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DESIGN AND DEVELOPMENT OF GTHTR300

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ABSTRACT

Development and recent successful operations of the HTTR in JAERI are coordinated with programs to study applied systems of the promising reactor technology. One such program being carried out from 2001 to 2008 is design and development of the Gas Turbine High Temperature Reactor, GTHTR300, with objective to allow for demonstration of the plant in 2010s in Japan. GTHTR300 features an original design of fuel cycle based on improved HTTR fuel element and of simplified plant system in pursuit of targeted economics with minimum development requirements. The fuel cycle characterizes on high burnup, low power peaking factor and extended refueling interval. The plant system applies such simplified design features as conventional steel RPV, non-intercooled cycle, horizontal single-shaft gas turbine generator and distributed modular maintenance of the overall plant. Research and development essential to validating the design includes component development and control testing. This paper describes the reference plant design and associated continuing R&D activities in JAERI.

1. Introduction

Development of high temperature reactor technology in Japan has centered in a multitude of research and development activities in JAERI for more than 20 years. The development results in the construction of the 30 MWt High Temperature Engineering Test Reactor (HTTR) in the institute's Oarai Research Establishment. The helium-cooled, graphite-moderated HTTR based on pin-in-block fuel attained the first criticality in November 1998 and has successfully risen to the rated power and 850°C coolant outlet temperature in tests since December 2001. Based on such experience, JAERI lunched an applied program of design and development for GTHTR300 power plant in 2001. The program that is an assigned work by ministry MEXT will be conducted until 2008 with ultimate goals for demonstration of a prototype GTHTR300 in 2010s and for commercialization in 2020s in Japan

Approach to GTHTR300 design is system simplicity and originality with which to yield economical performance at low development cost and risk. The reactor module is rated at 600 MWt and 587/850°C inlet/outlet coolant temperature and employs the same type of fuel proven in the HTTR. It relies on inherent and passive safety system. The reactor pressure vessel which is cooled in an intrinsic flow scheme makes use of conventional steel (SA533). The system design utilizes the simplest possible Brayton cycle, i.e. without cycle intercooling, because our analysis shows that cycle intercooling results in complexities in turbomachinery and system but provides no compelling advantage in busbar cost. The helium turbomachinery in the non-intercooled cycle exhibits superior aerodynamic efficiency by fewer stages and its rotor is lighter, shorter and more rigid, resulting in more robust vibration characteristics. The rotor is laid out horizontally so that demands on bearings are minimized and traditional industrial experience in handling of similarly oriented and sized turbomachinery is applicable. The turbomachinery and heat exchangers are sized and placed separately to permit modular construction and maintenance.

2. Plant Design Description

2.1 Utility/User Requirements

Utility/User Requirements for GTHTR300 are listed in Table 1 and were established in consultation with Japanese utilities and industries to guide the plant design and development so that it is directly responsive to the demand of future nuclear power generating market in Japan.

2.2 System Design

Table 1: User/Utility Requirements for GTHTR300

User Requirements	
Item	**Requirment**
Safety goal	Radioactive nuclides release be prevented by fully passive means; Meet the site evaluation requirement for a current LWR; and additionally, site evacuation shall not be necessary.
Site condition	Replacement of LWR site or new site
Seismic condition	The same as that of a next generation LWR
Fuel cycle	Once though (subject to approval of Atomic Energy Commission); fuel burnup more than 100GWd/ton
Nuclear proliferation	High amount of weapon grade Pu shall not be produced
Radiation protection	0.5manSv/ry
Radioactive waste disposal	Liquid: 1/10 of the latest LWR Solid: reuse of fuel blocks if possible
Power level	Modular type 100-300MWe/unit 100-4000MWe/site
Life time	60 years
Availability	More than 90%
Inspection	Once/2 years
Inspection period	< 30 days
Economy	Capital: 40-50 billion ¥/unit or ¥160-200k/kWe) Electricity: ¥4/kWh

The plant system consists of three basic subsystem modules including the reactor module, the gas turbine generator (GTG) module, and the heat exchangers (HTX) module, as depicted in Fig. 1. The functionally-oriented modules are contained in individual steel vessels situated in separate confinement silos. Partitioning the large plant into properly sized subsystems and arranging them separately facilitates cost-effective modular construction and independently-accessed modular maintenance. For example, the size and weight of the GTG and HTX modules are such that they can be factory built in whole or in large vessel subassemblies and transported to site for erection in parallel, followed by simple piping connection.

