JAEA'S VHTR FOR HYDROGEN AND ELECTRICITY COGENERATION : GTHTR300C

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Design study on the Gas Turbine High Temperature Reactor 300-Cogeneration (GTHTR300C) aiming at producing both electricity by a gas turbine and hydrogen by a thermochemical water splitting method (IS process method) has been conducted. It is expected to be one of the most attractive systems to provide hydrogen for fuel cell vehicles after 2030. The GTHTR300C employs a block type Very High Temperature Reactor (VHTR) with thermal power of 600MW and outlet coolant temperature of 950°C. The intermediate heat exchanger (IHX) and the gas turbine are arranged in series in the primary circuit. The IHX transfers the heat of 170MW to the secondary system used for hydrogen production. The balance of the reactor thermal power is used for electricity generation. The GTHTR300C is designed based on the existing technologies of the High Temperature Engineering Test Reactor (HTTR) and helium turbine power conversion and on the technologies whose development have been well under way for IS hydrogen production process so as to minimize cost and risk of deployment.

This paper describes the original design features focusing on the plant layout and plant cycle of the GTHTR300C together with present development status of the GTHTR300, IHX, etc. Also, the advantage of the GTHTR300C is presented.

KEYWORDS : VHTR, HTGR, HTTR, Hydrogen Production, IS process, Intermediate Heat Exchanger, Gas Turbine

1. INTRODUCTION

JAEA has accumulated a significant technology basis for the VHTR through several long term research and development programs. The construction and successful operations of the HTTR, which is a Japan's first HTGR with its thermal power of 30MW and outlet temperature of 950°C, were conducted to accumulate various operational data for the VHTR [1]. On the other hand, a development program for a highly efficient electric power generation system by the helium gas turbine with the VHTR was conducted in JAEA [2]. The program included the basic design of the GTHTR 300 and R&D for key technologies of the gas turbine system. In parallel, a research program for hydrogen production by the IS process method had also been conducted [3]. The IS process method with the VHTR offers an ultimate clean hydrogen production system without CO_2 emission and is highly expected to be a future energy system after 2030.

On the basis of the reactor and application technologies obtained in the above mentioned programs, the GTHTR 300C has recently been designed to provide a clean and economical source of hydrogen fuel and electricity while protecting the environment from global warming and so on. The GTHTR300C generates electricity by a gas turbine system similar to that of the GTHTR300 and produces hydrogen by the IS process method. It has the production capability to meet the anticipated domestic demand for electricity and hydrogen after 2030. The 46% efficiency of electric generation is competitive to existing and future electric generation systems. The hydrogen production is rated at 1.9 ton/hour at 45.5% efficiency.

An important design objective for the GTHTR300C is use of the technologies already accumulated in JAEA so that any new major technology development is limited and the investment risk is minimized. It is an equally important goal that the system be technically feasible and economically attractive as a new energy source after 2030.

2. DEPLOYMENT OF GTHTR300C

The GTHTR300C was designed in compliance with the same design philosophy of the GTHTR300, SECO (Simplicity, Economical Competitiveness and Originality). Greatly simplified design was adopted to avoid plant complexity and to minimize any significant technical development. Also, this system is made economically competitive to other systems. The existing technologies developed for the HTTR and those presently under development for the GTHTR300 and the IS process method for hydrogen production are applied. Most of the applied technologies have Japanese originality. The following describes the present status for each development.

2.1 GTHTR300 Development [2]

Figure 1 shows the conceptual view of the GTHTR 300, and Table 1 compares the major specifications of the GTHTR300 and GTHTR300C. The baseline design for the GTHTR300 employs a helium-cooled, graphite-moderated, prismatic core HTGR with 850°C outlet helium gas temperature and 600MW thermal power. The outlet temperature was determined as a trade-off of thermal efficiency and system complexity. For example, turbine blade cooling is not necessary in the case of outlet temperature of 850°C. Avoidance of sophisticated blade forced cooling greatly reduces risk of turbine malfunction and increases reliability, which is judged more important than having efficiency maximized during commercial launch. As seen in Table 1, the growth system for the GTHTR300 aims at 950°C with use of blade cooling or higher temperature

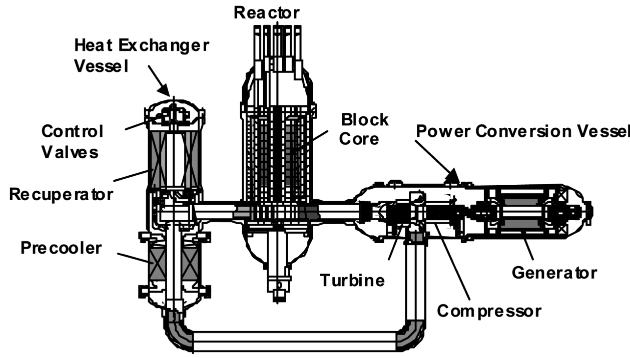

Fig. 1. Conceptual Views of GTHTR300

Table 1. Comparison of the Major Specification of the GTHTR300 and GTHTR300C

	GTHTR300 power plant	GTHTR300C H_2 cogeneration plant	GTHTR300C with higher H_2 production capacity
Reactor thermal power	600 MWt/module	600 MWt/module	600 MWt/module
IS process heat rate	-	170MWt/module	371MWt/module
Reactor pressure vessel	SA533(Mn-Mo) steel	SA533(Mn-Mo) steel	SA533(Mn-Mo) steel
Reactor core coolant	Helium gas	Helium gas	Helium gas
Core coolant flow	439/403 kg/s	322 kg/s	322 kg/s
Core inlet temperature	587/663°C	594°C	594°C
Core outlet temperature	850/950°C	950°C	950°C
Core coolant pressure	6.9MPa	5.1MPa	5.1MPa
Core power density	5.4W/cc	5.4W/cc	5.4W/cc
Average fuel burnup	120GWd/ton	120GWd/ton	120GWd/ton
Refueling interval	24/18 months	18 months	18 months
GT conversion cycle	non-intercooled direct Brayton cycle	non-intercooled direct Brayton cycle	non-intercooled direct Brayton cycle
GT cycle pressure ratio	2.0	2.0	1.47
Power conversion efficiency	45/50%	47%	38%
Electricity production	274/300 MWe	202 MWe	87 MWe
H_2 conversion process	-	thermochemical (e.g. S/I) or hybrid (thermal-electro)	thermochemical (e.g. S/I) or hybrid (thermal-electro)
H_2 conversion efficiency	-	45~55%	45~55%
H_2 production	-	1.9~2.4 ton/hr (21,000~27,000 Nm^3/hr)	4.1~5.2ton/hr (46,000~58,000 Nm^3/hr)
Total plant efficiency (net)	45~50%	46~49%	42~49%

