam. Geothermal energy is reusable clean energy, and its usage is expected to increase in the future to help prevent global warming.

In 1960, Fuji Electric delivered Japan's first commercial geothermal power generating facility to Fujita Tourist Enterprises Hakone Kowakien. Since then, Fuji has delivered a total of approximately 60 geothermal turbines within Japan and overseas, and is considered to be one of the top manufacturers of geothermal turbines in the world. This paper presents an overview of the recent technologies used in Fuji Electric's latest geothermal steam turbines.

Fig.1 Principles of geothermal power generation (double flash cycle)



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2. Recent Technologies for Geothermal Steam Turbines

2.1 Technology for improving corrosion resistance

Geothermal steam contains large quantities of chloride, sulfate, hydrogen sulfide and carbon dioxide and other such corrosive chemicals. The majority of these corrosive substances are removed by a separator (water/steam separator), a flasher (reduced pressure evaporator), demister (moisture separator), and so on located upstream from the turbine. Nevertheless, the corrosive substances contained in the steam that enters the steam turbine are 100 to 1,000 times more plentiful than in steam turbines for fossil fuel power plants where the feed water has been chemically treated. Therefore, measures are needed to prevent general corrosion, stress corrosion cracking (SCC), corrosion fatigue and erosion corrosion of parts and materials. In response to these needs, Fuji Electric has continued to develop technology and applied it successively to actual turbines[1]. Examples of the latest technologies applied to recent geothermal steam turbines are described below.

(1) Coating technology

Parts such as the rotors and stationary blade holders that are exposed to highly corrosive geothermal steam are particularly susceptible to general corrosion and erosion corrosion, which may lead to the problem of dropout of the seal fin between blades. As one solution, a thermal spray coating technology for the parts' surface has been developed. Basic tests in the laboratory and corrosion tests at geothermal sites were conducted to establish a practical technology using a HVOF (high-velocity oxygen-fuel thermal spray coating, high-velocity frame spraying) process to apply a coating of WC-CoCr thermal spray material. Using this technology, spray coating was applied to the seal fin area between blades of the turbine rotor at the Wayang Windu Unit 2 in Indonesia and resistance to corrosion and erosion was improved (Fig. 2).

(2) Shot peening technology

Corrosive material, which is likely to accumulate and concentrate in gaps between the blade root and rotor grooves, is a cause of SCC and corrosion fatigue. Therefore, based on the results of materials testing in the laboratory and at geothermal sites, the materials used for the rotor and the blade are selected from materials that are highly resistance to SCC and corrosion fatigue, and in addition, shot peening technology capable of withstanding even severer environments has been developed and applied to actual equipment. Shot peening technology bombards the high-stress areas of the blade and rotor with steel balls at high speed so that compressive residual stress is generated in the surface of the part, thereby enhancing the capability to withstand SCC and corrosion fatigue. SCC and corrosion fatigue tests were conducted on blade and rotor materials having been treated with shot peening, and a significant improvement in resistance was confirmed. The shot peening treatment parameters such as projection velocity and angle were optimized in advance, and the work was performed with a robot so as to realize stable quality (Fig. 3).

Fig.2 Spray coating of rotor

Fig.3 Shot peening of rotor blade

(3) Material technology

Steam turbines at geothermal power plants operate under environmental conditions that are much more severe than those of ordinary steam turbines at fossil fuel power plants. Evaluation of the corrosion resistance of materials is crucial for the stable long-term operation of devices under such environmental conditions. Therefore, in the laboratory, Fuji Electric has systematically tested materials in corrosive environments with simulated geothermal fluid, and based on the results, has selected materials and working stress levels that are suitable.

On the other hand, because the material properties of geothermal fluid vary by region, it is important to verify the behavior of materials at the actual geothermal site. Fuji Electric already has installed test equipment at geothermal sites throughout the world, and has been testing materials in geothermal fluid. Recently, over the course of approximately 1-year at Reykjanes, Iceland, Fuji Electric has performed onsite testing of materials for use in geothermal turbines. In onsite testing, corrosion tests, SCC tests, erosion corrosion tests, scaling tests and the like are performed by using actual geothermal steam. The appearance of the test equipment is shown in Fig. 4. The geothermal steam at Reykjanes is at a higher temperature and pressure than at a usual geothermal steam site, Therefore, materials were expected to exhibit different behavior than usual, but good results corroborating the efficacy of the original design were obtained.

Fig.4 Onsite materials testing at Reykjanes

Table 1 Standard materials for geothermal turbines

Part	Standard material
Blade material	13% Cr steel 16% Cr-4% Ni steel Ti-6% Al-4% V alloy
Rotor material	1% Cr-MoNiV steel 2% Cr-MoNiWV steel

Based on the verification results from various material tests, the materials of Table 1 were selected as standard materials for geothermal turbine-use, and optimal materials were selected according to the working environment, stress and other usage conditions.

2.2 Technologies for efficiency improvement

To improve the economic efficiency of geothermal power plants, increased reliability against the problems of corrosion, scaling and the like which are specific to geothermal power generation, and improved turbine efficiency are needed. Fuji Electric has applied its latest technologies, based on know-how acquired with fossil steam turbines, to geothermal turbine blades, and has realized a significant improvement in turbine efficiency. The latest technologies for efficiency improvement are introduced below.

(1) Development of a new generation low-pressure blade series

The design must be made in consideration of the high corrosiveness of geothermal steam, and SCC, corrosion fatigue and the like. Fuji Electric has developed a new generation low-pressure blade series for application to geothermal steam turbines, and is sequentially applying this series to actual turbines. Main features of the new generation low-pressure blade series are as follows.

Table 2 Series of new-generation low-pressure blades for geothermal steam turbines

50 Hz use (nominal annular area)	60 Hz use (nominal annular area)
348 mm blade (1.6 m^2)	290 mm blade (1.1 m^2)
487 mm blade (2.5 m^2)	406 mm blade (1.7 m^2)
555 mm blade (3.2 m^2)	462 mm blade (2.2 m^2)
612 mm blade (4.0 m^2)	510 mm blade (2.8 m^2)
697 mm blade (5.0 m^2)	581 mm blade (3.5 m^2)
798 mm blade (6.3 m^2)	665 mm blade (4.4 m^2)

Fig.5 Rotational vibration test of new-generation low-pressure blade for geothermal steam turbine

(a) Designed for high reliability in consideration of the corrosive atmosphere of geothermal steam
(b) High-efficiency blades incorporate the latest computational fluid dynamics (CFD) technology
(c) High-load design enables the realization of a more compact turbine size

Fuji Electric's lineup of new generation low-pressure blades for geothermal steam turbines is listed in Table 2. The 798 mm blade for 50 Hz-use and the 665 mm blade for 60 Hz-use are the world's largest class low-pressures blades for geothermal steam turbines and contribute to increased unit capacity. Rotational vibration tests were performed on prototype blades and the vibration characteristics verified (Fig. 5).

(2) High-load high-efficiency reaction blades

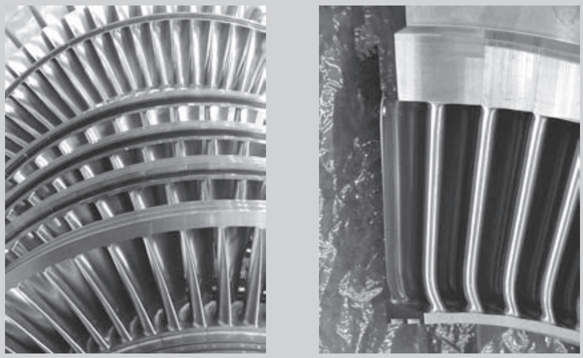
For blade rows that do not include low-pressure blades, the latest blade design technology has been utilized to create high-load high-efficiency reaction blades that maintain high efficiency while increasing the load per row. The application of these high-load high-efficiency reaction blades enables a 1 to 2% improvement in cascade efficiency compared to conventional blades. The reaction blades are all integral shroud blades and achieve high reliability even in the severely corrosive environment of geothermal steam (Fig. 6).

2.3 Compatibility with higher inlet steam pressure

Previously, geothermal steam turbines typically operated with an inlet steam pressure in the range of approximately 0.5 to 1 MPa, but owing to developments in geothermal well exploration technology and drilling technology, and the increased utilization of deep geothermal resources, nowadays the inlet steam pressure can exceed 1 MPa, and in some cases, even approach 2 MPa.

Fuji Electric has previously delivered many geothermal steam turbines compatible with inlet steam pressures of greater than 1 MPa. In recent years Fuji has delivered geothermal steam turbines to the Reykjanes Units 1 and 2 (1.9 MPa inlet steam pressure) and

Fig.6 High-load high-efficiency reaction blades



(a) Moving blades (b) Stationary blades

the Svartsengi Unit 6 (1.6 MPa inlet steam pressure) in Iceland, and these turbines have continued to operate smoothly.

The fluid that flows out of a geothermal well is typically a mixture of steam and brine, and a separator or flasher is used to extract the steam only. The inlet steam is inevitably saturated steam. Accordingly, as a result of the rising inlet pressure, the following issues must be addressed.

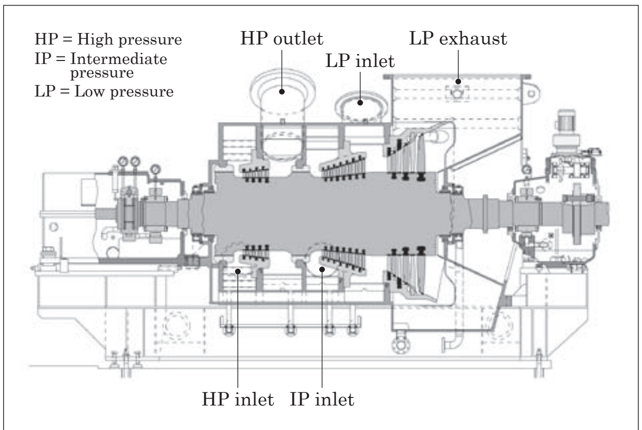
(a) Increased steam wetness of low-pressure stages
(b) Increased steam corrosiveness in dry-to-wet transition zone
(c) Turbine casing design capable of withstanding high pressure

The extent to which the progression of erosion can be limited in low-pressure moving blades is a challenge for (a) above. Fuji Electric provides drain slot midway on the turbine blade stages, and employs a mechanism for capturing and expelling water droplets in order to reduce erosion.

The extent to which erosion corrosion and SCC can be limited in the rotors, stationary holders and blades that face high-pressure and low-pressure steam paths is a challenge for (b) above. It is known that increasing the amount of Cr content in a material will generally reduce erosion corrosion dramatically. Fuji Electric uses 2% Cr steel rotors, stainless steel stationary blade holders, and highly SCC-resistant stainless steel as the blade material to meet the abovementioned challenge.

A pressure of 2 MPa is low compared to that used in fossil power generation. However, because geothermal steam turbines are larger in size than fossil power steam turbines of the same capacity, the magnitude of deformation becomes larger. Additionally, structural design that considers the corrosion allowance over the duration of long-term operation is also needed. Therefore, for (c) above, detailed structural analysis is performed utilizing 3-dimensional CAD and FEM (finite element method) techniques, and also based on the Fuji Electric's long-term experience with actual turbines, the deformation of the turbine casing is ascertained quantitatively and reflected in the design of actual turbines.

Fig.7 Sectional view of Svartsengi Unit 6 geothermal steam turbine



2.4 Utilization of multiple types of steam sources

With the trend towards higher pressures as described above, plants that use a triple flash cycle to flash brine at three stages (high-pressure, intermediate-pressure and low-pressure) and introduce each steam thusly obtained to the geothermal steam turbine have become common. Moreover, configurations in which multiple steam flows are introduced to a single geothermal steam turbine by utilizing surplus steam from existing geothermal steam power plants or by drilling new geothermal wells have also become more popular.

Beginning with the geothermal turbine for the Svartsengi Power Plant Unit 5, and later with the Salton Sea Unit 5 in the US and the Svartsengi Unit 6[2] (Fig. 7), Fuji Electric has delivered geothermal steam turbines that combine three or more steam sources.

3. Characteristics of Latest Geothermal Steam Turbines

3.1 Wayang Windu Unit 2

Unit 2 increases the capacity of the Wayang Windu Power Plant in Indonesia and was constructed subsequent to Unit 1 for which Fuji Electric delivered a turbine in 1999. The steam conditions, output, turbine structure and so on for Unit 2 are nearly the same

Fig.8 Sectional view of Wayang Windu Unit 2 geothermal steam turbine

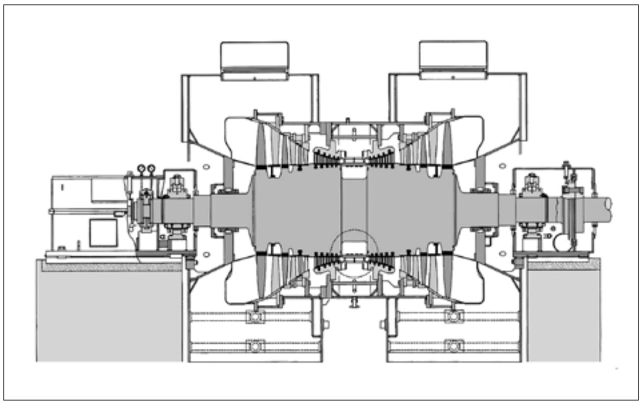


Table 3 Main specifications of Wayang Windu Unit 2 geothermal steam turbine

Turbine type	Single-casing dual-exhaust condensing
Generator output	117.0 MW
Rotating speed	3,000 r/min
Inlet steam condition	1.07 MPa, 182.8 °C (saturated)
Effective strength of last stage blades	697 mm
Nominal annular area	5.0 m^2

as for the existing Unit 1, but in order to provide enhanced corrosion resistance, the coating technology described in section 2.1 has been applied to the rotor and other parts of the turbine. The gross output of 117.0 MW is the world's largest for a single-casing type geothermal steam turbine (Fig. 8). Main specifications are listed in Table 3.

3.2 Svartsengi Unit 6

Unit 6 increases the capacity of the Svartsengi Power Plant in Iceland and was constructed subsequent to Units 3 and 5 for which Fuji Electric had delivered turbines in 1980 and 1999, respectively. At this plant, 1.6 MPa high-pressure geothermal steam had existed prior to constructing the Unit 6 shown in Fig. 9. However, the pressure had been reduced to this lower level prior to usage because the existing turbines had been designed for lower pressure conditions of 0.65 MPa. Moreover, this plant also supplies steam for district heating, and the effective utilization of excess steam generated seasonally was a challenge.

Fuji Electric was involved from the conceptual design stage in the project to expand capacity by adding Unit 6, and in order to optimize the thermal efficiency of the overall plant, collaborated with customers to consider the use of existing steam lines. These efforts resulted in the design and construction of a unique geothermal steam turbine as shown in Fig. 10 that uses controlled extraction and a separator at the turbine intermediate-pressure section.