In plant cycle, helium is heated in the core to 850^{o}C at 6.84 MPa. It enters the turbine for expansion to convert thermal energy into shaft power needed to drive the compressor and electric generator. The turbine exhaust helium enters the recuperator, wherein its residual heat is recovered in high effectiveness to preheat coolant to the reactor. Having finally been cooled to 28^{o}C by water in the precooler, the helium gas is raised by a pressure ratio of 1:2 to 7 MPa at 136^{o}C by the compressor, preheated to 587^{o}C in the recuperator, and heated in the reactor core to final outlet temperature of 850^{o}C. The cycle thermodynamic conditions are configured to yield peak cycle efficiency for the selected core outlet temperature with the lowest component costs. Table 2 summarizes the plant design and performance data.

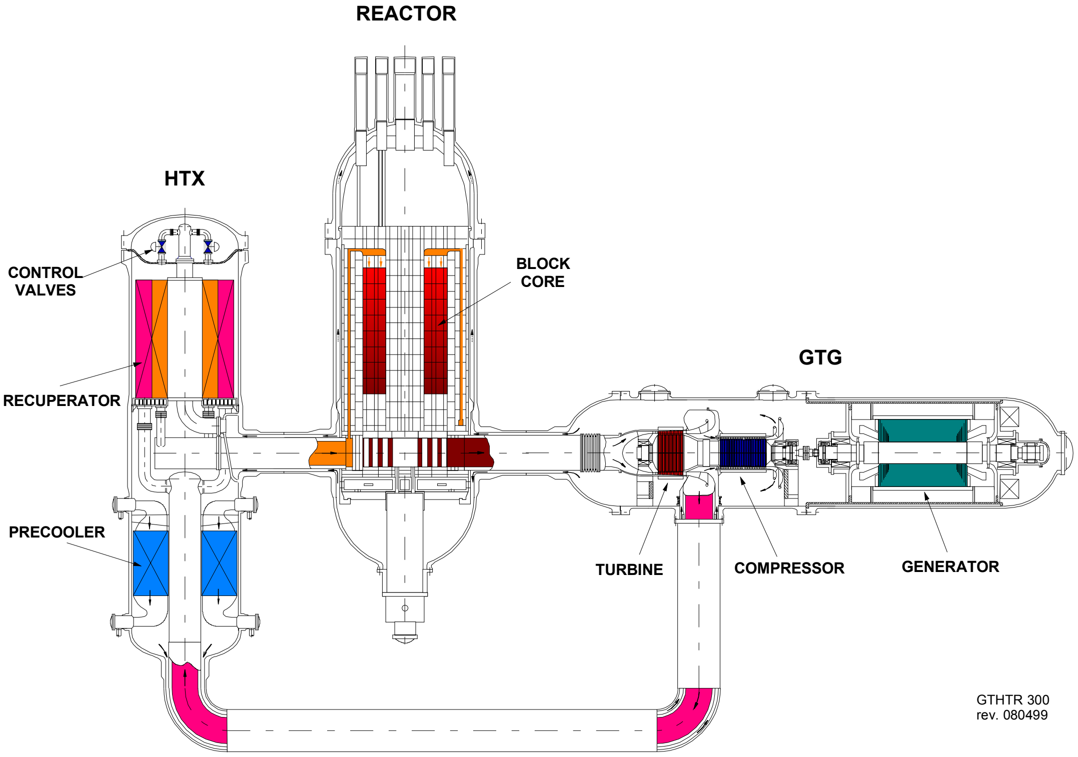


Fig. 1: System Arrangement of the GTHTR300

2.3 Reactor Module Design

The reactor pressure vessel (RPV) is cooled in a flow scheme unique to GTHTR300. The coolant is circulated to and from the core in the inner piping of a pair of coaxial vessel ducts leveled and symmetrically located near the reactor bottom. This unique piping structure makes it feasible to have the core inlet coolant channels embedded in the side reflector and is largely responsible to limiting the temperatures of the reactor lateral structure including the side reflector, core barrel and RPV. Moreover, the compressor-discharged helium at about 140°C and 7 MPa is circulated in the outer annular passage of the same pair of coaxial vessel ducts and through the vessel bottom interior from which a small gas stream is bypassed off the main circulating flow and vented to the annulus between the vessel and core barrel as shown in Fig. 2. It is this small bypass flow that is driven by an intrinsically positive pressure gradient towards the central core and which cools the RPV further as it flows upward in the annulus and enters the central core through top control rod guide tubes. The chart in Fig. 2 is used to determine the 0.5% cooling flow needed to keep the vessel operating temperature in a good margin from the material design limit over the entire operating power range. The vessel operating temperature is also in a regime where irradiation behavior of the vessel steel is sufficiently understood.