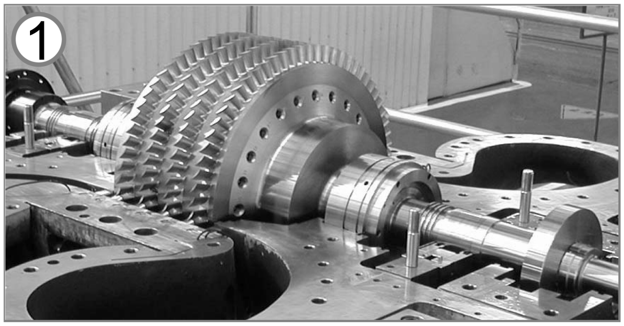

Fig. 2. Cross Section of 1/3 Scale Helium Gas Compressor

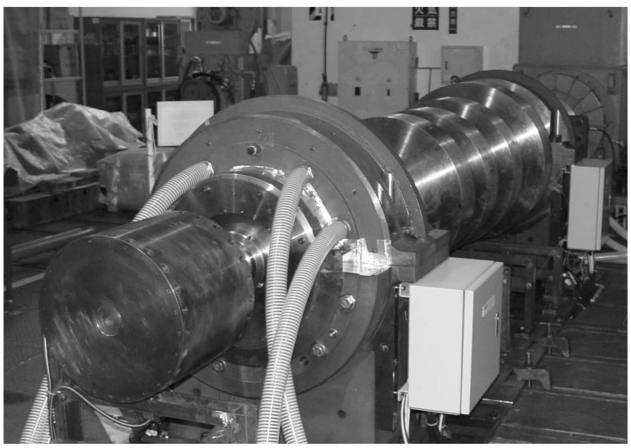

Fig. 3. Rotor of 1/3 Scale Magnetic Bearing Test

blade material. Thermal power of 600MW was determined in order to limit fuel temperature below 1600°C even in the worst accident that no forced cooling is expected. The gas turbine unit is horizontally located in the rector building, and the heat exchanger unit and the gas turbine unit are separately installed in the Power Conversion Vessel (PCV) and Heat Exchanger Vessel (HEX) respectively. Due to the unique system arrangement, maintenance is made easy because the gas turbine and heat exchangers may be simultaneously serviced without interference.

The reactor core design is based on that of the HTTR so as to reduce R&D needs for the new system. The pin-in-block type fuel blocks are stacked annularly in the core. Accordingly, fuel design and fabrication technology are almost the same as that of the HTTR except that the buffer thickness between the coating layers is now increased to improve retaining capacity of fission products in higher burnup necessary commercial fuel cycles.

The basic design phase including safety evaluation and economical assessment finished at end of FY-2003. During this design phase from FY 2001 through FT-2003, Check & Review (C&R) by a special board consisting of members from utilities, universities, industries and the other national research laboratories had been organized every six months so that the design can meet the requirement from private sectors. The final basic design reflected technical suggestions from this committee.

In addition to the basic design, the development of the compressor and magnetic bearing for the gas turbine system was carried out. The development aims to address the uncertainties remaining still in these key components, namely aerodynamics in the compressor and control performance of the magnetic bearing. In the compressor development, 1/3 scale compressor with four stages was fabricated and tested. In the magnetic bearing development, 1/3 scale rotor with simulated weights of turbocompressor and generator was manufactured and tested.

Figure 2 shows a model test compressor consisting of four axial stages in one third dimensional scale of the full size compressor stages. The test compressor was modeled after the aerodynamic features, including alternative sets of airfoils, under design consideration for the GTHTR300 turbine compressor. It was put in a dedicated helium loop for aerodynamic development testing. The data obtained in test are concerned with aerodynamic losses particularly near end walls and growth through multiple rotating blade rows, surge predictability, clearance loss and inlet and outlet performance effects, all to be correlated closely to the full-scale design conditions.

The multi-year compressor development and test program has just been concluded. The program has achieved the intended goals of exploring basic helium compressor aerodynamics, relative to those of air compressors, and establishing the analytical tools qualified to design and evaluate the full scale compressor. With the qualified tools, the full scale compressor is predicated to over-achieve the design target of 90.5% flange-to-flange polytropic efficiency at design flow and surge margin. The level of performance matches those found in modern air gas turbine compressors. The helium compressor aerodynamics has well been advanced to proceed to prototype demonstration.

A magnetic bearing development and test program is focused on evaluating optimal rotor-bearing clearance control method and developing magnetic bearing control algorithm to operate rotor above the 2^{nd} bending critical speed. A test rig has been constructed, and the commissioning test was completed. As shown in Figure 3, the test rig is a one-third scale mockup for the generator rotor of the GTHTR300 and has further built-in capability to test the multi-span and multi-bearing rotor configuration modeled after the GTHTR300 turbine-generator rotor drive train. Existing and new analytical techniques of rotordynamics and control were calibrated.

2.2 IS Process Method Development [3]

The IS process method has been studied since 1970s and General Atomics (GA) performed the most intensive work. In Europe and in Japan, several variations of the process have been studied which differed in the mode of reaction and methods to separate reaction products. Efforts on the process chemistry have been concentrated on how to separate the hydrogen iodide and sulfuric acid produced in the Bunsen reaction and on how to carry out the hydrogen iodide processing to produce hydrogen. Flowsheeting studies have been carried out and it was reported that thermal efficiency in the range of 40-50% might be possible when utilizing intensive and efficient heat recovery networks [4-6].

Researchers at JAEA have been working to demonstrate the continuous hydrogen production using an IS process variant featuring the liquid-liquid phase separation. Stable and continuous hydrogen evolution was successfully carried out with the rate of 1 liter hydrogen (STP) per hour by an integrated operation of the basic reactions and products separations using a glass-made apparatus [7].