Expanded steam at the turbine's high-pressure section is exhausted once outside the steam turbine; a portion is extracted to the existing steam lines and the remainder is re-introduced via a separator to the turbine intermediate-pressure section. In the case of excess steam in the 0.12 MPa existing steam lines, that excess portion is introduced to the turbine's low-pressure section. This turbine is connected to input piping and exhaust piping at total of 9 locations. The design employed 3-dimensional CAD-based structural design and piping design in order to ensure reliability.

This turbine achieved its rated load in December 2007, all design values such as controllability and thermal efficiency were confirmed to have been satisfied,

Fig.9 External view of Svartsengi Unit 6

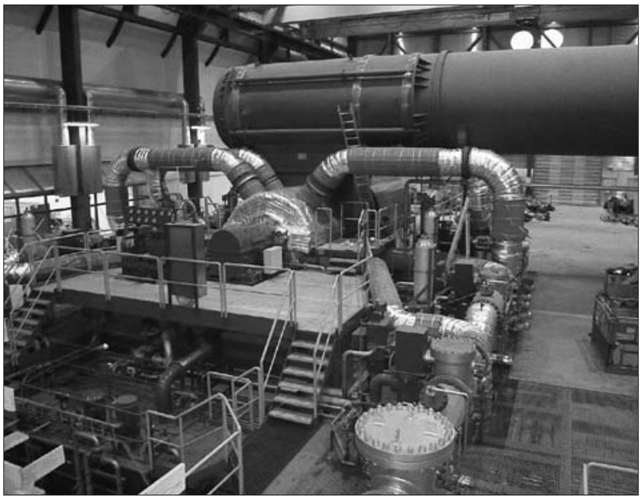


Fig.10 Svartsengi Unit 6 steam line drawing

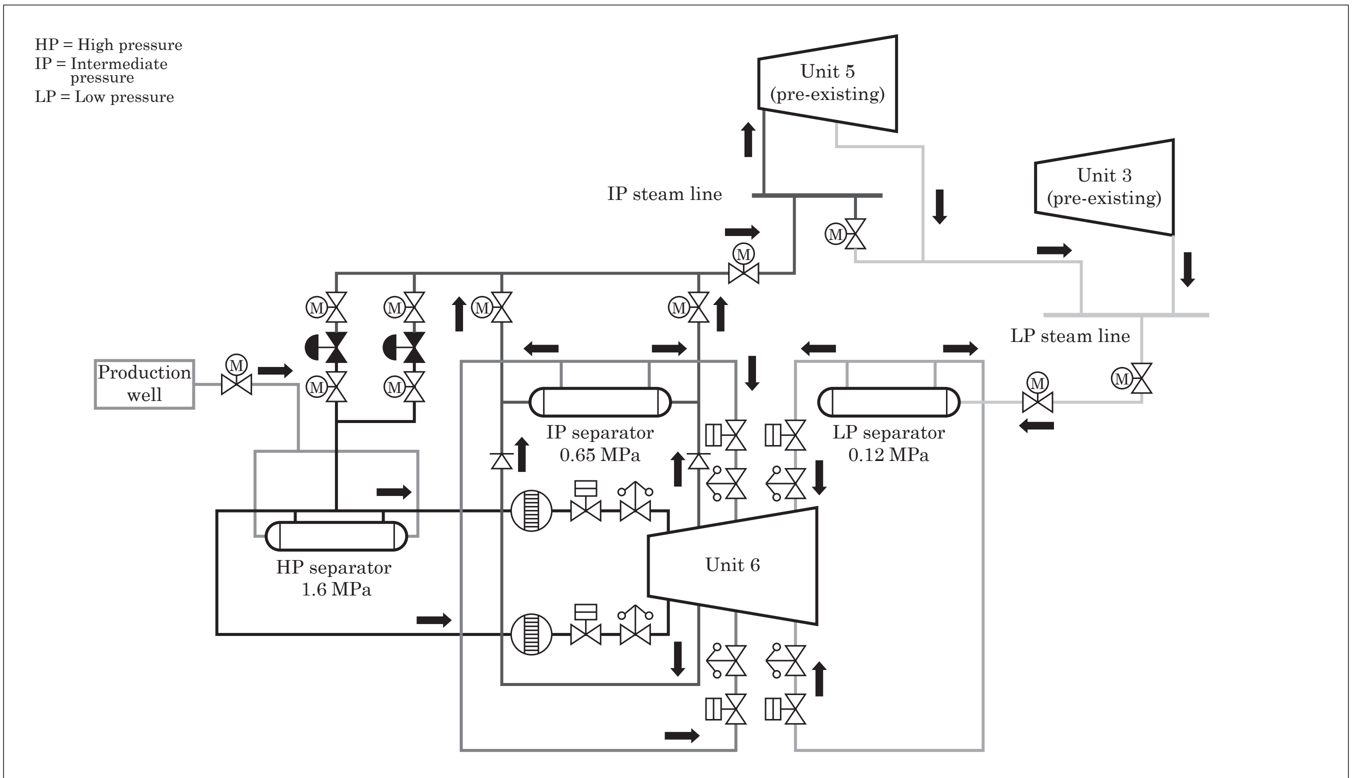
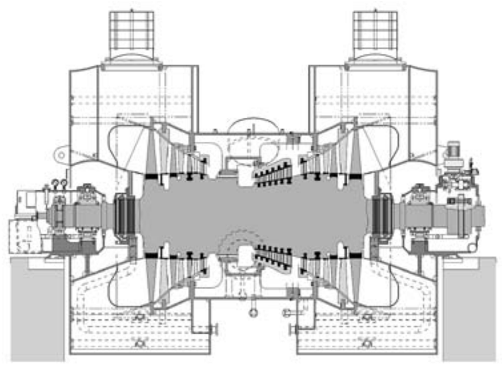


Table 4 Main specifications of Svartsengi Unit 6 geothermal steam turbine

Turbine type		Single-casing single-exhaust mixed pressure condensing
Generator output		33.3 MW
Rotating speed		3,000 r/min
Steam conditions	HP inlet	1.6 MPa, 201.4 °C (saturated)
	HP exhaust	0.67 MPa, 163.2 °C (wet)
	IP inlet	0.65 MPa, 161.8 °C (saturated)
	LP inlet	0.12 MPa, 104.8 °C (wet)
Effective length of last stage blades		487 mm
Nominal annular area		2.5 m^2

Fig.11 Sectional view of Kawerau Power Station geothermal steam turbine



and the turbine continues to operate in good condition. The main specifications are listed in Table 4.

3.3 Kawerau Power Station geothermal power plant

This turbine is produced for the Kawerau Power Station in New Zealand. As a primary EPC (engineering, procurement and construction) contractor, Fuji Electric is responsible not only for the geothermal steam turbine, but also for the design, fabrication and construction of the entire power plant.

The inlet steam is at a high pressure of 1.33 MPa (max.), and the geothermal steam turbine is characterized by its use of the world's largest 798 mm last stage rotor blades. In order to improve reliability in a geothermal steam environment, the shot peening technology described in section 2.1 is applied to the last 3 stages, and 2% Cr steel rotors are used. Moreover,

Table 5 Main specifications of Kawerau Power Station geothermal steam turbine

Turbine type		Single-casing single-exhaust mixed pressure condensing
Generator output		113.67 MW
Rotating speed		3,000 r/min
Steam conditions	HP inlet	1.33 MPa, 192.5 °C (saturated)
	HP exhaust	0.22 MPa, 124.4 °C (wet)
Effective length of last stage blades		798 mm
Nominal annular area		6.3 m^2

high-efficiency 3-dimensional blades are used in all stages (Fig. 11). Main specifications are listed in Table 5.

4. Postscript

The utilization of geothermal energy which is a reusable and clean is attracting attention worldwide as a means to help preventing global warming. With international cooperation, the Iceland deep drilling project (IDDP) is being advanced to drill a well 5,000 m below ground, and utilization of 400 to 600 °C geothermal steam is planned for the future. Moreover, Germany, which had previously not been considered a source of geothermal power generation, is moving ahead with a project to dig wells 3,000 to 5,000 m deep and to generate geothermal power. The utilization of geothermal resources is expected to become increasingly important in the future.

As a pioneer of geothermal power generation, Fuji Electric intends to continue to advance the development of geothermal power generation technology and to help facilitate energy utilization that is environment-friendly.

Reference

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Global Vacuum Pressure Impregnation Insulation Applied to Hydrogen-cooled Generators

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Masaru Yamazaki †

1. Introduction

In response to market needs concerning the economic efficiency, ease of maintenance and operability of electric power equipment in recent thermal power plants, Fuji Electric has expanded the application range of its air-cooled generators having global vacuum pressure impregnation insulation (see the "Explanation" on page 98) in the stator winding to 300 MVA, and has provided these generators to the market.

On the other hand, hydrogen cooling or water cooling must be used for generators that are too large for air cooling, and developing countries place particular importance on economic efficiency and maintainability as before. Responding to these needs, Fuji Electric has also developed an indirect hydrogen-cooled generator having global vacuum pressure impregnation insulation in the stator winding.

Fuji Electric has recently built an indirect hydrogen-cooled generator that uses a global vacuum pressure impregnation insulation system as the largest generator for the HPJSC Hai Phong power plant in Vietnam, and has completed factory testing. This paper describes the design of this generator and the technology that was applied.

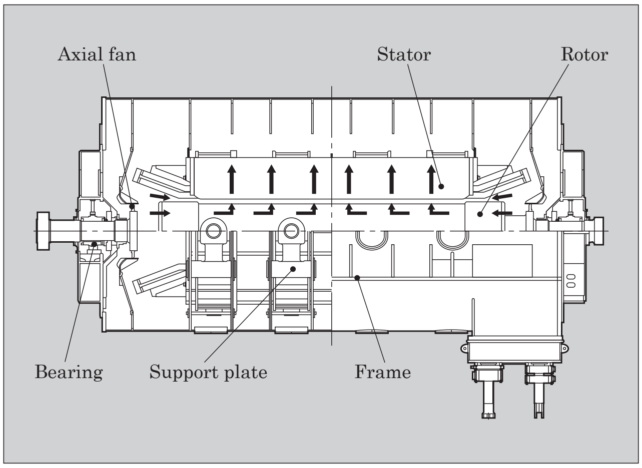
2. Specifications and Parameters

The main specifications and parameters of the generator are listed in Table 1. A sectional view is shown in Fig. 1.

Table 1 Main specifications and parameters of the generator

Specifications	Output	372.2 MVA
	Voltage	21 kV
	Power factor	0.85
	Frequency	50 Hz
	Coolant	Stator: hydrogen indirect
		Rotor: hydrogen direct
	Hydrogen gas pressure	0.3 MPa guage
	Cooling gas temperature	48 °C
	Rotational speed	3,000 r/min
	Excitation method	static
Parameters	Total length	13.4 m
	Total mass	394 t
	Stator mass	270 t
	Rotor mass	54 t

Fig.1 Sectional view of 372.2 MVA indirect hydrogen-cooled generator



3. Design

For this generator, the stator winding, stator core and rotor winding mostly use the same structures and manufacturing methods as do Fuji Electric's air-cooled generators. Thus, the generator will have good reliability based on the successful record of Fuji Electric's air-cooled generators, and the common technology and shared equipment enable the generator to be manufactured in a shorter amount of time and with improved economic efficiency.

3.1 Stator structure

The stator core is supported by a cylindrical stator frame via the support plate shown in Fig. 2. The stator frame is constructed with a support plate having appropriate elastic effect so as to suppress the transmis-

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Fig.2 Stator frame support plate spring

sion of electromagnetic vibrations from the core.

3.2 Cooling methods

Indirect cooling is used for the stator, and direct cooling via a cooling path provided radially in a conductor is used for rotor cooling.

As is shown by the arrows in Fig. 1, the ventilation path is configured such that cooling gas is fed from the axial fan at both ends of the rotor to the stator and to various parts of the rotor. The ventilation system for the stator is designed such that all of the rotor cooling gas flows from the inner diameter side to the outer diameter side.

The cooling and ventilation method is the same as that of air-cooled generators made by Fuji Electric. In order to obtain a uniform distribution of winding temperature, the optimal arrangement of cooling ducts and distribution of coolant flow were designed based on data acquired from experimental model machine and actual results.

4. Global Vacuum Pressure Impregnation Insulation Technology

Using global vacuum pressure impregnation insulation technology acquired over many years and the world's leading global impregnation manufacturing equipment, Fuji Electric applied a global vacuum pressure impregnation insulation system to the stator winding of a large-scale air-cooled generator in 1993. Since then, more than 100 units with this system have been delivered. With the global vacuum pressure impregnation insulation system, the impregnating resin integrates the stator winding and core into a single unit to provide such advantages as improved cooling performance of the stator winding, enhanced reliability against loose windings, and a reduction in associated maintenance.

Global vacuum pressure impregnation insulation technology was applied to Fuji Electric's largest capacity generator, an indirect hydrogen-cooled generator of the largest class capacity in the world, and 22 kV-class global vacuum pressure impregnation insulation technology is described below.

4.1 22 kV-class global vacuum pressure impregnation insulation technology

In the development of 22 kV-class global vacuum pressure impregnation insulation technology for application to a 400 MVA-class indirect hydrogen-cooled generator, the coil was made longer and the insulation thicker than in previous stator coils. For this reason, the development was particularly focused on evaluating the taping and impregnation characteristics of the main insulation layer and the reliability of the global vacuum pressure impregnation coil insulation.

(1) Taping technology for main insulation layer

The stator coil is fabricated by winding main insulating tape made of mica paper. The insulating characteristics are affected by the taping conditions such as the tape winding direction, tape dimensions, tape condition of overlap joints, and so on. In particular, the value of dielectric breakdown voltage is affected by the distribution of tape overlap parts. Therefore, the maximum dielectric strength must be obtained for a given number of winding insulation layers. For this purpose, Fuji Electric created a proprietary software program and performed analyses to obtain the optimal conditions for taping such that the number of overlapping layers is not reduced at the corners of the stator coil in sectional profile, where electrical fields from the operating voltage and withstand voltage tests concentrate. The optimization data was inputted into a taping machine and reflected in the actual generator production.