Table 2: GTHTR300 Design and Performance Data

Overall Plant	Reactor Power	600 MWt/unit (4 units/plant)
	Reactor pressure vessel	SA533 (Mn-Mo) steel
	Reactor safety system	no active emergency cooling
	Radioactive nuclide retention	confinement
	Plant Cycle	Non-intercooled Brayton cycle
	Power Generation	280 MWe
	Net Power Output	274 MWe
	Net Generating Efficiency	45.60%
	Plant Capacity Factor	90.0%
Reactor Core	Coolant Inlet/Outlet Temperature	587 / 850°C
	Coolant Inlet Pressure	6.92 MPa
	Core Coolant Pressure Loss	60 kPa
	Average power density	5.8 W/cc
	Fuel Element	pin-in-block prism
	Fuel Cycle	LEU once through cycle
	Enrichment	< 20%
	Average Burnup	112 GWd/ton
	Shutdown Refueling	once per 2-6 years
	Refueling Duration	30 days
Turbomachine	Shaft Design Type	horizontal, single-shaft
	Shaft Speed	3600 rpm
	Turbine Inlet Pressure	6.84 MPa
	Turbine Mass Flow	438.1 kg/s
	Turbine Expansion Ratio	1.87
	Number of Turbine Stages	6
	Turbine Polytropic Efficiency	93.0%
	Compressor Inlet Temperature	28°C
	Compressor Pressure Ratio	2.0
	Number of Compressor Stages	20
	Compressor Polytropic Efficiency	90.5%
	Generator Drive	cold-end, diaphragm coupling
	Generator Type	synchronous
	Generator Cooling	7 MPa helium cooled
	Generator Efficiency	98.7%
Heat Exchangers	Recuperator Design Type	plate-fin module x 6 modules
	Recuperator Thermal Rating	1006 MWt
	Recuperator Effectiveness	95.0%
	Recuperator Total Pressure Loss	1.7%
	Recuperator Construction Material	Type 316SS
	Precooler Design Type	helical-coiled finned tube bundle
	Precooler Thermal Rating	323 MWt
	Cooling Water Inlet Temperature	22°C
	Precooler Design LMTD	38°C
	Precooler Tubing Material	carbon steel (STB410)

The GTHTR300 core consists of 90 annular fuel columns, 73 and 48 inner and outer removable reflector columns and 18 outer fixed reflector sectors as shown in Fig.3. Effective core is about 3.6 to