Based on the know-how accumulated in the experiments, a scaled-up glass apparatus was constructed with nominal hydrogen production rate of 50 liter per hour. Its basic flowsheet is the same with the former one, except that it is equipped with newly devised pumps and sensors for monitoring process parameters such as flow rates and liquid levels. These modifications enable the continuous hydrogen production test under efficient process conditions.

In parallel with the hydrogen production test, selection of materials of construction for large-scale plant is another important issue of the process development, because very corrosive chemicals such as iodine and sulfuric acid shall be handled. Corrosion tests have been carried out in the typical process environments using commercially available materials.

Based on the results of above mentioned R&D, JAEA is planning to proceed to the bench-scale study that includes following subjects: (1) development of the components such as reactors, separators, pumps and piping, which are made of selected materials of construction, to be used in the design and fabrication of a pilot plant, (2) study on chemistry and technology required for the plant operation under high pressurized conditions, (3) development of the simulation codes and acquisition of supplemental physico-chemical data required for the process simulation.

2.3 IHX Development

The IHX for the HTTR is rated at 10MW and is a helically coiled He/He type in which the primary coolant flow passes the shell-side and secondary flow inside the tubes. Figure 4 shows the HTTR-IHX. JAEA had developed a Ni-base super alloy Hastelloy XR as the heat transfer tube and a tube bundle material. Besides the material development, JAEA developed a welding method between

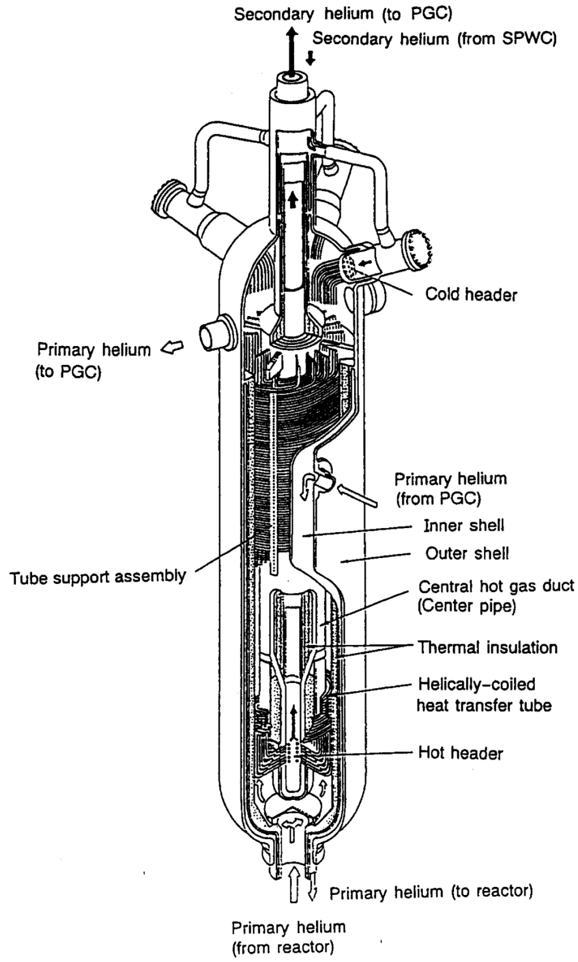

Fig. 4. Schematic View of the HTTR-IHX

Hatelloy XR and low alloy steel, high temperature resistance structures absorbing thermal expansion difference between high and low temperature helium gas, insulation structure, etc. Furthermore, JAEA proposed a structural standard and evaluation method for the high temperature structures consisting of Hastelloy XR[8]. So far, the structural integrity and thermal performance in 850°C condition and 950°C operations was confirmed in the steady states operation of the HTTR.

3. DESIGN DESCRIPTION OF GTHTR300C

3.1 Plant Layout and GT Design

Figure 5 shows the system layout of the GTHTR300C. The helically coiled He/He IHX is installed between the RPV and the gas turbine system. Even though the thermal