(2) Evaluation of insulation performance

The insulation reliability was evaluated by constructing a linear model bar and a large model of an actual generator. Thermal cycle endurance and voltage endurance tests were carried out with the linear model of 22 kV-class insulation, and the thermal cycle stability and high voltage endurance were verified. As an example of the results, Fig. 3 shows the voltage endurance characteristics for 22 kV-class insulation. The voltage endurance characteristics sufficiently satisfy the KEMA (N.V. tot Keuring van Electrotechnische Materialen) criteria. Also, the large model of the actual generator shown in Fig. 4 was constructed in order to verify reliability, including reliability of the insulation production method. The large model that assumes a 450 MVA indirect hydrogen-cooled generator has a lamirated core length of 4.5 m and has 5 slots. When initially constructed, the large model underwent a 45 (2E + 1) kV withstand voltage test and then 25 iterations of thermal cycle endurance tests, and during this testing, the tan δ characteristic did not change from its initial value, and the stability of the insulation characteristics was verified. Additionally, after the 25 thermal cycles, a dielectric breakdown voltage test was

Fig.3 Voltage endurance characteristics of 22 kV-class insulation

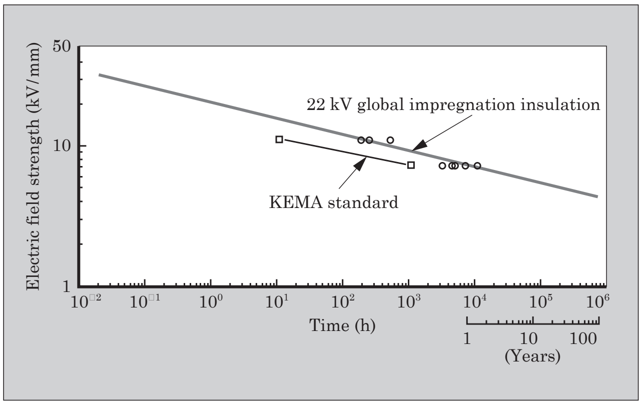
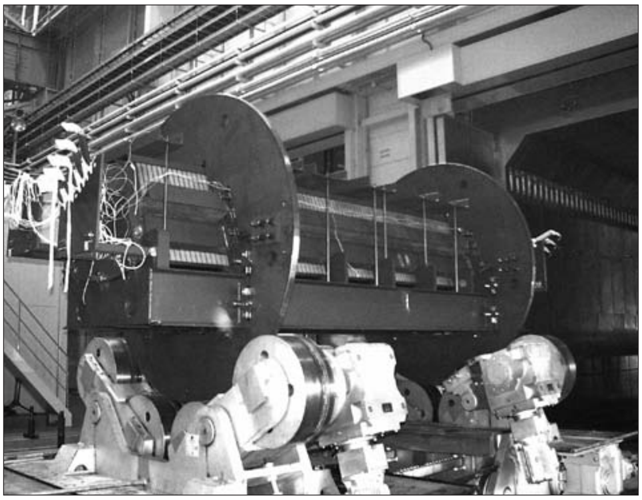


Fig.4 22 kV-class large model of actual generator



performed in air, and the dielectric strength was confirmed to be sufficient.

4.2 Application of 22 kV-class global vacuum pressure impregnation insulation to a generator

The completed stator is shown in Fig. 5. In the fabrication of the stator windings for this generator, previously acquired global vacuum pressure impregnation insulation technology and the 22 kV-class vacuum pressure impregnation technology described in section 4.1 were applied.

In order to verify the impregnation characteristics, the impregnated state of the stator windings was monitored with a charging current impregnation monitor and the characteristics were verified to be within their control values. Moreover, the impregnation monitor insulation bar, which was impregnated together with the stator winding, was analyzed after having been actually impregnated, and sufficient impregnation of the insulation layers by the impregnating resin was verified.

Four stators, all having the same specifications, have been completed thus far. The results of all insulation characteristic tests were similar to the tan

Fig.5 Stator for indirect hydrogen-cooled turbine generator

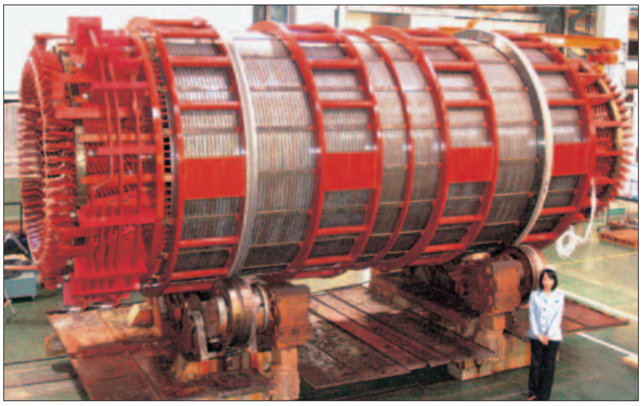
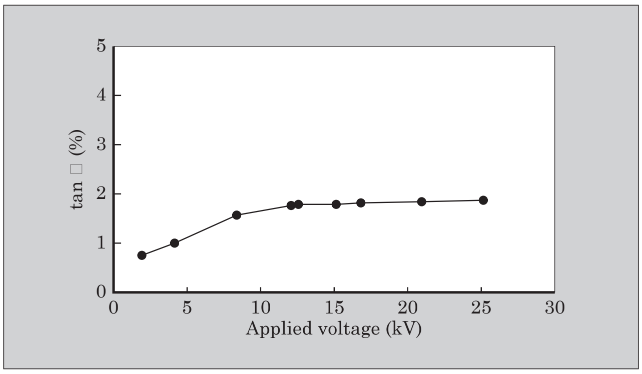


Fig.6 Tan δ vs. voltage characteristics (for each of 3-phases)



δ vs. voltage characteristic shown in Fig. 6, and this characteristic is similar to the favorable insulation performance characteristics verified experimentally with the large model coil. Moreover, during construction of the actual generator, we confirmed that the developed insulation technology was realized. Additionally, in a partial discharge test, the value of $q_{\max}$ (maximum partial discharge magnitude) when the rated voltage (21 kV) is applied was a favorable value below the 1,000 pC level, which is extremely small.

Thus, the favorable insulation characteristics of the stator winding were verified.

5. Analysis Technology

5.1 Ventilation, temperature analysis

Owing to recent performance improvements in hardware and software, the number of elements in the analysis model for ventilation can be increased, and complex flows such as the cooling ventilation in a generator can be computed with relatively high precision. Moreover, because actual measurements of the flow inside the rotor during operation are extremely difficult to obtain, the application of thermo fluid analysis is an important tool for assessing the flow distribution and the like. When designing the generator, thermo fluid analysis was used to realize optimal ventilation cooling.

An example of flow analysis for the inside of the ro-

Fig.7 Model for rotor ventilation analysis

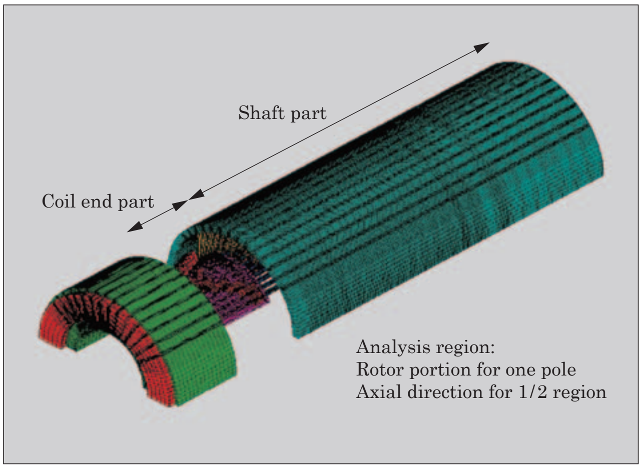
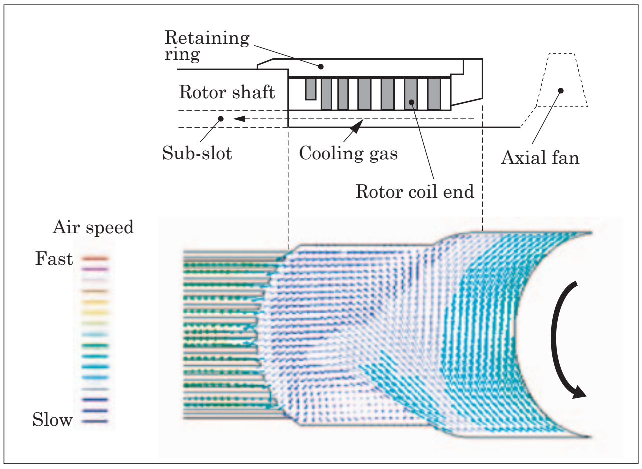


Fig.8 Results of analysis of rotor coil end inner diameter ventilation



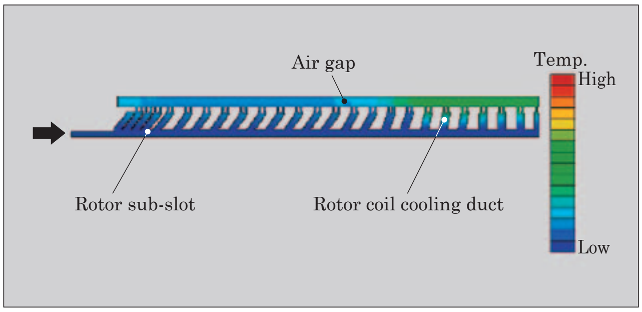
tor is described below. Figure 7 shows the ventilation analysis model. The outlet part of the axial fan at the shaft end, the space on the inner side of the coil end, and the conductor duct and air gaps were modeled. There are approximately 3,780,000 elements. Computations were made in consideration of the turbulent flow of the flow-field when the rotor rotates at its rated speed. The gas flow distribution, which is computed separately, is used for determining boundary conditions at the axial fan part, which forms the cooling gas inlet, and at the air gap, which forms the cooling gas outlet.

Cooling gas emitted from the axial fan flows along the space on the inner side of the rotor coil end and into a sub-slot, known as the axial ventilation path, provided at the bottom of the slot. The distribution of flow along the space on the inner side of the rotor coil end is uneven and depends on the gas in-flow direction as determined by the rotor rotation and the axial fan blade angle, and on the structure of the inner-side of the coil end. This flow unevenness results in non-uniform distributions of cooling gas flow into the sub-slot and in conductor temperature, and must be reduced. In the design phase, factors such as the dimensions of the coil end inner-side space, the fan blade angle and inflow rate were analyzed and the design was optimized to reduce unevenness in the flow. Figure 8 shows an example of the results of an analysis of the rotor coil end inner diameter ventilation.

Figure 9 shows an example analysis of the flow and temperature of a cooling duct of the rotor conductor. The distributions of conductor and cooling gas temperatures in the axial direction was verified by the thermo fluid analysis with the consideration of the Joule loss in the conductor.

Rotor temperature had conventionally been computed using ventilation and thermal network approach. The thermo fluid analysis was used to obtain the specific optimal conditions based on differences in the pitch and angle of axially-arranged cooling ducts because it is difficult to calculate these conditions with the conventional computation method.

Fig.9 Rotor coolant temperature analysis results



5.2 Structural analysis

Various structural and strength related analyses were performed. Especially for gas turbine or combined cycle power generation applications, reliability for frequent starting and stopping operations must be considered. So that the retaining ring supports the rotor coil end while rotating under centrifugal force, the retaining ring is shrink-fitted, with a certain shrink fit allowance, to the rotor shaft. When stopped, compressive stress is generated on the rotor shaft, and when rotating, that compressive force is released due to the expansion of the retaining ring diameter as a result of centrifugal force. Thus, starting and stopping operations generate repeated stress. In order to avoid concentrated stress and to investigate reliability against repeated stress, the strength of the rotor retaining ring shrink-fit part was analyzed.

Figure 10 shows the analysis model. Since the structure is complex, a three-dimensional model was used for the strength analysis of the retaining ring shrink-fitting part. Moreover, so as to model the stress condition correctly, the non-linearity of strain and stress was considered and the shrink-fitted surfaces of the retaining ring and rotor were analyzed as contact elements.

As an example of the analysis results, Fig. 11 shows

Fig.10 Retaining ring strength analysis model

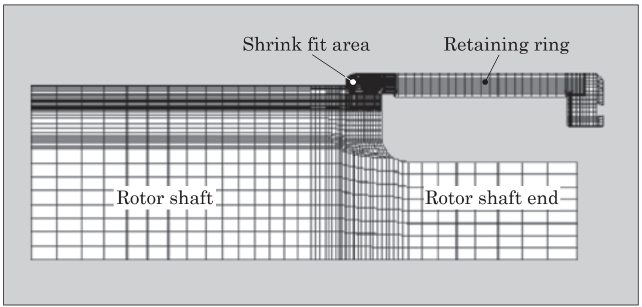
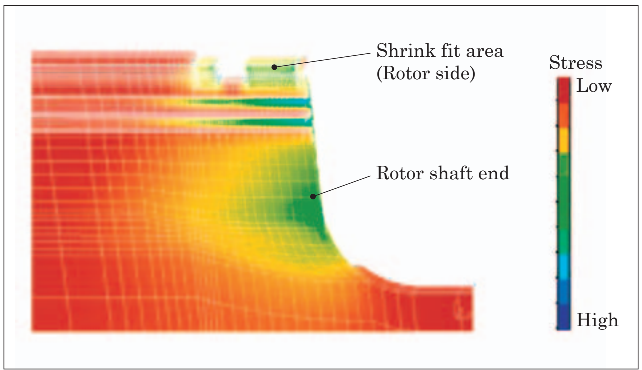


Fig.11 Results of compressive stress distribution analysis of rotor shaft end



the distribution of compressive stress at the rotor shaft end part when stopped. The capability for accurate assessment of the stress at each part of the rotor, both when stopped and when rotating, enables verification of the static strength and low cycle fatigue strength at the rotor shaft end part. Moreover, the optimal shape was also investigated and reliability for frequent starting and stopping operations was improved.

6. Factory Test Results

6.1 Performance verification tests

A no-load saturation test, sustained three-phase short-circuit test, loss measurement, temperature rise test, sudden three-phase short-circuit test, and an over-speed test were performed in December 2007, and various performance characteristics were verified. Figure 12 shows appearance of the generator during the factory test.

The factory test yielded good results which satisfied the specifications. Main test results are described below.

(1) No-load saturation test and sustained three-phase short-circuit test

The field current was measured when the generator was at no-load with rated voltage and when at rated current with three-phase short-circuited, and the results were in good agreement with the design values.

(2) Winding temperature rise

The temperature rise at each part during rated load operation was estimated using an equivalent temperature test method. The temperature rise of stator windings, rotor windings and other each part satisfy the limit values for thermal class B, and good results were obtained.

(3) Efficiency

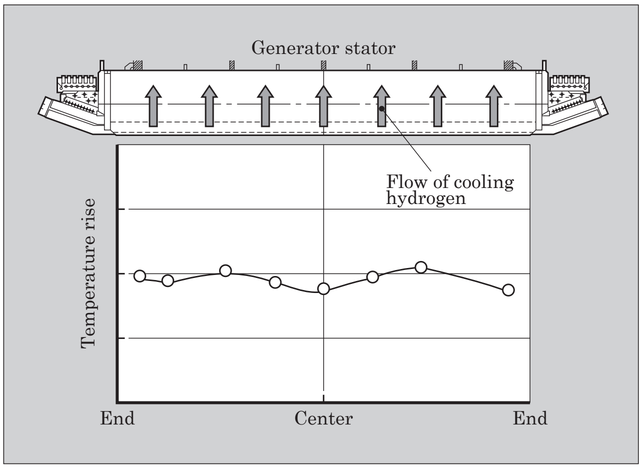
The loss of each part was measured, and the conventional efficiency was computed in accordance with IEC 60034-2. The computed results for efficiency during rated operation were favorable and exceeded the level necessary to guarantee rated efficiency.

(4) Reactance and time constant

A sustained three-phase short-circuit test was performed on the generator, and the generator's reactance and time constant were measured and the results were in good agreement with the design values.