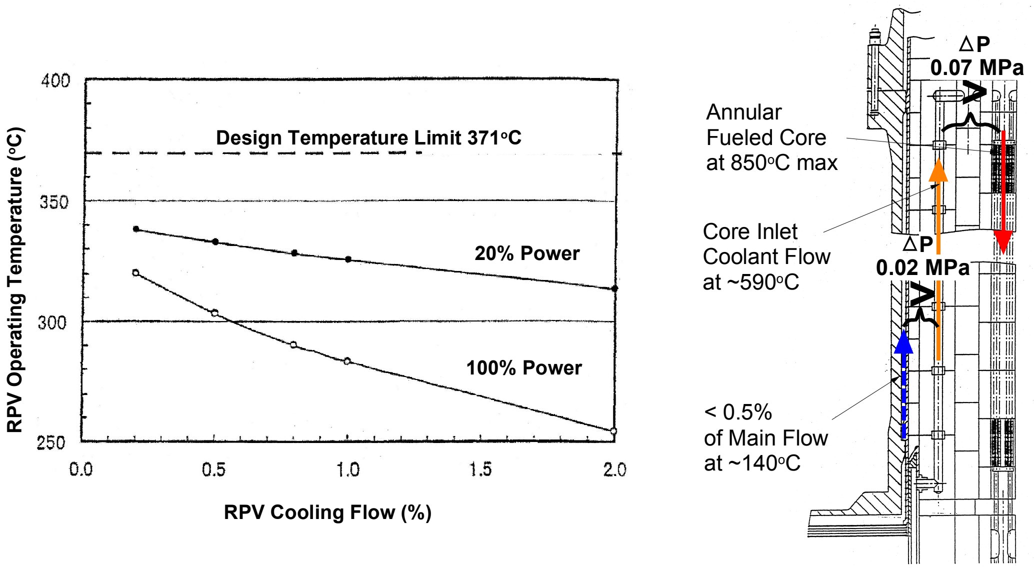


Fig. 2: Reactor Pressure Vessel Cooling Method

5.5m in inner to outer diameter and 8m in height. The fuel column is stacked in 8 axial layers of fuel elements. The fuel element is a hexagonal graphite block with 57 fuel pins, 405mm across flat and 1000mm in height. The fuel pin is improved in an integral design to pass heat flux more efficient. The fuel pin is made up of stacks of fuel compacts with advanced enlarged coated fuel particles having a diameter of 550µm fuel kernel and a 140µm thick buffer layer for maintaining the integrity of the particles in high burnup conditions.

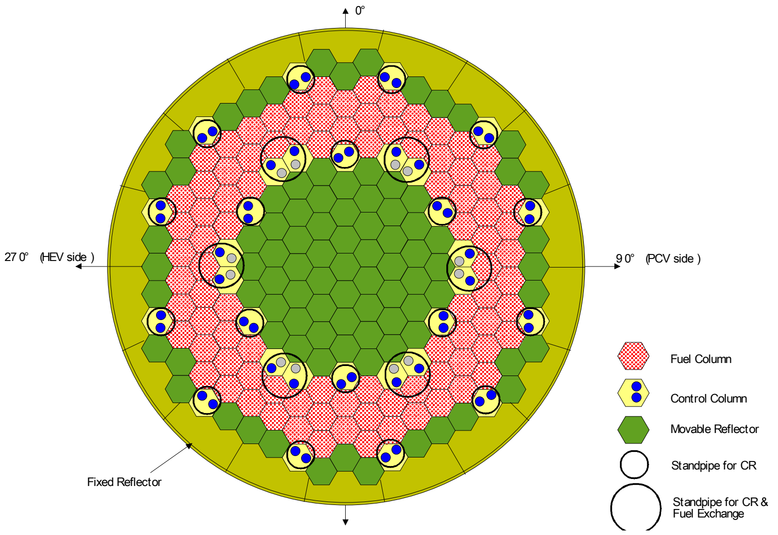


Fig. 3: Cross-Section of GTHTR300 Core

Another unique feature of GTHTR300 core is a two-batch axial fuel shifting scheme combined with strong recovery burnable poisons and some fully inserted power rods. Spent fuel is unloaded from alternate axial layers and the remaining fuel blocks are shifted downward while the new fuel is reloaded in the vacated layers, as illustrated in Fig.4.