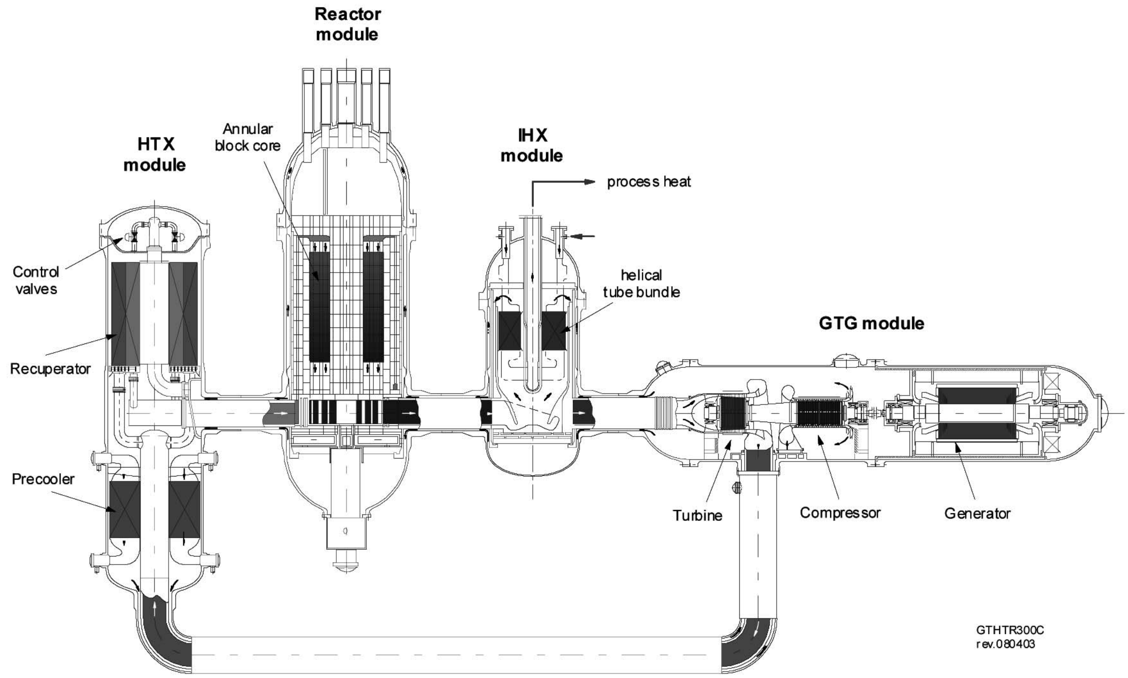

Fig. 5. System Layout of the GTHTR300C

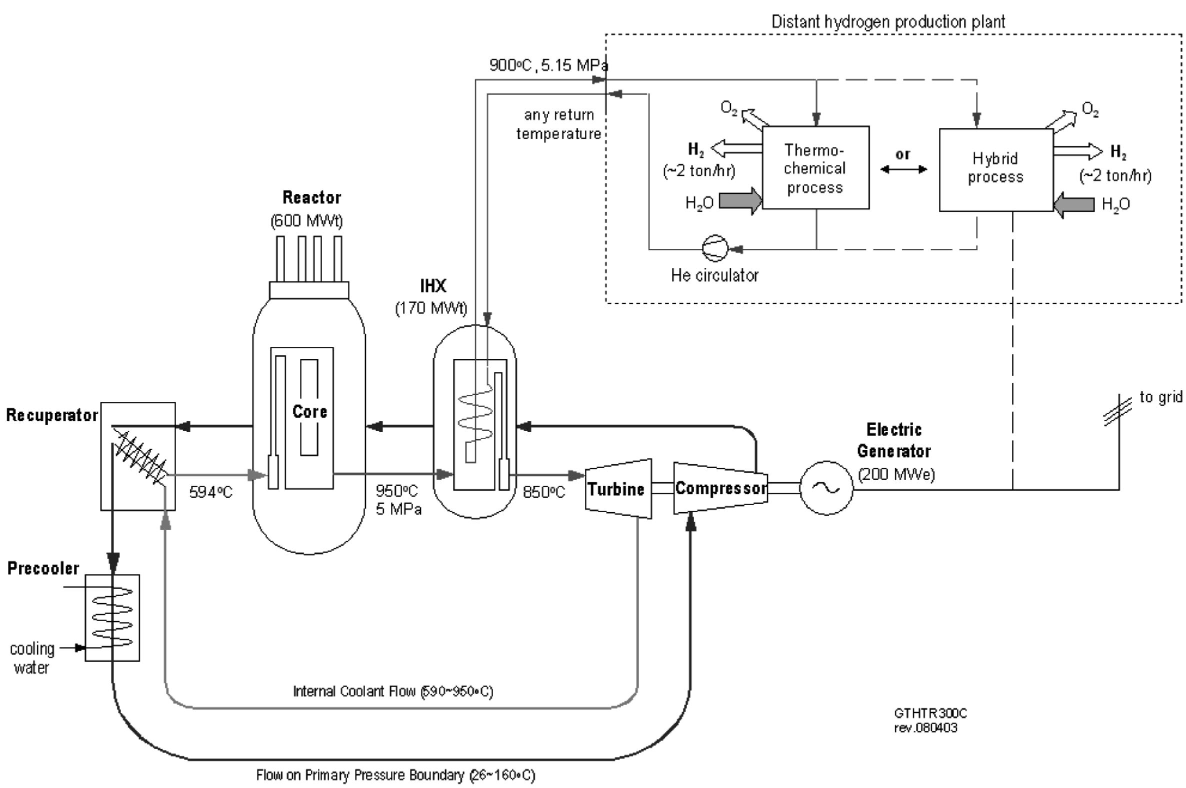

Fig. 6. Cycle Process Scheme of the GTHTR300C

capacity for the gas turbine system decreases to 430MW from 600MW for the GTHTR300, no major design change of the primary components was made except the addition of the IHX. A comparison of major design specifications between GTHTR300 and GTHTR300C was shown earlier in Table 1.

Figure 6 shows the cycle process scheme of the GTHTR 300C. The reactor power is 600MWth and its outlet coolant gas temperature is 950°C. Of the total reactor thermal power, about 170MWth is used for the process heat and the balance for the gas turbine system. The reactor heat is transferred via the IHX to a secondary helium loop and then through a compact heat exchanger to the third loop of hydrogen production system. The reactor outlet helium gas of 950°C enters the shell side of the IHX and exits it at 850°C. The helium gas of 850°C from the IHX drives the turbine and goes to the recuperator, precooler and compressor. The outlet helium gas of 135°C from the compressor is guided to cool the RPV to allow for the vessel made of the pressure vessel steel used in existing LWR. The plant generates approximately 200MWe of electricity.

Only IHX of a compact surface geometry, such as plate type, was previously thought to be economically viable for IHX. This would be correct if a small drop in temperature, say 50°C, were presumed across the IHX. In the case of the GTHTR300C, however, the LMTD (logarithmic mean temperature difference) of the IHX is about 150°C, made possible by the particular location of IHX installation where primary heat is transferred to secondary loop in a high, narrow temperature range of 950-850°C. Because LMTD is inversely proportional to surface area required, a compact IHX unit is obtained of helical tube-and-shell construction in the present system.

Since settling primary coolant pressure is no longer governed by desire to down-size a primary gas circulator, which is not needed in the GTHTR300C, the primary coolant pressure is lowered to about 5MPa from 7MPa of the power-only reactor for the following two design needs. The first is to reduce the total pressure difference imposed on heat exchangers between reactor and hydrogen loops so that the lifetime of the heat exchangers (IHX and process heat exchangers) can be greatly extended. The second need is to maintain design and performance of the gas turbine system similar to that of the GTHTR300. As a result, the gas turbine system is made common in both design and performance to both the GTHTR300 and GTHTR300C. Although the lower primary pressure increases specific cost of gas turbine equipment, the cost saving in heat exchangers and primary circulator in addition to the pressure vessels mitigates economic penalty to overall system.

Since power output is rated lower, the weight and length of the electric generator rotor is proportionally reduced from those of the GTHTR300 generator, making the rotor considerably stiffened and reducing the number of critical speeds in rotational speed range. The technical uncertainty for the magnetic bearing suspension of this system will be cleared once the ongoing magnetic bearing R&D for the GTHTR300 is to be completed. Also, no technical problem is foreseen for the compressor and turbine after completion of present compressor and turbine development for the GTHTR300.