Fig.12 Generator factory test

Fig.13 Sustained three-phase short-circuit temperature rise test results (Stator winding axial temperature distribution)



6.2 Other verification testing

During the factory test, in addition to the performance verification tests for required specifications, measurements were taken to verify various other parameters. Figure 13 shows the stator winding axial temperature distribution during the sustained three-phase short-circuit test. From the optimal cooling duct arrangement and gas flow distribution, the temperature was verified as being uniform.

7. Postscript

The design and applied technology of an indirect hydrogen-cooled generator using a global vacuum pressure impregnation insulation system have been described. In the future, Fuji Electric intends to continue to develop technology to meet the needs of the market, and to produce high quality, high reliability generators.

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Explanation **Global Vacuum Pressure Impregnation Insulation**

Insulation for the stator winding of a rotating machine is configured from such materials as mica which has excellent corona resistance and epoxy resin which has excellent thermal resistance. Global vacuum pressure impregnation insulation is used in applications ranging from small motors to the large generators described in this paper, and is the main method for manufacturing stator winding insulation. With global vacuum pressure impregnation insulation, the insulation for each coil comprising the stator winding is not completed individually, and instead, a non-impregnated coil is inserted into the stator core, the coils and leads are connected to configure the stator winding, and then the entire stator winding is impregnated all at once to complete the insulation. Thus, this process is called global vacuum pressure impregnation insulation since the entire stator is impregnated to complete the insulation. Because the stator core and the coil are integrated into a single body, global vacuum pressure impregnation insulation provides the advantages of improved cooling performance, prevention of loosening of the windings, and for the user, higher reliability and reduced maintenance. Large capacity global vacuum pressure impregnation insulation can be achieved through the careful quality control of large-scale manufacturing equipment and insulation materials used, and the coil manufacturing, coil assembly and resin impregnation processes.

Recent Rehabilitation Technology for Aging Thermal Power Generation Equipment

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Mitsuhiro Uemura †
Yutaka Tamaya †

1. Introduction

Having successfully delivered many power generating plants both in Japan and overseas, Fuji Electric is proposing that equipment which has been in service for a long time at aging thermal power plants be rehabilitated completely instead of just being inspected periodically and parts replaced as part of preventive maintenance. Specifically, Fuji Electric proposes such solutions as increasing the efficiency and output capacity of the turbines, implementing remaining life extending countermeasures for critical equipment devices which has deteriorated, making modifications to support changes in fuel conversion and process steam, and so on to meet the needs of our customers.

This paper presents examples of rehabilitation projects for aging thermal power generation equipment that has been implemented recently by Fuji Electric and also describes the maintenance service technology.

2. Recent Rehabilitation Projects

2.1 Rehabilitation of Unit 9 at Mae Moh Power Plant

The Mae Moh Power Plant is located approximately 3 hours by car from Chiang Mai in northern Thailand. The Mae Moh Power Plant was delivered by Fuji Electric and is a coal-fired thermal power plant operated by the Electricity Generating Authority of Thailand (EGAT) and is the largest in Southeast Asia (10 turbines, Units 4 to 13). Figure 1 shows a photo of EGAT's Mae Moh Power Plant, and Table 1 lists the history of turbine deliveries to the Mae Moe Plant.

The recent rehabilitation of Unit 9 is described below.

This turbine has a 3-casing structure configured as a high-pressure/intermediate-pressure/low-pressure turbine. In the rehabilitation project, advanced technology was applied to increase the efficiency, output power (increasing more than 5 MW) and to increase the reliability of the main parts of the low-pressure turbine (low-pressure rotor, low-pressure internal casing, stationary blade ring, diffuser, etc.). Table 2 lists

† Fuji Electric Systems Co., Ltd.

Fig.1 Mae Moh Power Plant

Table 1 History of turbine generator deliveries to Mae Moh Power Plant

Unit	Output	Year of operation startup
Units 4 to 7	150 MW × 4 units	1984 to 1985
Units 8 to 13	300 MW × 6 units	1989 to 1994
Total	2,400 MW total (10 units)	

Table 2 Main specifications of Mae Moh Power Plant Unit 9 turbine

	Before modification	After modification
Type	3-casing reheat condensing	
Output	300 MW	Increased to more than 5 MW
Operating method	Constant pressure throttle governing method	
Main steam pressure	161 bar abs	
Main steam temperature	538 °C	
Reheat steam pressure	37.94 bar abs	
Reheat steam temperature	538 °C	
Vacuum	0.0771 bar abs	
Rotational speed	3,000 r/min	

the main specifications of the Unit 9 turbine and Fig. 2 shows a sectional view of the turbine assembly and a diagram of the scope of this modification work.

(1) Use of completely three-dimensional design reaction blade entirely with CAD

As one measure to improve efficiency, row completely three-dimensional design reaction blade was applied for the reaction blades of stages 1 to 4 of the low-pressure turbine blade to be highly efficient and have significantly less profile loss than conventional reaction blades (Fig. 3).

(2) Use of new generation low pressure blades

New generation low pressure blades that were designed using supersonic fluid analysis (3-dimensional time marching method) and provide largely improved performance are used. Lean-radial stationary blades that are curved in the circumferential direction are used as the last stage stationary blades and realize a large improvement in efficiency (Fig. 4).

(3) Use of improved exhaust diffuser

The exhaust diffuser provided to reduce exhaust loss of the low-pressure last stage trailing flow has been replaced, incorporating a new design to enhance the performance of the exhaust diffuser and realize a reduction in exhaust loss.

(4) Use of labyrinth opposing fins

A double-fin type (opposing fin type) that is highly effective in sealing steam is used at the steam seal of the low-pressure blade row to reduce steam leakage loss and improve efficiency (Fig. 5).

(5) Measure to prevent stress corrosion cracking (SCC) in blade root part

The large low-pressure moving blade groove of the low-pressure rotor is processed into a fir tree type root blade shape. In order to decrease the risk of stress corrosion cracking (SCC) by deterioration of the operating environment (steam properties), shot peening (a method in which tiny steel balls are projected onto the rotor surface to forcibly provide compressive residual stress) is performed on the blade groove of the low-pressure rotor to improve resistance to SCC.

Fig.2 Sectional view of the turbine assembly and diagram of scope of renewal work

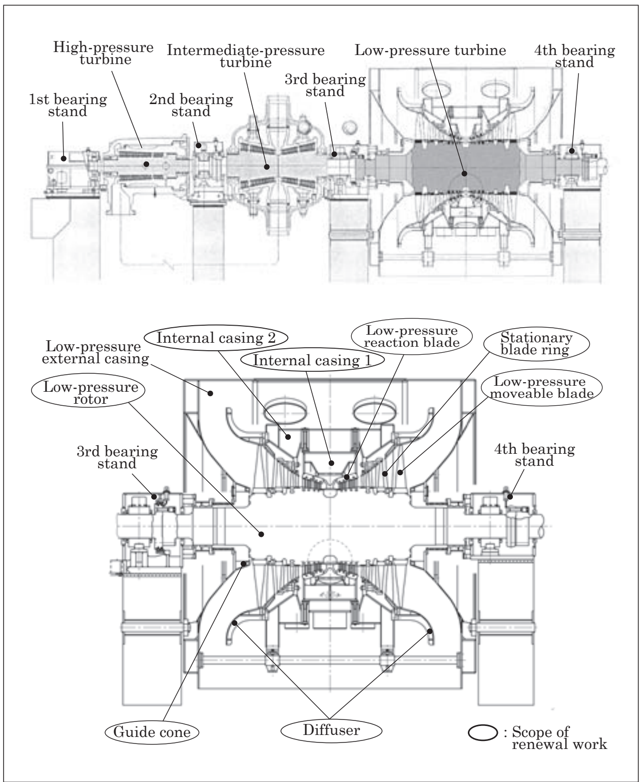


Fig.3 Reaction blades designed entirely with 3-dimensional CAD technology

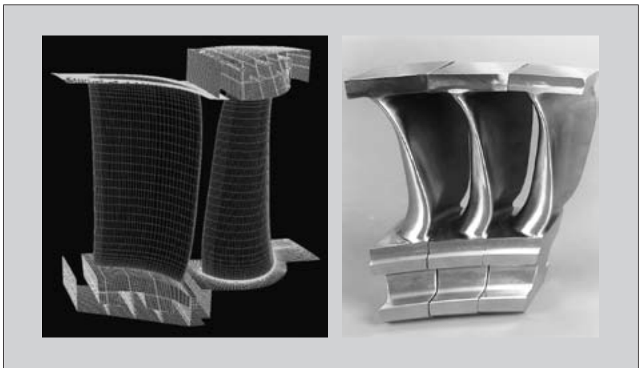


Fig.4 Lean-radial stationary blades

Fig.5 Double fin-type labyrinth

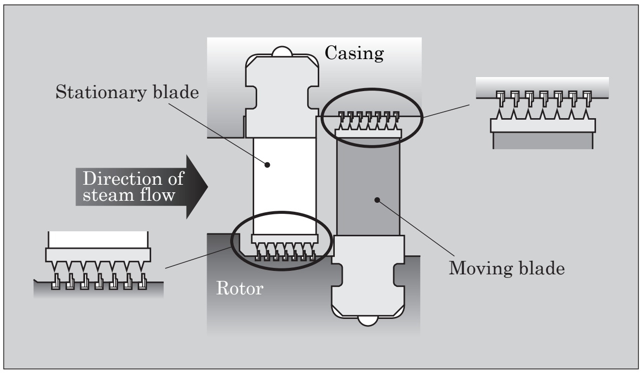
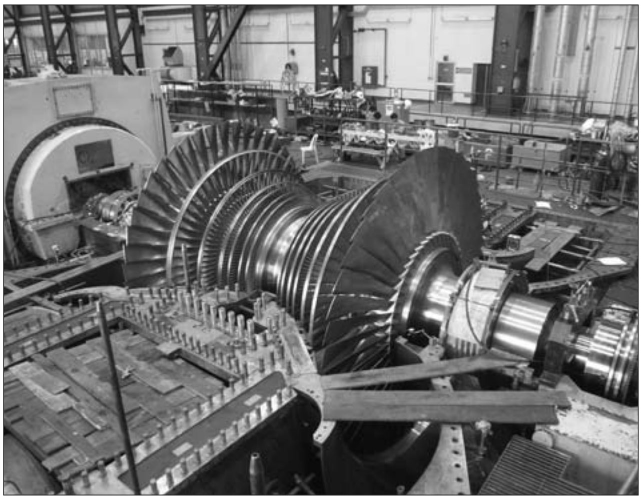


Fig.6 Onsite partially assembled new low-pressure rotor



(6) Use of hydraulic coupling bolts

With the renewal of the low-pressure rotor, all coupling bolts were replaced with hydraulic coupling bolts, enabling modifications to be performed more quickly and reducing the time required for future periodic inspections. Figure 6 shows a new low-pressure rotor in the process of being assembled onsite.

2.2 Rehabilitation of Grand Haven Power Plant

The Grand Haven Power Plant is located on the eastern bank of Lake Michigan in the United States, and is a municipal coal-fired thermal power plant in the city of Grand Haven, Michigan. This thermal power plant facility began operation in 1982 and has been running for more than 20 years, and in this rehabilitation project, the steam turbine unit was modified, and a part of the generator and transformer were replaced in order to increase power output from 73.2 MW to 80 MW. Table 3 and Fig. 7 list main specifications of the turbine for the Grand Haven Power Plant and show a sectional view of the turbine assembly, respectively.

This turbine has a 2-casing structure and is configured from a high/intermediate pressure turbine that combines a high pressure part and a low pressure part, and a low-pressure turbine. The rotor, internal casing, moving/stationary blades, and other such parts have been updated to the latest design, resulting in higher output power and increased efficiency. Figure 8 shows a new high/intermediate pressure internal casing that is in the process of being assembled onsite. The main modifications are as follows.

(a) Reduced throttle loss by using constant pressure throttle governing method
(b) Improved efficiency by using completely three dimensional design reaction blade
(c) Increased cooling capacity of power plant air cooler
(d) Increased cooling capacity of main transformer
(e) Optimization of governor and automatic voltage regulator

Table 3 Main specifications of turbine for Grand Haven Power Plant

	Before modification	After modification
Type	2-casing reheat extraction condensing	
Output	73.2 MW	80 MW
Operating method	Constant pressure nozzle governing method	Constant pressure throttle governing method
Main steam pressure	101 bar abs	
Main steam temperature	538 °C	
Reheat steam pressure	25.6 bar abs	25.0 bar abs
Reheat steam temperature	538 °C	
Vacuum	0.085 bar abs	
Rotating	3,600 r/min	

Fig.7 Sectional view of turbine assembly

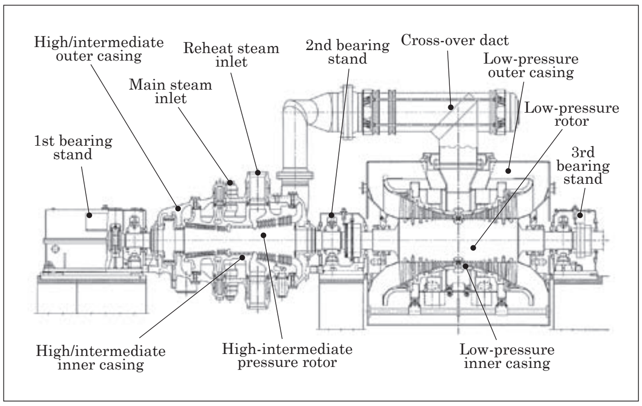


Fig.8 New high/intermediate pressure internal casing partially assembled onsite

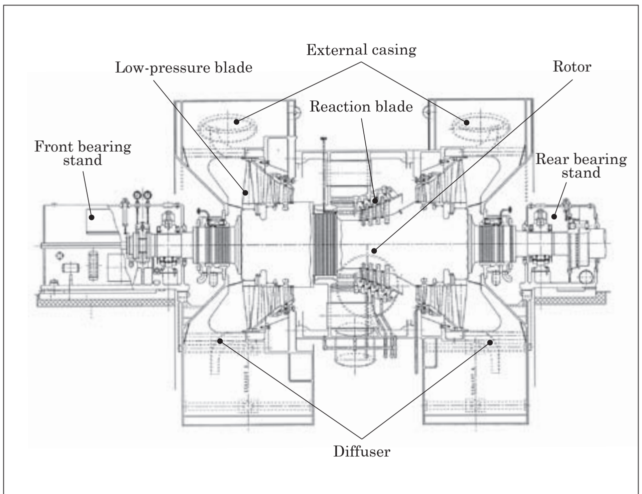
2.3 Rehabilitation of Dixie Valley Geothermal Power Plant

The Dixie Valley Geothermal Power Plant is located approximately 200 km from Reno, Nevada, USA. The steam source properties (pressure, temperature, flow rate, impurities, etc.) for this geothermal power

Table 4 Main specifications of turbine for Dixie Valley Geothermal Power Plant

	Before modification	After modification
Type	Single-casing admission condensing	
Output	60.5MW	64.7MW
Main steam pressure	6.2 bar abs	6.14 bar abs
Main steam temperature	161.7°C	459.4°C
Admission steam pressure	1.43bar abs	1.52bar abs
Admission steam temperature	112.8°C	111.7°C
Vacuum	High-pressure vacuum region 0.055 bar abs, low-pressure vacuum region 0.090 bar abs	
Rotational speed	3,600 r/min	
Blade length of last stage	658 mm	665 mm

Fig.9 Sectional view of turbine assembly



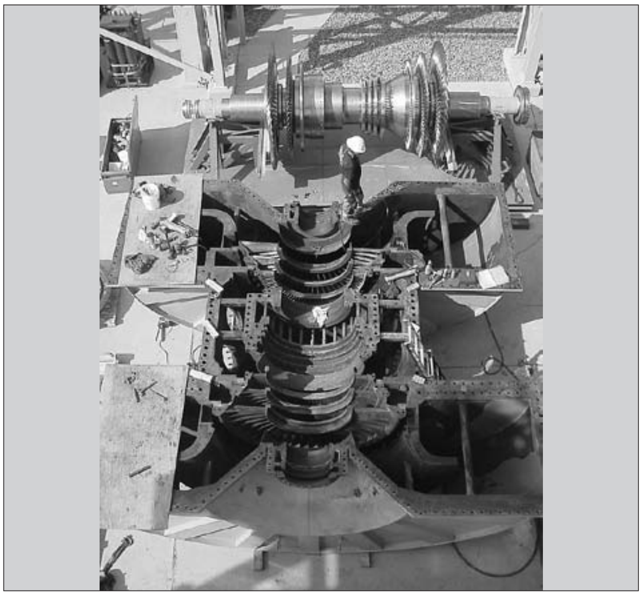
plant have changed with age. This geothermal steam turbine began operation in 1988, and as a result of changes in the steam conditions due to the long-term operation, a decrease in turbine efficiency was observed and optimization of the power generating equipment had been required.