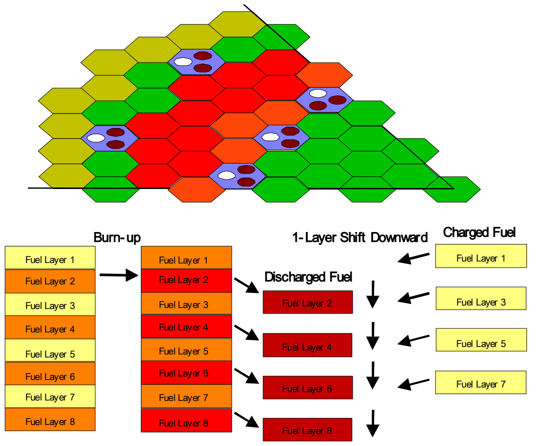


Fig. 4: Two-Batch Axially Shifted Refueling

The combined properties of the present core nuclear design result in a minimally peaked power profile at an enrichment of 14% only, as shown in Fig.5, and nearly uniform burnup in the core. Such favorable power distribution maintains peak fuel temperatures low in normal operations and keeps the maximum fuel temperature below the 1600°C limit in a loss of coolant accident. The latter is shown in Fig. 6 along with RPV and core barrel temperatures for a depressurized conduction cooldown event. The proposed new refueling scheme plus burnable poisons allows for 1460 days (4 years) of in-core fuel residence with two-batch refueling only and high 112GWd/t average burnup. In sum, the GTHTR300 reactor design is shown to not only retain the inherent and passive safety but also provide low fuel cycle cost and more than 90% plant availability.