3.2 Reactor Core Design

The maximum fuel temperature during the rated operation shall be lower than 1400°C to reduce fission product release from the fuel during the long-term operation. Because of fission product plate-out on the surface of the primary components, it is not easy to access to the gas turbine system for maintenance. In the GTHTR300, the maximum fuel temperature during the rated operation is about 1400°C and it occurs at the beginning of the operation [9]. In order to meet the requirement from utilities such as two-year continuous operation, the initial enrichment of the GTHTR300 is 14wt%. The control rod is inserted and the arrangement of burnable poisons is optimized to compensate the excess reactivity at the beginning of the core. That skews the reactor power profile and makes the power density peak as high as about 13-15W/m^3. In the GTHTR300C, the continuous operational period is reduced to 1.5 years. In addition to the change of the operational condition, the cooling performance of the fuel was enhanced by increasing the coolant flowrate around the fuel with the high peaking factor. Unlike the GTHTR300, some fuels different in uranium enrichment are used to lower the power density peak. The combination of requirement and design change keeps the maximum fuel temperature in the GTHTR 300C almost 1400°C despite the outlet temperature increases to 950°C. Therefore, the existing coated fuel particle made of SiC is available for the system.

3.3 IHX Structural Design

Table 2 makes a comparison of the major specifications between the HTTR-IHX and the GTHTR300C-IHX. Hastelloy XR is used for heat transfer tubes and tube bundles in both designs. The GTHTR300C-IHX is rated 170MWt and designed on the basis of the shell & tube type IHX adopted in the HTTR. Figure 7 shows the conceptual drawing of the GTHTR300C-IHX. Similar tube bundle structure is also used in the two designs so that the experience gained in design, fabrication, and operations of the HTTR-IHX is applicable to the GTHTR300C-IHX. As the conceptual design phase, while the size of heat exchanger tubes and the tube bundle was determined, the primary stress of the heat transfer tube and the tube bundle was evaluated. To meet the acceptable IHX design life, it is essential that the creep damage of the high temperature structures be kept as low as possible. The heat transfer tube is exposed to 950°C helium gas that makes the creep strength quite low. Unless the pressure between the primary and secondary helium gas is essentially balanced, the creep damage of

Table 2. Comparison of the Major Specifications Between HTTR-IHX and GTHTR300C-IHX

	Unit	HTTR IHX	GTHTR300C IHX
Design Type	-	He/He helical tube and shell	He/He helical tube and shell
Thermal Rating	MWt	10	170
LMTD	°C	113	154
Heat transfer area	m^2	244	1448
Shell side flow			
Flow rate	kg/s	3.4	324.2
Temperature (inlet/outlet)	°C	850 / 387(950 / 389)*	950 / 850
Inlet pressure	MPa	3.91	5.00
Tube side flow			
Flow rate	kg/s	3.0	80.3
Temperature (inlet/outlet)	°C	187 / 810(187 / 900)*	500 / 900
Inlet pressure	MPa	4.02	5.15
Tubing			
Type	-	Bare tube	Bare tube
Material	-	Hastelloy-XR	Hastelloy-XR
Tube size (O.D. × t)	mm	31.75 × 3.5	45.0 × 5.0
Tube effective length	mm	22	14
Tube bundle			
Bundle diameter (I.D. × O.D.)	m	0.84 / 1.31	1.84 / 4.57
Number of tubes	-	96	724
Number of coiled colums	-	6	22
Tube pitch (traverse/longitudinal)	mm	47 / 47	65 / 65
Pressure vessel			
Steel	-	$2^1/_4$Cr-1Mo	SA533(Mn-Mo)
Outer diameter	m	1.90	5.70

* High temperature test operation

the heat transfer tube due to the pressure load becomes high and quickly exceeds the limit of 1.0. In the GTHTR 300C-IHX, the pressure difference is kept lower than 0.015MPa by a differential pressure control system to limit the creep damage. The same pressure control system of the HTTR is used for the GTHTR300C. In the HTTR design experience, it was found that not only the pressure origin primary stress but also the own weight origin primary stress is significant for the creep damage. In the HTTR, a lifetime of 20 years was available due to the limitations of the creep damage and the primary stress. In the GTHTR 300C-IHX, the primary stress due to the pressure difference and the own weight is at a level comparable to that of the HTTR-IHX. Therefore, a lifetime of 20 years is assured for the GTHTR300C-IHX.

3.4 Safety Philosophy

The safety design philosophy of the GTHTR300C is generally as the same as that of the GTHTR300. The control rod system safely stops the reactor at any accident condition. The backup shut down system is used in the case that the control rod is assumed not to work. The reactor cavity cooling system installed around the Reactor Pressure Vessel removes the residual heat from the core after reactor shut-