In response to such customer needs, in the rehabilitation work, the latest designs were applied to the main components (rotor, moveable/stationary blades, stationary blade ring, diffuser, etc.) of the turbine, the turbine output was increased from 60.5 MW to 64.7 MW, and the turbine efficiency was also increased. Table 4 lists the main specifications of the Dixie Valley Geothermal Power Plant and Fig. 9 shows a sectional view of the turbine assembly.

Figure 10 shows an onsite turbine undergoing modification. The main modifications are as follows.

(a) Improved efficiency by using complectely three dimensional design reaction blade
(b) Improved efficiency by new generation low-pressure blades

Fig.10 Onsite turbine undergoing modification



(c) Improved efficiency by improved exhaust diffuser
(d) Optimization of automatic voltage regulator

3. Fuji Electric's Maintenance Service

(1) Leak buster

In a condensing-type turbine, the turbine exhaust pressure is a vacuum, but if there is an increase in leakage of external air into the vacuum region, the degree of vacuum will deteriorate and performance will decrease, leading to increased fuel costs and the corrosion of devices. The leak buster is a service that detects air leaks in the vacuum region, uses helium gas to identify the leak locations accurately, and then quantitatively computers the amount of leakage.

The leak buster specifies leak locations and leakage amounts with significantly more accurate than the various leakage detection methods employed in the past. The leak buster has been used in equipment in Japan, but has also recently been used with turbines delivered overseas and with turbines made by other manufacturers, and has met customer expectations.

(2) Hybrid gas extraction system

Geothermal power plants use natural steam to generate electric power. This steam, however, often contains 1 to 8% (weight percentage) of non-condensable gases such as carbon dioxide gas, hydrogen sulfide gas and so on.

In the case of a condensing steam turbine plant, these non-condensable gases must be extracted from a condenser, and larger-capacity gas extraction system is required than in the case of a typical thermal power plant.

Gas extraction system usually employs a steam ejector system or gas compressor system. The steam ejector method does not involve a rotating parts and is therefore maintenance-free, but its efficiency is poor and requires a large amount of driving steam. In order to improve efficiency at existing plants that use the steam ejector system, replacement with a hybrid system combining a vacuum pump is proposed. The hybrid system combines a first-stage ejector and a second-stage vacuum pump (Fig. 11). The use of a vacuum pump reduces the amount of ejector drive steam, and increases the turbine output with the surplus steam, and even if the ejector drive steam amount is deducted, the net generation line output can be increased dramatically. These improvements increase efficiency the more at plants where there is the higher percentage of non-condensable gases.

(3) Phased array inspection

As turbines become larger in size, the turbine low pressure blades are being made longer. In order to ensure the soundness of the root part of a blade, MT (magnetic particle testing) had previously been performed on the root parts of low-pressure moveable blades during periodic inspections in which the turbine casing is opened up. As a technology for inspecting the moveable blades without having to remove them, phased array ultrasonic testing is recently being performed onsite. Figure 12 shows the phased array inspection of a fir tree type root of a low-pressure moveable blade.

Fig.11 Hybrid gas extraction equipment

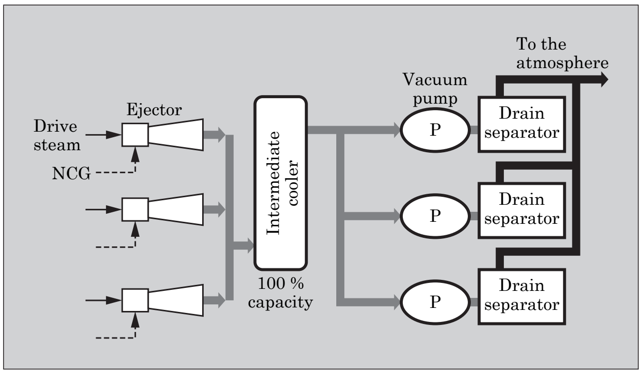


Fig.12 Phased array inspection of fir tree type root of low-pressure moveable blade

(4) Turbine residual life evaluation service

Since developing turbine residual life evaluation technology in 1987, Fuji Electric has performed approximately 50 residual life evaluations and had these valuable data. Inspection methods suitable for the structure and characteristics of each device are optimally combined to conduct highly reliable residual life evaluations, and advices regarding device replacement and repair are provided.

Residual life evaluations have focused mainly on turbines in Japan, but recently, residual life evaluation service is also being provided to aging thermal power plant equipment that has been delivered overseas.

(5) Patrol QC (quality control) assessment service

For overseas thermal power plant equipment, preventive maintenance is sometimes inconsistent, and periodic inspections that involve opening the turbine casing are often not performed. Symptoms of trouble due to long-term operation are often overlooked.

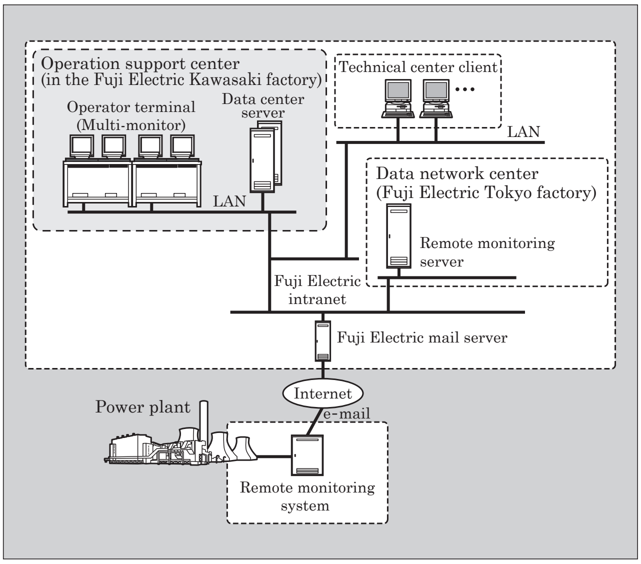
Under these circumstances, since 2002, Fuji Electric has been providing a QC assessment service centered on the Taiwanese region, and based on the assessment results has proposed periodic inspections by opening the turbine casing and preventative maintenance to prevent trouble from occurring and increase the reliability of the equipment.

Future plans call for the patrol QC assessment service to be expanded to the Asian region to meet customer needs.

(6) Operation support center

With the increase in thermal power plant equipment delivered overseas, Fuji Electric has developed and introduced a remote monitoring system (RMS) as a support service for our customers, and sampled data from the power plant and the control system status can be monitored remotely from the operation support center. With the operation support center, not only

Fig.13 System configuration



can long-term operation data be acquired, but services ranging from daily operational support to error diagnosis performance evaluations, proposals of preventative and predictive maintenance, and so on are provided.

Judgments based on the relative and trend monitoring of the operation data enable abnormalities in the power generating equipment to be predicted, and provision of guidance for required countermeasures to customers help prevent accidents. Moreover, if an accident were to occur, this data can be supported to identify the cause of the accident or provide support for recovery rapidly, thereby increasing customer satisfaction (CS).

With the operation support center, the use of a power plant facility information total management system (POP-FIT) enables databases of equipment specifications, design drawings, user manuals, recorded inspections, equipment history, and the like to be accessed, and the appropriate support provided quickly. Figure 13 shows the system configuration of a remote monitoring system.

4. Postscript

Examples of Fuji Electric's recently implemented rehabilitation of an aging thermal power plant facility and maintenance services have been presented.

As the number of aging thermal power facilities increases in the future, Fuji Electric intends to continue to provide optimal rehabilitation plans and maintenance services as solutions that meet customer needs.

Improved Three-dimensional Image Processing Technology for Remote Handling Auxiliary System

Chiaki Tomizuka †
Keisuke Jinza †
Hiroshi Takahashi †

1. Introduction

Remote handling devices are used in the radioactive environment of nuclear power plants since humans cannot enter the work environment to perform handling operations. Fuji Electric has developed a remote handling auxiliary system based on shape recognition technology to identify the location and orientation of a handling object (target) virtually. The operator adjusts a virtual screen to the desired viewing direction so that a handling device such as a manipulator can be operated with ease. This paper presents an overview of the remote handling auxiliary system and describes details of its development.

2. Development Background

With fuel handling equipment, which are typical conventional remote handling devices, the nuclear fuel to be handled was placed at a precise location and orientation, and accurate and sophisticated remote controlled movement in a harsh environment was required. Most operations, however, such as moving a certain distance along a predetermined trajectory, stopping, and then performing a separate operation were planned in advance.

However, in recent years there has been an increase in the use of targets which have a non-distinct profile. In such cases, an articulated manipulator is operated manually. When dismantling a nuclear power reactor during decommissioning and when performing remote operations within a cell, an articulated manipulator and camera are placed in the work environment, and the operator implements manual operations while viewing the camera video in an operation room. Figure 1 is an example of a nuclear power reactor remote dismantling test device. Using this device, in a remote operation test (Fig. 2) in which a manipulator picks up a target from the floor, the effect that changing the number of cameras had on work efficiency (work time) was investigated. With video images from a camera, depth is difficult to sense, and in some cases, the target may be obstructed by an object in the forefront, making it impossible to obtain an adequate image. If the number of cameras is increased to compensate for such a problem, the work efficiency improves. On the other hand, performing the time consuming task of adjusting a large number of images and visually comparing the results increases the burden on the operator, and as a result, work efficiency may decrease. Additionally, the cameras cannot always be installed at the best locations for all scenes.

Marks or guides placed nearby the target are often used as references for operation. Figure 3 shows an example wherein, in order to insert the tip of a tool into the hole in a target, a laser pointer attached to the tool shines a laser spot onto the target, and the operator

Fig.1 Examples of camera images of dismantling work

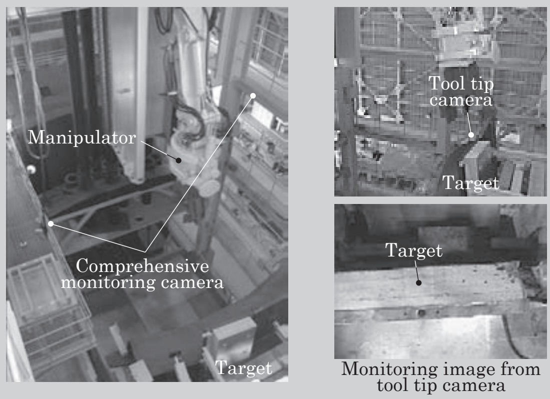
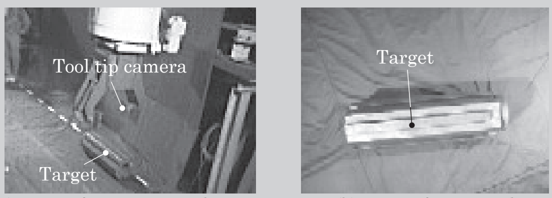


Fig.2 Examples of monitoring image

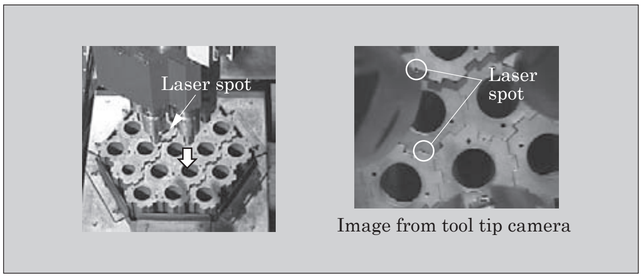


(a) Image from a comprehensive monitoring camera

(b) Image from a tool tip camera

† Fuji Electric Systems Co., Ltd.

Fig.3 Example of alignment according to positioning mark



positions the tool while watching the camera image. However, the presence of adjacent objects other than the target will cause the operating environment to become more challenging and as a result, more camera images will be needed. The determination of which cameras to use from among the available cameras, how to best adjust the image (orientation and angle) to facilitate the operation, and how to use positioning marks depends upon the experience of the operator. Therefore the skill level of an operator affects the work efficiency and the quality of the work.

For this reason, a system capable of providing uniform quality of work, regardless of the skill level of the operator, is desired.

3. Concept of the Remote Handling Auxiliary System

The concept of a remote handling auxiliary system developed under these circumstances is shown in Fig. 4.

This remote handling auxiliary system displays the location and orientation of the target on an operation screen during remote operation, and provides the necessary images and distance information for manual operation of the manipulator. The operation screen displays the actual image from the camera and also displays a monitoring image, which is a virtual representation of the operating environment (scene). The scene is obtained as point-cloud data by using a distance sensor installed in the work environment to scan an area that includes the target. Based on this point-cloud data, the relevant objects are expressed as multiple layers of computer graphic (CG) images, and exhibit the following characteristics.

(a) The scene is expressed by a point-cloud containing three-dimensional data (having spatial three-dimensional coordinates).
(b) The contour of the target and outline of the manipulator are displayed in the scene.
(c) The line of sight along which the scene is viewed may be moved freely.
(d) The distance between two arbitrary points, such as between the manipulator tip and the target, can be obtained by pointing on the monitoring screen.