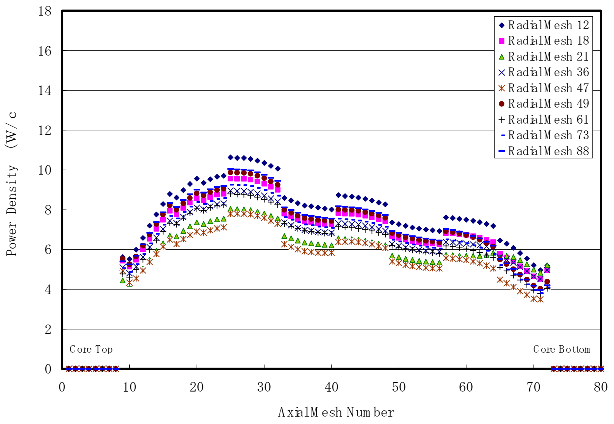


Fig. 5: Power Distribution 100 Days after Refueling

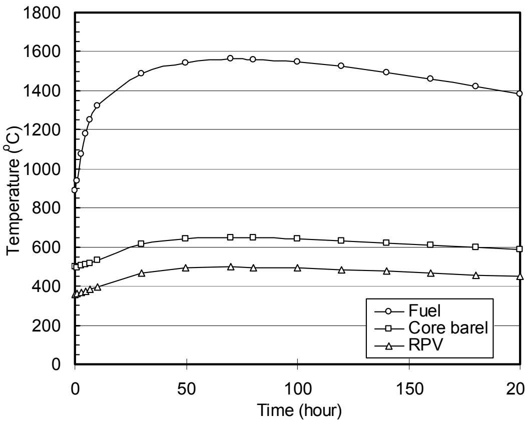


Fig. 6: Temperature Transient in Depressurized Conduction Cooldown

2.4 Power Conversion System Design

Gas Turbine Generator (GTG) Module

Design of the GTG module is shown in Fig. 7. The gas turbine is of axial-flow design consisting of a six-stage turbine and a twenty-stage compressor and drives a synchronous generator on the same shaft at 3,600 rpm. The gas turbine casings are interfaced by solid connections in the GTG module interior. A diaphragm coupling connects the gas turbine and generator shafts and effectively isolates vibration modes and alignment of the two rotor groups. Selection of horizontal rather than vertical rotor orientation simplifies bearing requirements and has the benefits of more conventional design and maintenance practice. With an exception of magnetic bearings, the mechanical design of the turbine and compressor is remarkably similar to that of conventional air breathing gas turbines in that it has similar number of axial stages, similar inlet and outlet geometries, similar rotor bearing span and arrangement, and similar shaft coupling. The aerodynamics of the turbine and compressor is designed based on the same principles and advanced blading features proven in the modern air gas turbines, resulting in high predicated aerodynamic efficiencies, low inlet and outlet losses and balanced axial shaft thrust. Pressurization in the helium-cooled generator cavity does not lead to performance degradation. Instead, the generator is designed to deliver the comparable level of efficiency seen in existing units. The main performance data of the gas turbine and generator were included in Table 2.

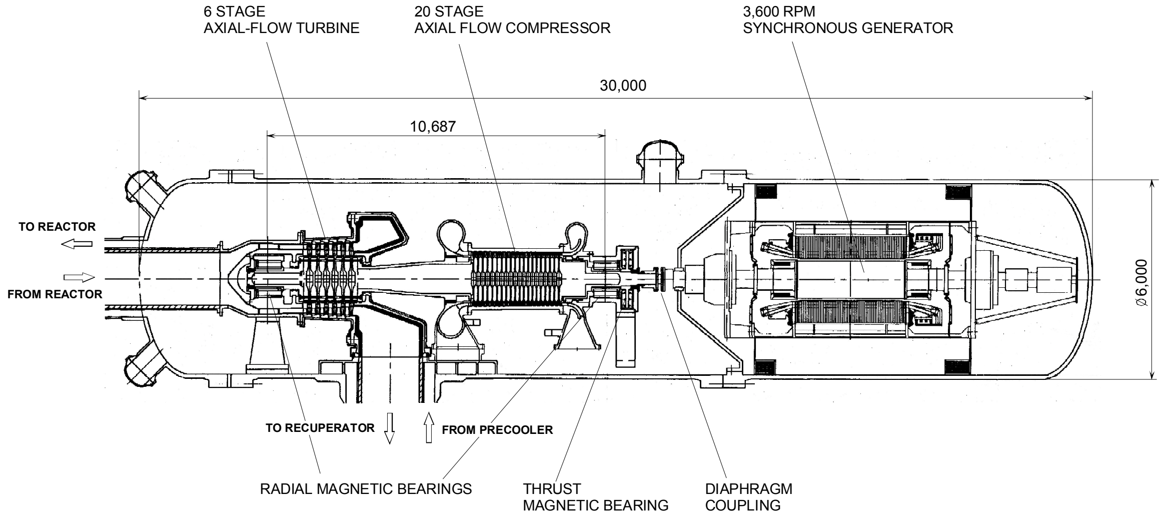


Fig. 7: Gas Turbine Generator Module of GTHTR300

Heat Exchangers (HTX) Module

The HTX module contains the recuperator and the precooler in a vertical steel pressure vessel. The recuperator is made up of six compact plate-fin heat exchanger modules that operate in parallel and are arranged in the upper annulus inside the pressure vessel. The precooler is a helically-coiled finned tube bundle with water circulating in the tubes and helium in the shell. The tube bundle is placed in the lower section of the pressure vessel. The major design data were given for the recuperator and precooler in Table 2. The essential technologies employed in the recuperator and precooler designs have already been developed in Japan.