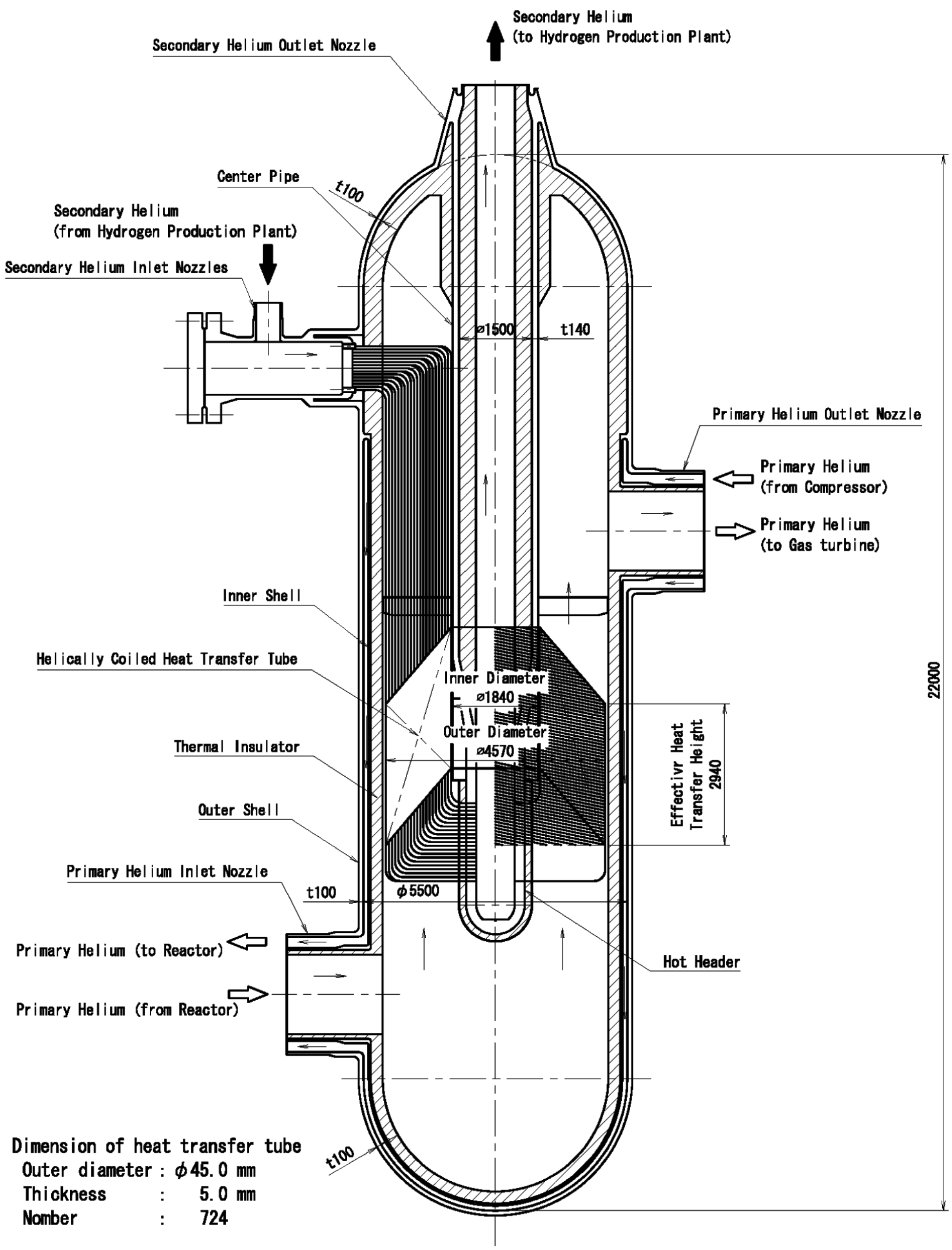

Fig. 7. Conceptual Drawing of GTHTR300C-IHX

down. Core direct cooling is not necessary in any accident condition thanks to the inherent safety characteristics of the HTGR such as the large thermal capacity of the core, the strong negative coefficient, etc. The reactor confinement system is enough to reduce the release of fission products in the depressurization accident triggered by a primary pipe rupture. The coated fuel particle can retain the fission product even if its temperature reaches to 1600°C in the depressurization accident.

The hydrogen production system utilizing the heat of the secondary helium of the IHX is designed and operated based on an existing non-nuclear industrial standard applied to a conventional chemical plant. In essence, the hydrogen production system is not expected as the reactor core cooling

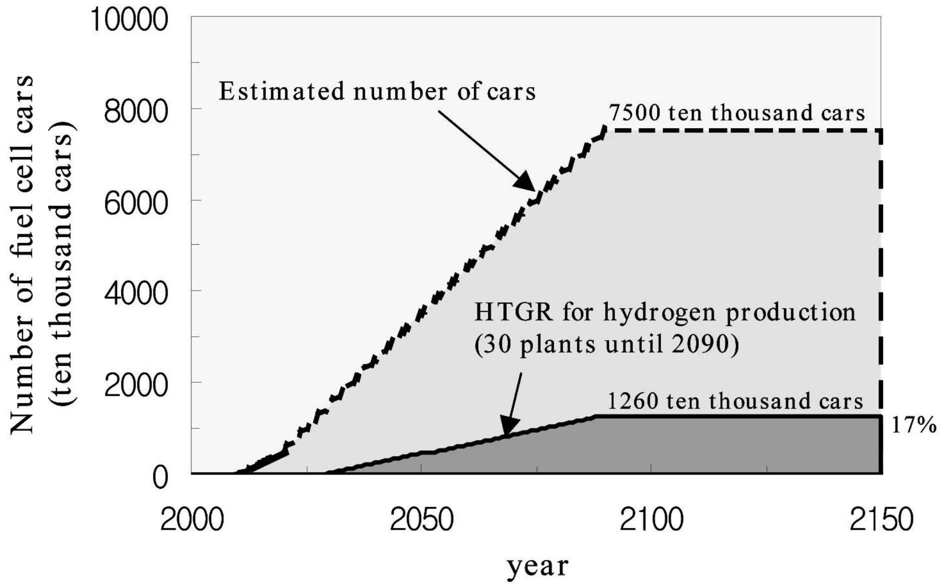

Fig. 8. The Estimate Number of Fuel Cell Vehicles
and the Number of the FCV for which GTHTR300C will Supply Hydrogen

system. In case of an abrupt thermal load change by the malfunction or the accident of the hydrogen production system, three control valves installed in the primary helium circuit mitigate the turbulence of inlet helium temperature of the gas turbine and keep the rotation speed of the generator constant. Even in these off-normal conditions, the reactor and the gas turbine system can operate stably.

When the secondary helium is depressurized by the malfunction in the hydrogen production system, the hydrogen production system is isolated from the IHX by the isolation valve. The helium pressure between the IHX and the isolation valve is recovered by the helium supply system to continue the power generation operation.

External events of hydrogen gas release or toxic gas release shall be considered in the safety design of the GTHTR300C. An adequate separation distance between the safety items in the nuclear plant and the hydrogen production system shall be taken. Some physical protections such as blast-proof wall and the filtering of intake air are effective to reduce the hazard.

3.5 Deployment

3.5.1 Hydrogen Supply for Fuel Cell Vehicle

Figure 8 shows the estimate number of the fuel cell vehicle (FCV) and the number of the FCV for which the GTHTR300C will provide hydrogen. The number of the FCV is expected to grow 15 million by 2030 and continue to increase until all gasoline driven automobiles will be replaced with the FCV. In this estimation, the total number of automobiles is assumed not to increase and to be kept about the current number of 75 millions, taking into account of the decrease of population in future.