The operator observes both the actual image from

Fig.4 Remote handling auxiliary system

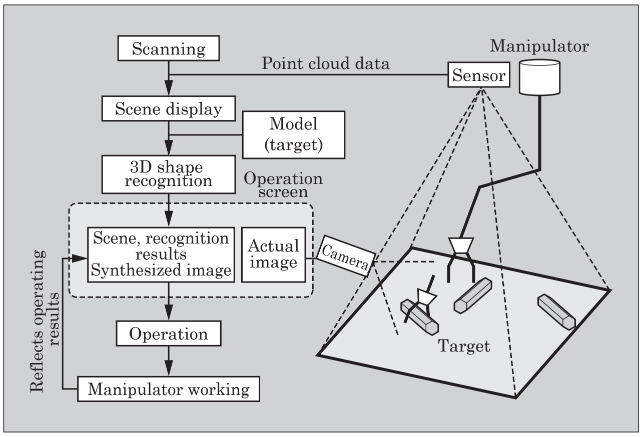
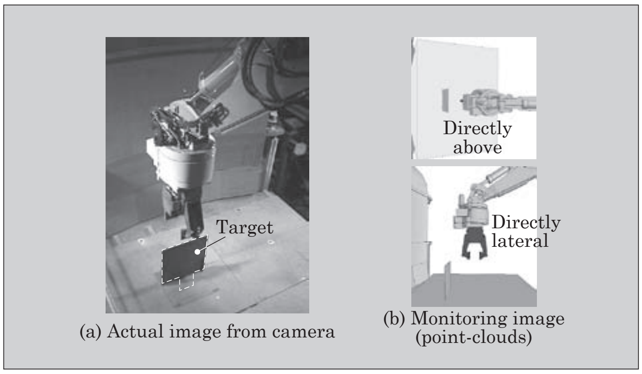


Fig.5 Operation screen (image)



the onsite camera and the above-described monitoring image while performing the appropriate operation. Figure 5 shows an image of the operation screen. The operation screen shown in Fig. 5(a) is the actual image from the camera. Figure 5(b) is a virtual image generated by the system.

Even in cases where only a portion of the target has been captured by the sensor, the application of three-dimensional shape recognition technology to the outline of the visible portion of the target provides the capability to view a virtual CG-synthesized display of the entire image, and this is the greatest benefit of using a virtual image. Additionally, this virtual image also synthesizes a display of the manipulator outline, so that the image may be changed freely to show the desired line of sight. By observing the virtual image, the operator gains a sense of gazing around the positional relationship between the target and manipulator. In Fig. 5, the actual image is from a camera fixed in a specific direction and a sense of distance is difficult to grasp. When viewed in combination with the virtual images viewed from directly above and lateral perspectives, a sense of horizontal and vertical distance is easier to grasp. If combined with distance display on the screen, the scene in Fig. 5 will provide the operator with an understanding of how and by what distance to move the manipulator.

When the manipulator is moved, the virtual manipulator shown in the virtual image will also move in the same manner in real time. When the manipulator is being moved, the desired task can be accomplished while monitoring the status of the virtual image.

This remote handling auxiliary system is provided with dictionaries containing multiple point cloud target shape models that are compared with the target chosen to be handled and the scanned scene (point cloud data). The primary objective of this system is to realize the capability to identify the location and orientation of a target, even when only a portion of the target is visible. The system was developed by focusing on three-dimensional shape recognition technology.

4. Three-dimensional Shape Recognition Technology and the Remote Handling Auxiliary System

Computer-aided visual recognition technology is required for the automation of tasks involved in recognition and judgment making by humans. We are still learning about the processes by which humans recognize and make judgments, and general-purpose recognition algorithms are still being researched. The application of a recognition algorithm often involves the use of custom recognition algorithms developed for each of the specific tasks to be automated.

The technology to automate visual recognition and judgment using an image from a camera or other two-dimensional image is spreading to industrial inspection and recognition devices and to biometric recognition devices. These devices, however, assume an environment having a fixed observing point for viewing the object and therefore have difficulty in providing sufficient support for an environment in which multiple observing points are required, such as for remote operation by a manipulator.

Three-dimensional recognition technology is effective in solving the aforementioned types of problems. The processing of data in three dimensions involves dramatically more data than does two-dimensional data processing, but high-speed processing has become possible through the rapid development of computer technology. Moreover, three-dimensional measurement technology is also being widely utilized and the cost of distance sensors is decreasing for both laser and stereo vision methods. Under such conditions, research into three-dimensional recognition technology is being accelerated, but at present, there is still no established technique.

When observing a three-dimensional object in two dimensions, the resulting image is treated as a two-dimensional image from a certain observing point, and for the same object, this image will differ if the observing point changes. Humans are able to comprehend the shape of an object empirically, and can recognize an object even when the image is from a different observing point. A computer, however, does not possess empirical knowledge, and thus in order to achieve the same recognition results, must either retain two-dimensional data from all observing points and apply a two-dimensional recognition algorithm, or apply a three-dimensional recognition algorithm that does not depend on the observing point. The former has the advantage of allowing existing technology to be utilized, but has difficulty in providing a sense of perspective such as when the size of the object changes according to its proximity.

The development of the remote handling auxiliary system involved the following two research topics.

(a) A scene including the arbitrary location and arbitrary orientation of the assumed object (model) is measured by a distance sensor as point cloud data, and three-dimensional shape recognition technology is used to recognize the type and orientation of the model.

(b) Construction of an auxiliary system that enables easy remote operation of a manipulator when a non-expert operates a screen displaying a CG image showing the recognition results, and then verifies the image from a convenient observing point.

4.1 Three-dimension shape recognition principles, application and evaluation results

In case there exists a large quantity of data of the object to be recognized, as in the case of an image, for example, rather than processes that data directly, the recognition algorithm typically converts the data to a low-loss quantity of a reduced dimensionality (known as the characteristic quantity) and then processes the data. In order to realize recognition that does not depend on the observing point, the orientation of the object, and the distance to the object, a characteristic quantity that does not depend on the observing point, orientation or distance must be used. Three-dimensional recognition was implemented with this system using a characteristic quantity having the following properties.

(a) Low dependency on perspective and orientation of the object

(b) Low dependency on distance from observing point

(c) Low susceptibility to influence from other objects positioned nearby

This assumes the case where the object is partially blocked by an obstructing object in its vicinity and only a part of the object can be measured (partial absence).

The principles for recognition using this characteristic quantity are described below. Firstly, a point-cloud of the object to be recognized (the model) is prepared in advance, and a characteristic quantity is computed at each sampling point spaced apart at regular intervals. Each characteristic quantity is mapped to the three-dimensional coordinates of a point on the model. A dictionary that combines three types of data, i.e., characteristic quantity, model type and three-dimensional coordinates of the corresponding point, is prepared in advance.

Next, during the recognition processing, the point-clouds of a scene that includes the object to be recognized is measured and then the characteristic quantity is computed for an arbitrary sampled point. Using a pattern recognition technique, this characteristic quantity is compared to characteristic quantities in the dictionary, and a similar characteristic quantity is selected. As a result, the point sampled from the scene is mapped, via the characteristic quantity, to three-dimensional coordinates of the model type and in the model. Based on multiple mapping relationships obtained thusly, the type, location and orientation of the model in the scene are obtained.

By applying the above principles, the following elemental technologies were developed and applied.

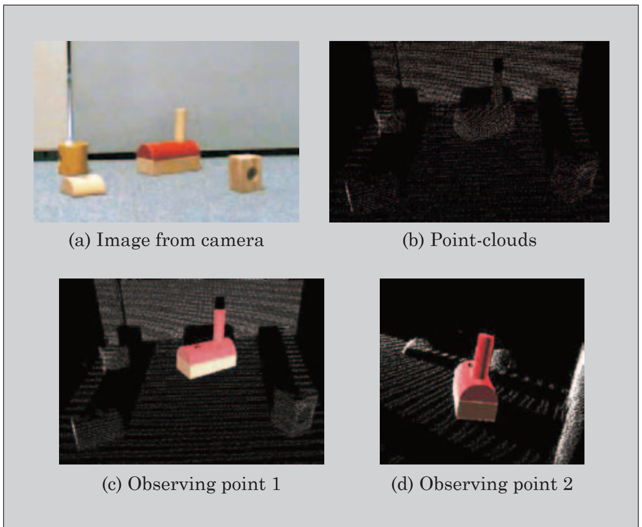
(a) Algorithm for extracting a specified object from a combination of multiple objects (segmentation)

(b) Algorithm for recognizing a rotating object (columnar, etc.), for which recognition had been difficult according to the principles of three-dimensional recognition

(c) Algorithm (typically an application of the ICP method) for matching the dictionary data with the measured data using an iterative approach with the above-mentioned recognition results as initial values

The results of evaluations performed using the recently developed three-dimensional recognition algorithm are described below. The example of recognition results in Fig. 6 shows (a) an image from a camera, (b) measurement data of point-clouds from a three-dimensional distance sensor, (c) a virtual image as viewed from a different observing point and displayed as a CG model of the recognition results, and (d) a virtual image from an observing point approaching the object.

Fig.6 Examples of camera image, point-clouds and recognition results



Good recognition performance was achieved in cases where the three-dimensional characteristics (at parts having unevenness or other characteristics) were measured or where three surfaces of a solid body could be measured. However, the recognition was difficult in cases where three-dimensional characteristics could not be measured (from directly lateral to or from directly above, etc.), since the measurement data did not contain three-dimensional characteristics. As a solution, the three-dimensional characteristics must be re-measured from an observation point at which the three-dimensional characteristics can be measured. For approximately 10 types of objects prepared for evaluation-use, the recognition results were nearly always correct when the three-dimensional characteristics could be measured.

4.2 Remote handling auxiliary system

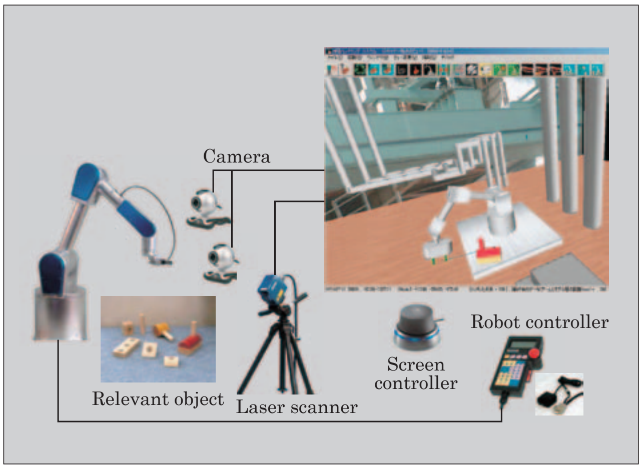
A remote handling auxiliary system that incorporates results from three-dimensional shape recognition is described below.

Figure 7 shows the system which is configured from a control PC, a three-dimensional mouse for screen control, a laser scanner, a robot, a robot control terminal, and a camera for image recognition. The object, having been measured by the laser scanner, is recognized by the PC and the results are expressed as a CG image, and the manipulator, expressed as a CG image, and the measured point-clouds are displayed. The operator uses the three-dimensional mouse to change the observing point to one that is easy to view, displays the screen from that easy-to-view observing point, and then uses the robot control terminal to operate the robot. The coordinate systems for the robot and laser scanner are calibrated beforehand using a calibration tool that has been developed.

Recognizing the shape of the model and then expressing the results as a CG image has the following two advantages.

(a) The contour of the entire target surface can be

Fig.7 System configuration



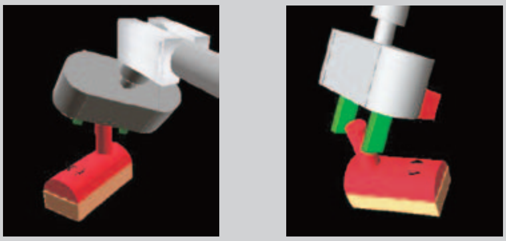
displayed. By moving to an arbitrary observing point with a simple mouse operation, the image from an observing point from which observation is not actually possible or the image of a region that has not been measured can be displayed to provide visually accurate information. The remote handling auxiliary system is particularly effective in the case of utilizing an observing point located at the hand at the tip of the arm.

(b) Specifying certain arbitrary points in the measurement data and the recognition results enables the distance between the observing point and object to be calculated, and is effective in obtaining information that provides a sense of perspective.

While the manipulator is moving, information from each axis (encoder values) is acquired in real-time so that the CG image of the manipulator can move with the same movements as the actual manipulator.

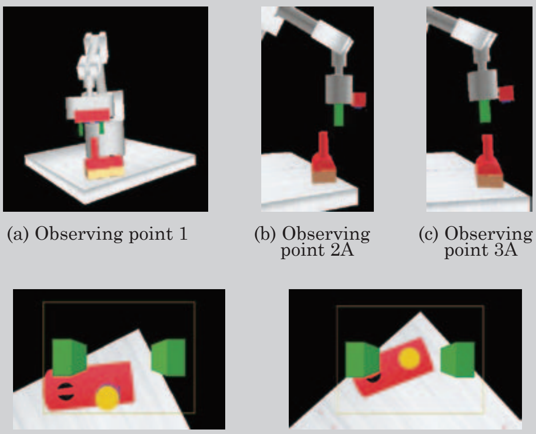
Thus, as is shown in Fig. 8, the point-clouds of measurement data, the CG representation of the recognized model and the CG representation of the manipulator are superimposed to create a display of augmented reality. In Fig. 8(a), the object is obscured by the hand part and cannot be seen, but in Fig. 8(b), the observing point has been changed so that the object status can be confirmed.

Fig.8 CG representation of manipulator and model



(a) Observing point 1 (b) Observing point 2

Fig.9 Example of handling by moving the observing point



(a) Observing point 1 (b) Observing point 2A (c) Observing point 3A

(d) Observing point 2B (e) Observing point 3B

An example of auxiliary handling by moving the observing point is described below. Figure 9(a) is an image from an observing point in the direction of the measuring instrument, and whether the manipulator has been moved to a location where it can grip the object is unclear in the figure. Performing a mouse operation to move the observing point of the image enables a determination to be made as to whether an object lies in a location that cannot be gripped as shown in Figs. 9(b) and (d), or whether it lies in a state in which the object can be gripped as shown in Figs. 9(c) and (e).

As described above, with this system, the object to be gripped is expressed as a CG image based on the results of three-dimensional shape recognition. Side surfaces that cannot be actually viewed can be displayed and the CG representation of the manipulator enables observation from an arbitrary observing point. Moreover, multiple observing points can be specified and multiple observation images can be displayed continuously. As a result, the object can be verified from a direction in which a sense of distance is easy to grasp, the object can be viewed from an observing point that avoids other obstructing objects, and this system can provide suitable assistance for handling operations by an operator having a non-expert level of skill.