Power Conversion System Maintenance

The plant system has been laid out with both modular construction and modular maintainability in mind. The latter is particularly critical for maintenance of the gas turbine because by regulations it requires frequently scheduled maintenance removal, more often than all other major power equipment, and because of radioactivity plateout in its metal surfaces. The steps taken in the modular maintenance on the gas turbine are illustrated in Fig. 8. First, a remote tool is inserted into the vessel interior through the opened hatches located on the vessel header and side wall to respectively disconnect the internal hot gas duct from the turbine intake transition piece and the shaft diaphragm coupling between the gas turbine and generator shafts. After the bolts on the vessel flanges (1A and 1B) and on the lower duct (2) are removed, the building overhead crane is used to lift the gas turbine vessel section as "cartridge" up to the ground maintenance floor. Sealed at both ends, the pressure vessel provides shielding and particle retention from interior radioactivity. No separate case is used and no immediate removal of the machinery from the vessel interior is performed. Instead, the removed gas turbine vessel cartridge is taken to maintenance facility where it is serviced over the time and after radioactive decay. A previously refurbished and fully aligned gas turbine vessel cartridge is immediately installed by the same steps in reversed order. The present maintenance method requires one spare gas turbine vessel cartridge per a four-reactor plant site.

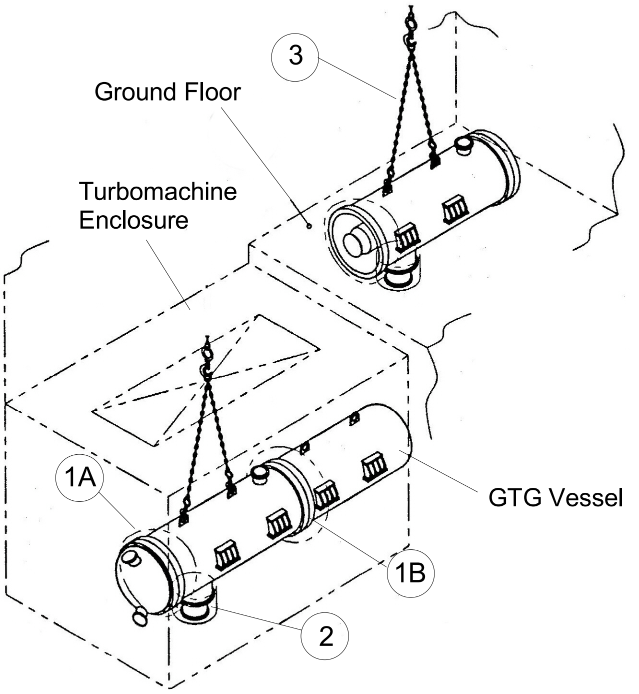


Fig. 8: Gas Turbine Vessel "Cartridge" Replacement

Maintenance removal of the generator is much less frequent and is performed following a removed gas turbine vessel section. The generator core, which is free of radioactivity, is pulled axially out of its own pressure vessel section towards the space vacated by the removed gas turbine vessel section. It is then lifted by building crane up to the ground maintenance floor where hands-on maintenance ensues immediately.

The recuperator modules are accessible and replaceable, if necessary, through the opened top closure of the HTX pressure vessel, following the self-explaining steps as shown in Fig. 9. The tubes in the precooler are serviced from outside of the vessel. The tubes forming individual circuits from inlet to outlet are accessed in the tubesheet inside the nozzles located outside of the vessel side wall to perform ISI on tubes or plugging of a damaged tube. The water in the tubes is completely drainable.