In the deployment scenario, first 10 plants of the GTHTR300C will be constructed form 2030 to 2040 and next 20 plants of the GTHTR300C with higher hydrogen production capacity will be constructed at the ratio of 2 plants per 5 years from 2040 to 2090. Although the thermal power of the GTHTR300C is 600MW, the amount of the thermal power for the hydrogen production can be increased from 170MW to 370MW. After 2090, the total number of the GTHTR300C will be maintained 30. Fist ten units of the GTHTR300C with lower hydrogen production capacity will be gradually replaced with one with higher hydrogen production when they will reach to the plant life time. And, Mixed-Oxide (MOX) fuels made of plutonium produced in the LWR or the FBR will be used for the GTHTR300C after 2090, while the uranium fuel will be used for the first 30 units of the GTHTR300C before 2090.

The GTHTR300C can supply hydrogen for almost 195 thousand vehicles on the condition that its availability is 90%, and the thermal efficiency of hydrogen production is 50%. Hydrogen demand per vehicle is assumed to be 1100Nm^3/year [10]. Consequently, 30 plants of the GTHTR 300C with lower hydrogen production capacity can supply hydrogen for almost 5.9 million vehicles which is almost 8% of 75 million vehicles. The GTHTR300C with higher hydrogen production capacity can supply hydrogen for almost 420 thousand vehicles. Its 30 plants can supply hydrogen for almost 12.6 million vehicles which is almost 17% of 75 million.

3.5.2. Accumulated Demand of Natural Uranium

Figure 9 shows the accumulated demand of natural uranium in Japan. Line (a) indicates the accumulated demand from the Light Water Reactor (LWR) for electricity generation with the direct disposal of all spent fuels (once-through fuel cycle). Line (b) indicates the accumulated demand from the LWR for the electricity generation with plutonium thermal utilization (LWR recycling). Line (c) indicates the accumulated demand from the LWR and the Fast Breeder Reactor (LWR and FBR recycling). In this case, the current LWR is gradually replaced with the FBR after 2030. This plan was presented in a New Nuclear Policy-planning Council by Japan Atomic Energy Commission[11]. Line (d) indicates the accumulated demand from the GTHTR300C for hydrogen production in addition to the LWR and the FBR for electricity generation(VHTR, LWR and FBR recycling).

It is assumed that the electricity generation capacity by the nuclear power plant will increase to 58GWe until 2030 and keep 58GWe after 2030. In the LWR recycling, the multi-recycle of plutonium thermal utilization will be performed, in which spent Mixed-Oxide (MOX) fuels of the LWR will be mixed with spent uranium fuels. In the LWR and FBR recycling, all spent fuels will be reprocessed, spent MOX fuels will be also reprocessed and collected plutonium will be used in the FBR.

The accumulated demand of natural uranium increases in the LWR with the once-though cycle. In the LWR recycling, it increases at the lower rate. In the LWR and FBR recycling, it saturate at almost 830 thousand ton after 2100 and it is not necessary to import natural uranium from other countries. In the VHTR, LWR and FBR recycling, the accumulated demand of natural uranium increases to almost 890 thousand ton but it finally saturates. It is possible to operate 30 GTHTR300C with 600MWt of thermal power without increasing the demand of natural uranium.

4. ADVANTAGES OF GTHTR300C

4.1 Meeting the Goals of Hydrogen Economy

By combining power generation and substantial production of hydrogen in an efficient commercial cogeneration plant, the GTHTR300C will provide cost-competitive, CO_2 emission-free electricity for traditional energy consumption while meeting a significant new demand for hydrogen as transportation fuel.

4.2 Simplifying R&D

The system takes advantage of the technologies that are currently available or under present development in JAEA.

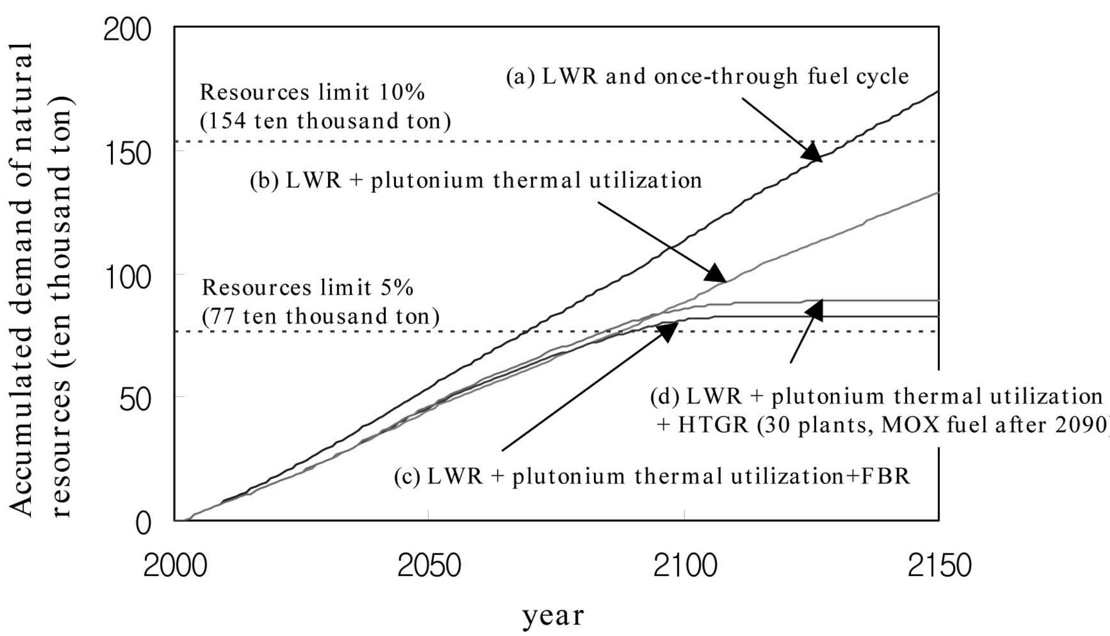

Fig. 9. Accumulated Demand of Natural Uranium in Japan

Helium gas turbine system

Advanced technologies for the helium gas compressor and gas turbine, magnetic bearing are the key to this system. The key technologies developed in this R&D program for the GTHTR300 are directly used for the GTHTR300C. The design advantage of the GTHTR300 gas turbine system such as the horizontal turbomachine layout, the conventional steel RPV, the highly efficient recuperator and so on are directly applicable to this system.