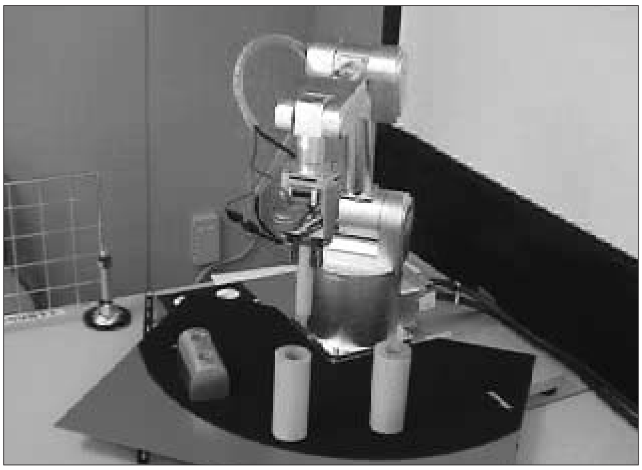
The following functions were developed to assist the remote handling by an operator.

(a) Image from an observing point at the hand: An image in which the observing point is the hand location is useful when performing an operation of gripping the object with the hand. (Fig. 9(d) and 9(e)).

(b) Automatic observing point change: A manual operation can be performed to display an image from an observing point clearly showing the relationship between the hand and the object to be gripped, but a clearly visible observing point can also be computed automatically and the image displayed.

(c) Environment creation function: Three-dimen-

Fig.10 Tabletop robot manipulation system



sional information in the vicinity of the hand is acquired as needed, via a stereo camera mounted on top of the hand, and combined with three-dimensional information acquired by the laser scanner to create three-dimensional information of the peripheral environment. Thus, collisions between the manipulator and obstructions can be avoided.

As a prototype system that combines these elemental technologies, Fuji Electric developed a tabletop robot manipulation system that automatically recognizes an object placed at an arbitrary location and performs automated tasks. (See Fig. 10.)

4.3 Issues to be resolved for practical application

The following issues must be resolved for practical application.

(a) Improvement of three-dimensional recognition function: Elemental technologies that boost the recognition percentage and increase recognition accuracy are at the research and experimentation stages. Improvement in the recognition percentage, recognition accuracy and recognition speed is needed before this function can be incorporated into practical applications.

(b) Recognition of metal objects: The three-dimensional measurement of metal objects presents a difficult challenge. Improved mechanisms for measurement of metal objects or techniques for recognizing the shape without measurement must be explored.

(c) Non-rigid, flexible objects: Rope, cables and the like are non-rigid, flexible objects that can also change their shape. Laser scanners or other similar measuring instruments that require time to perform their measurements are not well suited for capturing the movement of these types of objects. For tracking such movement closely, stereo vision imaging that is capable of high-speed measurement must be explored.

(d) Radiation tolerant cameras: Laser scanners cannot be used in a radioactive environment. Stereo vision that uses multiple radiation tolerant cameras is thought to be well suited for obtaining three-dimensional information in a radioactive environment.

5. Postscript

Development for the remote handling auxiliary system has focused mainly on shape recognition technology, and the original objective of achieving the capability to identify a target from within a scene has been achieved. In the future, Fuji Electric plans to develop a simple and easy-to-use human-machine interface that assumes a more practical work environment. Moreover, this system was developed as a manually operated auxiliary system, but it could also conceivably be applied as an automated location measurement function that targets the arbitrary location and orientation of objects to be handled, and can be developed in the future as a combined system that also includes automated operation.

The use of remote handling devices is not limited to the nuclear power field. Applications involving the handling of dangerous substances and the use of a crane to handle large and heavy objects are tasks requiring skill for remote operation and candidates for application of a remote handling auxiliary system. The application of this system not only increases efficiency, but also enables such tasks to be performed by operators who may not be highly skilled, and this is believed to be a significant advantage. Use of the remote handling auxiliary system in fields other than nuclear power is anticipated.

Completion of Equipment for the Materials and Life Science Experimental Facility at J-PARC

Takemitsu Kodama †

1. Introduction

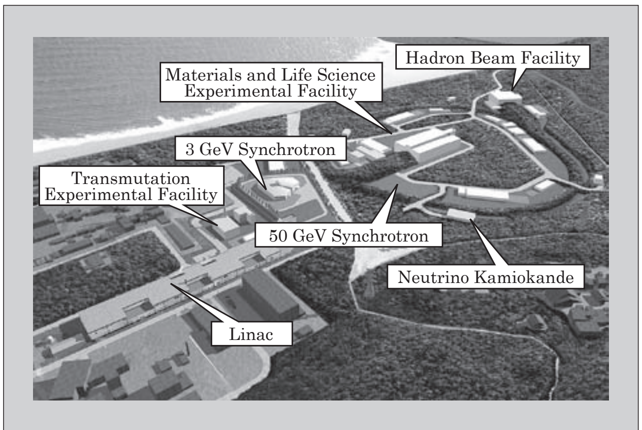
The Japan Proton Accelerator Research Complex (J-PARC) being constructed at the Tokai Research and Development Center's Nuclear Power Scientific Research Lab by the Japan Atomic Energy Agency (hereafter referred to as JAEA), an independent administrative agency, in Tokai Mura, Ibaraki Prefecture, Japan, is a research facility where neutrons and other secondary particles (mesons, neutrinos, muons, etc.), generated when the world largest-class high intensity proton beam is aimed at a target, are used to conduct research in various fields such as life science, materials science, atomic nuclei and elementary particles, astrophysics and energy research. Figure 1 shows an image of the completed facility.

The equipment that configures the Material and Life Science Experimental Facility was designed by JAEA, and from the design to manufacturing and installation stages of the construction, each part was procured through a competitive bidding process. The target and surrounding moderator pipes become highly radioactive due to the strong proton and neutron irradiation, and must be exchanged at intervals ranging from a half-year to several years. Fuji Electric has received orders for the design, manufacture, installation and adjustment of three types of relevant equipment: a target trolley for installing and moving a mercury target, moderator-reflector remote handling devices for exchanging moderator pipes, and irradiated component storage facilities for storing the mercury target and moderator pipes after having been exchanged.

This equipment is required to support remote handling and highly accurate interfaces between devices. Leveraging its remote handling technology which has been acquired over many years, from 2002 to 2007 Fuji Electric designed devices suited for remote operation, established interface conditions among equipment to be linked, and conducted comprehensive combination tests and performed installation and adjustments.

This paper introduces an overview of the aforementioned three types of equipment and describes their design, manufacture and testing.

Fig.1 Full-view of J-PARC (image of completed facility)



† Fuji Electric Systems Co., Ltd.

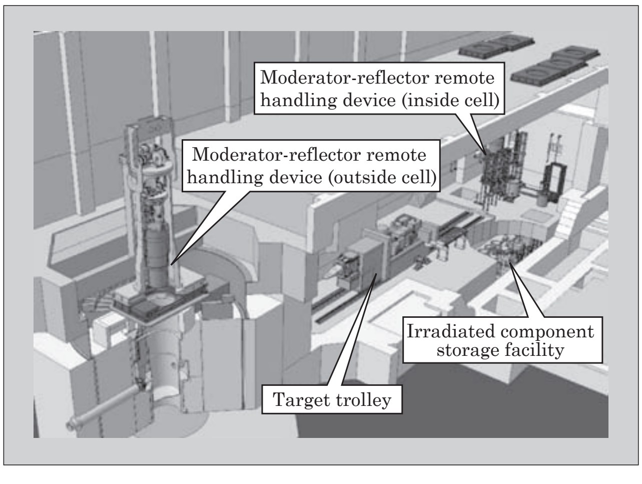
2. Equipment Overview

Figure 2 shows a schematic diagram of the three types of equipment, i.e., the target trolley, moderator-reflector remote handling devices and irradiated component storage facilities that are introduced herein.

2.1 Target trolley

Attached to the front of the target trolley is a tar-

Fig.2 Schematic of three types of equipment



get vessel which, when caused to collide with a beam from a high intensity proton accelerator, emits neutrons through a spallation reaction. The target trolley moves the target vessel between an operating position and a remote exchange position. The position of the target vessel during operation has a large effect on the neutron performance. The position accuracy for target trolley is required to insert the target vessel between a reflector and a moderator. Additionally, a function for shielding radiation rays emitted from the spallation reaction part inside the helium vessel and a function for supporting a 300 kN pressing force in order to maintain a sealed condition with the flange surface of the helium vessel are also requested.

The entire trolley, including the target vessel, has a total length of approximately 14 m, a height of approximately 4 m, and because a heavy shield is placed on the trolley, a mass of approximately 300 t. The drive function of the trolly is a rack and pinion system, and the trolley travels with a linear roller-way on an exclusive trajectory . The stopping accuracy in the forward and reverse directions is within ± 1 mm. The rear of the trolley is equipped with a mercury circulation system, tank, piping and the like for circulating mercury within the target vessel.

2.2 Moderator-reflector remote handling device

The moderator-reflector remote handling device operates remotely to take out such components as the reflector and moderator installed inside the helium vessel, the proton beam window that forms a boundary between the helium vessel and the proton beam line, and the like with the plug still attached, and then to exchange the components such as the moderator and proton beam window. Because these components are highly radioactive, they are collected in a shielded transfer cask, and then transferred to a hot cell where the component exchange operation is carried out.

A support stand whose orientation can be changed accurately and that supports an inner plug, an outer plug and the proton beam window exchange plug, and a moderator exchange device that can attach and detach moderator piping and the proton beam window through remote operation are provided in a hot cell. Additionally, floor valves for opening and closing 1.9 m-diameter passage openings are provided at five hatches located on the outside of the hot cell ceiling.

2.3 Irradiated component storage facility

The irradiated component storage facility is configured from various devices relating to the handling of irradiated components, such as an in-situ cutting device for cutting to reduce the volume of the moderator piping and the proton beam window that have been removed from their respective plugs by the moderator-reflector remote handling device, a storage facility primarily for the purpose of temporarily storing irradiated components that are planned to place in an irradiated component storage chamber beneath the hot cell, and a target vessel exchange device that performs supplemental tasks while the target vessel of the target trolley is being exchanged.

The cutting device is a shear-cutting type, and is requested to have the capability for cutting mostly 90 mm-diameter multi-layered pipes. The storage facility is equipped with a dedicated storage pit or frame structure. The target vessel exchange device aligns itself with the attaching part at the tip of the target trolley, and holds, transfers and receives the target vessels.

3. Device Design

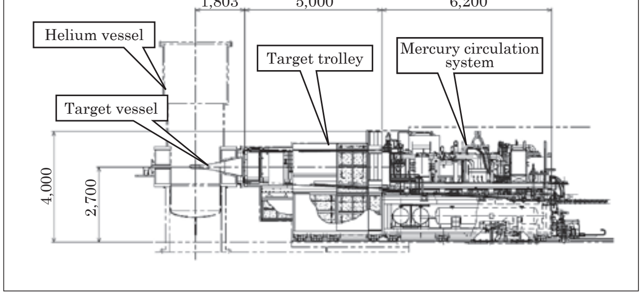
3.1 Target trolley

The target trolley is provided inside a hot cell as shown in Fig. 3, and is equipped with a large shield block that shields radiation rays emitted from the spallation reaction in the helium vessel. So that shield blocks can be assembled and dismantled by an in-cell crane, each shield block weighs less than 20 t and is aligned with vertical pins and stacked.

The building's shielded wall is provided with a rectangular-shaped penetrating part through which a target trolley attached with a target vessel can advance toward the helium vessel. In order to provide reliable shielding for the hot cell side, the gap between the shield and the penetrating part must be limited to 20 mm or less. In consideration of the manufacturing error in both the shield and penetrating part, and in order to maintain this gap across the 4.5 m insertion length for an opening of 2.6 m width × 4.0 m height, the outlines of all stacked shield blocks are pre-formed with a smallish size. In accordance with the finished dimensions on the building-side, a plate-shaped shield for adjusting outline dimensions is bonded over the entire surface of the shield block in the finishing method for the final dimensions, and the requested gap accuracy is achieved.

The target vessel must be exchanged every half-year because of radiation damage, and is bolted to the target trolley at the flange part. The two pipes from the mercury circulation system are connected by inserting the tool at the tip of a power manipulator into the attaching portion inside the tip of the target trolley,

Fig.3 Target trolley



and remotely operating the connection mechanism provided with the target vessel. Because the bolt coupling part of the target vessel flange and the bolt coupling part of the power manipulator insertion sealed flange are frequently screwed and unscrewed, exchangeable implanted screw fittings were used to prevent damage to the screw holes on the target trolley side.

Moreover, parts requiring maintenance or exchange, such as the drive device, mercury piping coupling part, and the wiring coupling part for power and instrumentation, all have a structure that enables removal or attachment operations to be implemented remotely using a power manipulator, master-slave manipulator and cranes.

3.2 Moderator-reflector remote handling devices

Moderator-reflector remote handling devices are classified as either hot cell-external devices or hot cell-internal devices. In the case of a hot cell-external device, the transfer cask shown in Fig. 4 is provided for removing the moderator-reflector plug from the helium vessel or the proton beam window plug in the forward direction of the beam.

The transfer cask is a cylindrical structure having an inner diameter of 1.9 m and a height of 11 m. The lower part of the transfer cask's cylindrical body is completely surrounded by a 290 mm-thick shield, and when housing the heavy moderator-reflector assembly (mass 36 t), the total mass becomes 130 t. The transfer cask is provided with a gripper and elevator, and with the plugs having been lowered into and housed in the transfer cask, a ceiling crane transports the transfer cask to a floor valve passage opening at a predetermined location on the hot cell, and lower the moderator-reflector assembly into the hot cell.

The gripper has a rotary-type claw capable of grabbing both inner and outer plugs or inner plugs only of the moderator-reflector assembly having a concentric cylinder shape with internal and external parts, and is provided with a vertical stroke of 35 m so as to be able to reach the deepest part of the irradiated component storage facility.

As shown in Fig. 5, inside the hot cell, an inner plug support stand and an outer plug support stand are provided, and the plugs are lowered onto these support stands. Moderator piping that is affixed to the plug, or the proton beam window, is rotated precisely to the appropriate required direction for exchanging operations with the moderator exchange device.

The moderator exchange device has a function for moving the entire assembly in the forward, backward, left and right directions and a function for raising, lowering and rotating a mechanism for coupling to an adapter for the moderator piping, and performs removal or attaching operations in conjunction with the power manipulator. When installing the moderator piping, a secure fit at the predetermined location is verified by a video image, and the pressing force is controlled by attaching a load sensor to ensure that an excessive force is not applied.