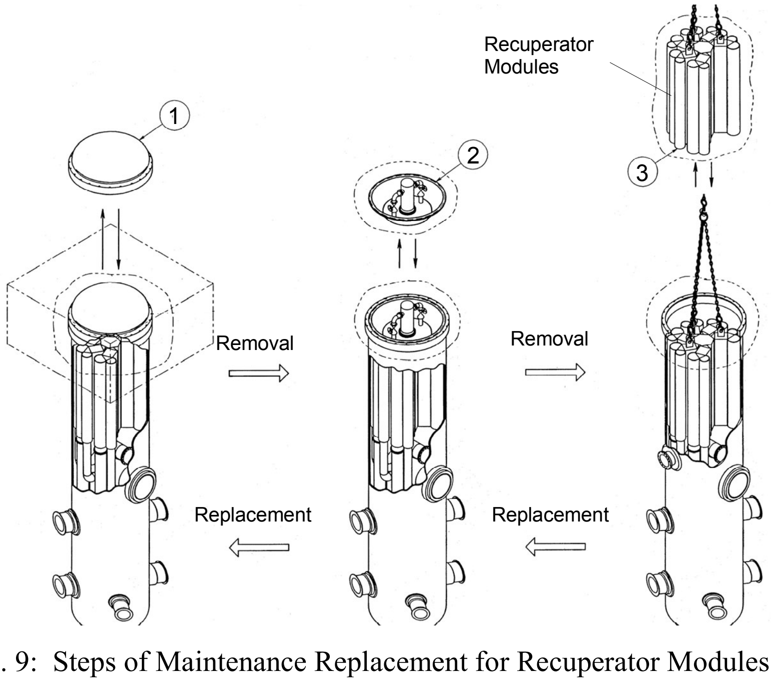


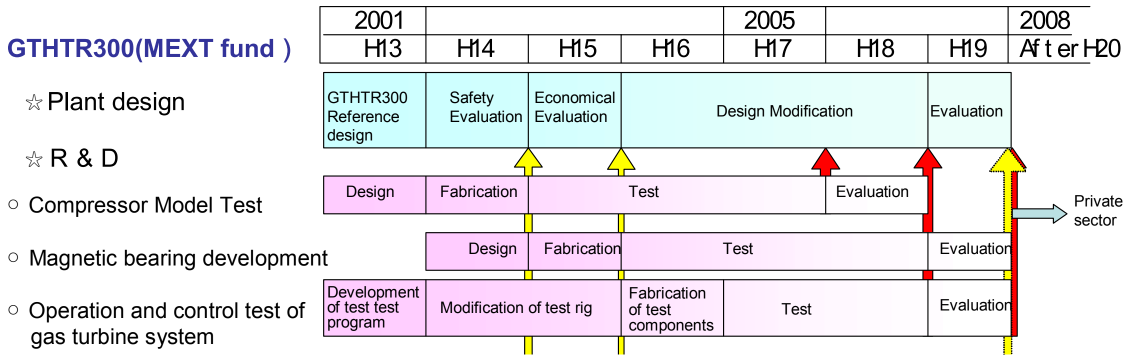
Fig. 9: Steps of Maintenance Replacement for Recuperator Modules

The maintenance replacement activities outlined above for the gas turbine and generator and for the heat exchangers can be amply accommodated within the 30-day period of reactor refueling, without adverse effect on plant availability.

3. R&D Activities

Research and development necessary to verify the GTHTR300 plant design includes performance confirmation test of helium compressor, development of magnetic bearing control algorithm, and control test on a small-scale closed cycle system. The R&D activities are conducted by JAERI in accordance with the plan outlined in Table 3. The compressor model test is intended to confirm the specific aerodynamic features of the compressor design for the full-scale GTHTR300. The key issues are concerned with predicated compressor surge margin, aerodynamic losses near the end wall in the blade flow path as well as inlet and outlet performance. The magnetic bearing development is focused on evaluation of control algorithms through 1/3 scale rotordynamic model testing. Lastly, the small-scale (~10MWt) closed cycle helium turbine system will be built to test the proposed control and protection schemes. The results from the R&D activities will be incorporated in GTHTR300 detailed design which begins in 2002.

Table 3: Design and R&D Schedule for GTHTR300



4. Conclusions

GTHTR300 reference design was concluded in fiscal year 2001 and the detailed design comprising safety and economical evaluation and necessary design upgrading by R&D has begun in the current year. The R&D needs to complete validation of the design have been identified and the systematic development activities have been planned and are being executed accordingly. It is through this effort that we hope GTHTR300 as a safe and economical prime mover will respond to the demand for new nuclear power generation in Japan in 2010s.

Acknowledgement

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