IHX

The same design philosophy of the IHX in the HTTR is applied to that in the GTHTR300C. Also, the same material, welding method, structure are used for the IHX. Design conditions of this system such as temperature, pressure difference between the primary and secondary helium gas are almost the same as those of the HTTR. For example, the pressure difference between the primary and secondary helium gas is controlled as low as 0.015MPa to keep the creep damage of the heat transfer tube as low as possible. Due to this design philosophy, no significant development is necessary for the GHTR300C-IHX in this system. Existing technologies are available.

However, the GTHTR300 with higher hydrogen production capacity needs technical developments of the IHX.

Reactor core

The reactor technology for this system is based on the technology developed for the HTTR. The pin-in block type prismatic core is used for the reactor core. An advanced coated fuel particle such as ZrC is not indispensable for this system. Accumulation of performance data for the high burnup fuel is necessary for the system.

Primary and secondary circulator

Large-scale helium gas circulators shall be placed in the primary circuit unless the gas turbine is installed. The maximum size of the helium gas circulator with a gas bearing is not applicable to the 600MWth reactor. It is in the current state of technology that the size of the HTTR circulator is near the maximum. In the HTTR, three main circulators are operated in parallel to provide the total core coolant circulation necessary. As the total flow rate of the 30 MW HTTR is 12.2 kg/s or 4.0 kg/s for each circulator, a sum of 80 gas circulators would have been needed for the total flow of a 600 MWth reactor or very large-size circulator with a magnetic bearing must be used. However, design manufacturing and operational experience for this type and size of circulator has never been obtained.

In the secondary circuit, a helium gas circulator with an oil or water bearings can be used because potential water or oil ingress into the secondary circuit does not damage the system significantly.

IS process

The hydrogen production system by the IS process method is installed in the third loop in the system. The malfunction of the hydrogen production system does not impair the continuous operation of the reactor to generate power.

5. R&D NEEDS FOR GTHTR300C

By sharing technologies of the HTTR and GTHTR300, additional development needs for the GTHTR300C are reduced to the following:

5.1 Compact Heat Exchanger in Secondary Loop

Development of a compact heat exchanger in the secondary circuit is necessary. The design requirement is relatively low and many design options are available based on future technology developments in a conventional system because it does not comprise the primary boundary. However, it still needs R&D for material development and performance demonstration.

5.2 System Performance Demonstration

The GTHTR300C, which is meant for commercial unit, shall demonstrate its ability to operate in normal cogeneration mode or with electric or hydrogen system operating alone in such a case as forced shutdown of either system. The results of the system performance analysis showed that the reactor could be continuously operated with the above variable load conditions. However, an actual demonstration test is warranted for performance confirmation.

6. CONCLUSIONS

The GTHTR300C incorporates a block type modular VHTR rated at 600MWth and 950°C outlet coolant temperature and employs a Brayton-cycle gas turbine for electricity generation and an IS process method for hydrogen production. The system can be deployed after 2030. It offers the following additional design advantages as a future VHTR cogeneration system:

- The system meets the future potential demand for hydrogen and electricity in Japan.
- The technologies developed for the HTTR and the GTHTR300, and to be developed for thermochemical IS process method are directly applicable to this system. Therefore, additional development is limited and commercial deployment can be pursued at low risk by entwining with advanced development of HTTR and GTHTR300.
- New development for a primary system large-capacity helium circulator or a primary system IHX is not necessary. This enables nearer term and lower cost of deployment for this system.

REFERENCES

[1] S. Fujikawa, H. Hayashi, T. Nakazawa, K. Kawasaki, T. Iyoku, S. Nakagawa and N. Sakaba, "Achievement of Reactor-Outlet Coolant Temperature of 950C in HTTR", Journal of Nuclear Science and Technology, Vol.41, No.12, p1245-1254, (2004).

[2] K. Kunitomi, S. Katanishi, S. Takada, T. Takizuka and X.

Yan, "Japan's future HTR-GTHTR300", Nuclear Engineering Design 233, p309-327, (2004).

[3] Shinji Kubo, Hayato Nakajima, Seiji Kasahara, Syunichi Higashi, Tomoo Masaki, Hiroyoshi Abe and Kaoru Onuki, "A demonstration study on a closed-cycle hydrogen production by the thermochemical water-splitting iodine–sulfur process", Nuclear Engineering Design 233, p347-354, (2004).

[4] J.H. Norman, G.E. Besenbruch, L.C. Brown, D.R. O'Keefe, C.L. Allen, Thermochemical water-splitting cycle, bench-scale investigations, and process engineering, *DOE/ET/26225-1*, *GA-A16713*, (1982).

[5] M. Roth and K.F. Knoche, *Int. J. Hydrogen Energy*, 14, p545-549, (1989).

[6] I.T. Oeztuerk, A. Hammache, E. Bilgen, *Trans. IChemE.*, 72 Part A, p241-250, (1989).

[7] H. Nakajima, M. Sakurai, K. Ikenoya, G.-J. Hwang, K. Onuki, S. Shimizu, A study on a closed-cycle hydrogen production by thermochemical water-splitting IS process, *Proc. 7th Int. Conf. Nuclear Engineering (ICONE-7)*, Tokyo, Japan, April 1999, ICONE-7104.

[8] K. Kunitomi, M. Shinozaki, M. Ohkubo, and et al., "Stress and strain evaluation of heat transfer tubes in intermediate heat exchanger for HTTR, Proc. of 2nd ASME/JAME Nuclear Engineering Conference, Vol.2, p847-853, (1993).

[9] K. Kunitomi, S. Katanishi, S. Takada and et al., "Reactor Core Design of Gas Turbine High Temperature Reactor 300", Nuclear Engineering Design, 230, p349-366, (2004).

[10] T. Takeda et al., Deployment Scenario of GTHTR300 Cogeneration System, Proceedings of GLOBAL 2005, Paper No.325, (2005)

[11] Japan Atomic Energy Commission, Document No. 13 in the 9th New Nuclear Policy-planning Council, Analysis of nuclear fuel cycle parameters (revised) http://aec.jst.go.jp/jicst/NC/tyoki/sakutei2004/sakutei09/siryo13.pdf, (2004).