Fig.4 Transfer cask and object to be handled

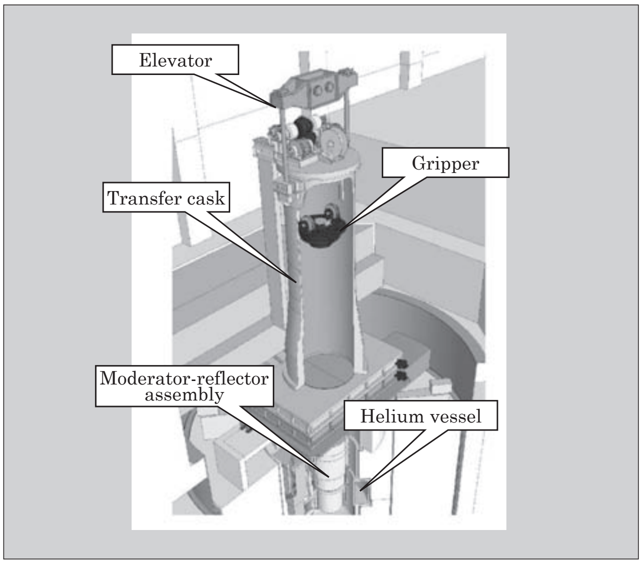
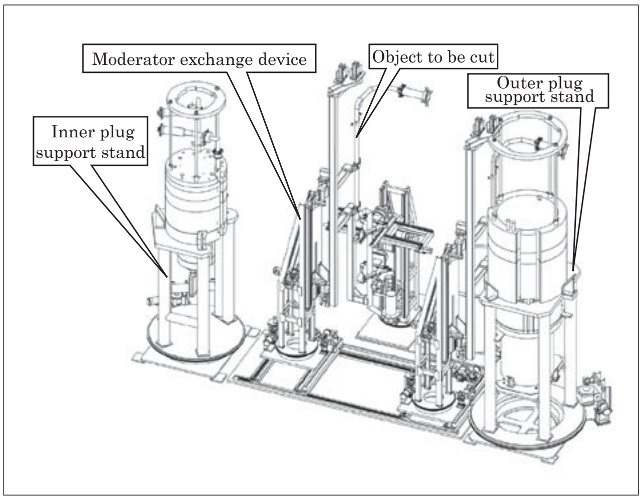


Fig.5 Configuration of hot cell-internal device



The moderator piping and proton beam window that have been removed are transferred to the cutting device of an adjacent irradiated component storage facility.

This series of operations is implemented from an operator panel outside the hot cell and is verified visually from a shield window and by using radiation tolerant cameras attached to the walls, floor, in-cell crane, and the power manipulator inside the hot cell.

3.3 Irradiated component storage facility

The cutting device is a shear cutting type, and the cutter is combined with two grippers for changing the cutting position by vertically feeding the object to be cut. The cutting device also has a function for rotating the entire device to change the orientation of the grippers and the cutter to two positions: the position of the cutting work and the transfer position of moderator

Fig.6 Cutting device

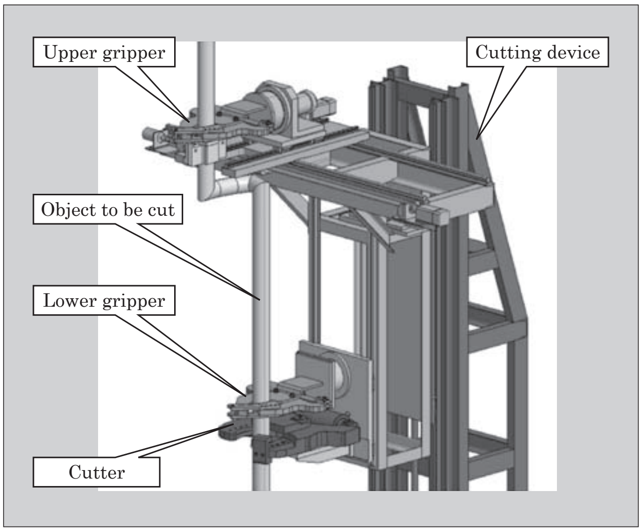
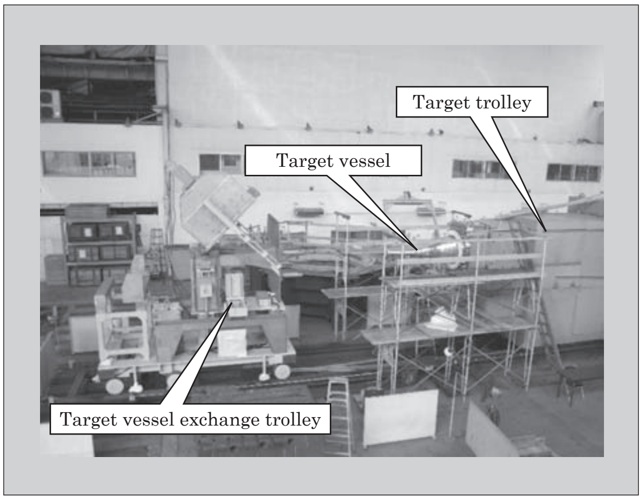


Fig.7 Comprehensive factory assembly test of target trolley



exchange device

The shear cutter, as shown in Fig. 6, operates by holding the object to be cut from the outside and cutting toward the inside, and is designed such that the object to be cut does not protrude outside the shears. The objects to be cut can have a wide range of diameter, ranging from 64 to 100 mm, and as in the case of the shear cutter, since the object to be cut is inserted on the inside between the gripping mechanisms, it will be secured at a predetermined location inside, regardless of its shape and dimensions.

The storage facility is configured from a variety of structures for storing irradiated components, such as the target vessel, moderator-reflector assembly, proton beam window exchange plug, muon target plug, and so on. So that of these objects to be stored or the moveable structures inside an irradiated component storage chamber can be handled by the hoisting attachment of an in-cell crane only, the shapes of the handling parts on the object side are standardized to appropriate uniform shapes.

The target vessel exchange trolley is arranged at the front of the target trolley in a hot cell on the upper stage of the irradiated component storage chamber when the target vessel is being exchanged, and while oriented to receive the target vessel, waits for completion of the bolt loosening by the power manipulator. After the removed target vessel has been received, a new target vessel is received and the orientation reverts to that prior to removal, and this orientation is maintained for the duration of the attaching work by the power manipulator.

4. Factory Tests

In factory tests, the performance of each of the aforementioned three types of equipment was verified using simulated objects. To test the operation of each type of equipment operating in conjunction with other equipment, the equipment was arranged under quasi-actual conditions and operation was implemented in conjunction with another equipment. Details that verify certain demonstrated performance parameters and tests to verify the cutting capability of the cutting device are described below.

4.1 Comprehensive factory assembly test of target trolley

Within the facility, the target trolley operates with a combination of target vessels and mercury circulation systems that have been manufactured in response to separate orders from multiple companies. Prior to being delivered onsite, factory test processes are adjusted for each company responsible for manufacturing, the target vessels and mercury circulation systems are collected and assembled together at Fuji Electric's Kawasaki Factory, and comprehensive factory assembly tests are conducted to verify their combined performance.

After having been put into operation, to verify the ease of remotely attaching and removing the target vessel at a frequency of once every 6 months, the assembled target vessel exchange trolley of the irradiated component storage facility was set up as shown in Fig. 7, the remote operation was simulated using the actual procedure and sequence, and adequate functionality was verified. The performance of the seal at the junction between the target vessel and the target trolley, having been attached using the above series of operations, was confirmed to be adequate.

On the other hand, the target vessel also required to maintain a tight seal with the helium vessel securely attached inside the facility. In this case, in order to assess the seal performance, a pressing force of 300 kN on the seal material is needed; the target trolley is requested to have a function for supporting the reactive force of this seal, and the accompanying rail equipment includes an anchoring apparatus to hold down the entire trolley. In a comprehensive factory assembly test, a simulated helium vessel flange was tightly secured to the test rail, and a series of actions were implemented, i.e., the target trolley was advanced in the forward direction, pressing force was generated due to the seal mechanism. The reaction force of the seal of the target trolley was supported, and the requested level of performance was verified for each action.

4.2 Cooperation between moderator exchange device and cutting device

The moderator exchange device of the moderator-reflector remote handling device and the cutting device of the irradiated component storage facility are arranged adjacently in the hot cell, and the moderator piping and the proton beam window removed by the moderator exchange device are delivered to the cutting device.

In the factory test, the stand-alone performance of each device was tested, and as shown in Fig. 8, both devices were installed in the same positional relationship as in an onsite installation, and using a simulated cutting object, the smooth performance of the actual cooperating operation was verified, and positioning data and operational performance data were acquired at that time for each device.

Fig.8 Test of moderator exchange device and cutting device

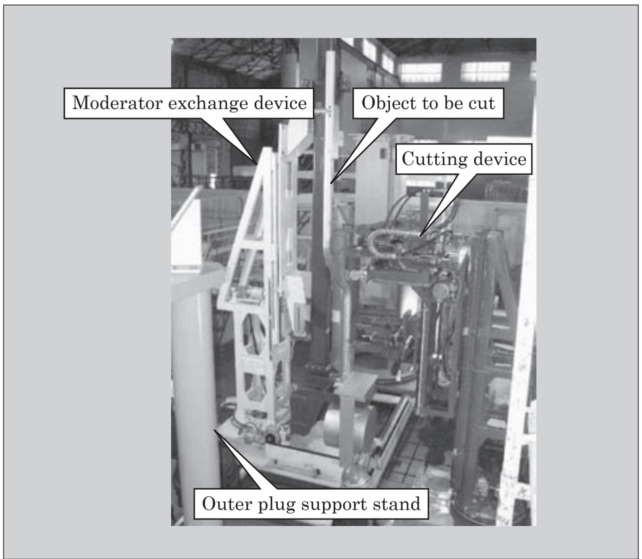
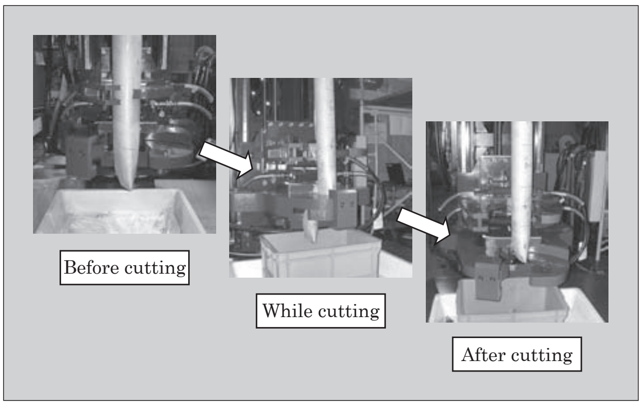


Fig.9 Cutting capability verification test



4.3 Cutting performance verification test of cutting device

On the cutting device, a custom cutting blade is attached to the shearing part, and the moderator piping is cut to a short length of approximately 1 m. To obtain data of the exchange frequency for the cutting blade, test objects were fabricated and a cutting test implemented based on actual operation plans.

A six-year supply of cutting test objects that simulate a muon target that is exchanged every 6 months, a proton beam window that is exchanged every 2 years and moderator piping that is slated to be exchanged once in 6 years were fabricated, and cutting was performed continuously with a single blade until an abnormality was observed in the blade tip.

Cutting was performed 49 times in total. The test objects prepared as entire 6-year supply were cut without any chips or cracks occurring in the cutting blade. This result verifies the adequate durability of the cutting blade.

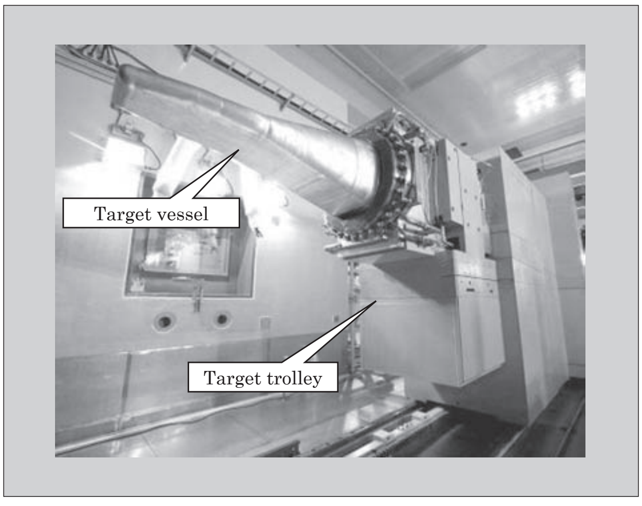
Figure 9 shows the appearance of the cutting test.

5. Onsite Installation and Assembly Test

5.1 Target trolley

A target vessel approximately 1.8 m long at the tip of the target trolley must be inserted between the moderator and reflector which are mounted inside the helium vessel, with no more than a 5 mm deviation in the vertical and horizontal directions. After the target trolley has been installed on an onsite rail, and using a separately installed helium vessel as a reference, dimensional measurement, jack-up and liner insertion operations are performed repeatedly to adjust its position. This method is being considered and prepared based on the progress of the factory assembly test, and settings within the targeted accuracy could be realized by following the procedure exactly as specified. However, since the location of interest was narrow and could not be verified directly, a tape-type contact sen-

Fig.10 Target trolley after completion of onsite installation



sor having a thickness of 2.3 mm was adhered onto the surface of the target vessel, and by inserting the target vessel carefully while verifying that it does not contact the surrounding periphery, we ultimately verified that there were no interfacing problems. Figure 10 shows the target trolley after completion of the onsite installation.

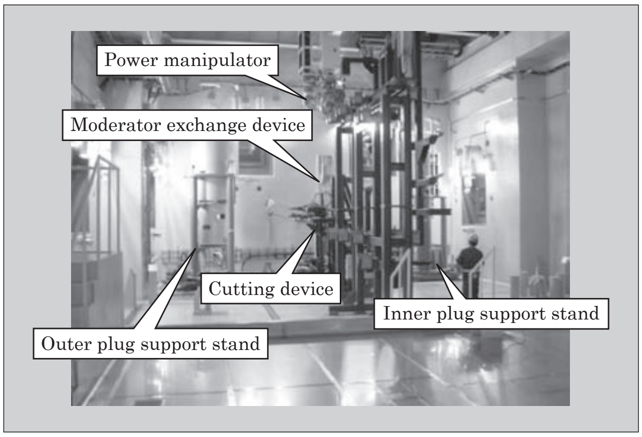
5.2 Moderator-reflector remote handling device and irradiated component storage facility

Devices internal to the hot cell of a moderator-reflector remote handling device and irradiated component storage facility were installed so as to reproduce the configuration of the aforementioned factory test. Figure 11 shows the installed state inside the cell.

In an assembly test after all devices have been installed, the transfer cask outside the hot cell is mounted on the top of the helium vessel, and the moderator-reflector assembly and proton beam exchange plug are removed and lowered into a temporary storage location of the irradiated component storage facility and then delivered to the devices inside the hot cell, and the predetermined positioning accuracy and the presence of a vertical stroke were verified.

Inside the hot cell, as a result of cooperative operation between the plug support stands and moderator exchange device and the hot cell-inner equipment of the in-cell crane and power manipulator, we verified based on visual observation from outside the hot cell and from monitoring camera image and operating signals that the moderator piping and the proton beam window could be removed and attached via remote operation.

Fig.11 Onsite installed state of devices in the hot cell



6. Postscript

All the devices designed and fabricated for the J-PARC Material and Life Science Environmental Facility are required to be remotely operable and maintainable. Because other devices are also related both structurally and operatively, cooperative tests were carried out at the factory test stage and onsite installation test stage, and the design and performance of each device were verified to be adequate for the entire facility.

Finally, the authors wish to express gratitude to the concerned parties at JAEA for the tremendous amount of guidance received in the design, fabrication and testing of the target trolley, moderator-reflector remote handling device and the irradiated component storage facility.

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