GTHTR300 DESIGN VARIANTS FOR PRODUCTION OF ELECTRICITY, HYDROGEN OR BOTH

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Abstract

Japan Atomic Energy Agency has undertaken an extensive design study of gas turbine high temperature reactor, named the GTHTR300. A design philosophy of system simplicity, economical competitiveness, and originality has enabled the evolution of a family of GTHTR300 plant design variants with production ranging from electricity to hydrogen or both. The key elements of this design philosophy are sharing of common system technologies, incorporating original design simplification, and focused research and development in quest for a strong and practical plant economy.

Common to all design variants is a block reactor of top rated power 600 MWt with passive safety and highest coolant outlet temperature 950°C by existing fuel and material. The reactor is combined, when appropriate, with an iodine-sulfur thermochemical process for hydrogen production and with a mechanically and aerodynamically similar line of direct cycle helium gas turbines for electricity generation. The generated electricity supplies reactor and hydrogen plant operations in addition to grid output. In all design variants the gas turbine circulates reactor coolant directly, obviating need for a dedicated primary coolant circulator. Comprehensive research and development programs have been carried out for enabling technologies, with the aim of supporting commercial readiness around 2015.

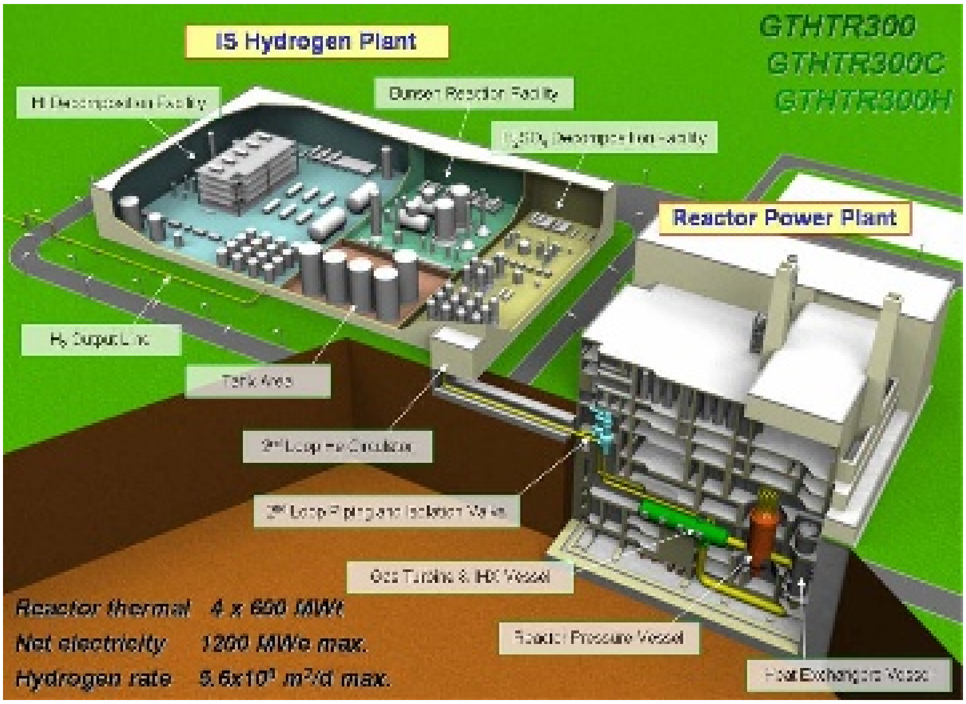
This paper discusses the family of GTHTR300 plant variants, their underlying system designs and associated research and development programs.

1. Introduction

JAEA has developed the HTTR, a 30 MWt engineering test HTGR [1]. Since the initial criticality achieved in 1998, the reactor has attained full power and 950°C coolant temperature operations and has been subject to other tests of reactor design validation and safety demonstration. Comprehensive experience and know-how in reactor design, construction, operation and maintenance have been acquired through the decades of HTTR development [2].

The JAEA design study of commercial-scale HTGR has progressed over a decade from a multi-year feasibility study to the proposal and basic design of the GTHTR3000 plant systems. Substantial contribution throughout the progress has been made by the domestic industries who also participated in the HTTR development. The feasibility study confirmed economical prospect and exposed major technical issues for follow-on design and development resolution. Accordingly, a conceptual design study was carried out that resulted in the original proposal for the first plant variant, the GTHTR300, a system shown as the part of reactor power plant in Figure 1 [3]. The plant combines a 600MWt block reactor and a direct cycle gas turbine for sole generation of electric power.

Figure 1. The GTHTR300 design variants enable electric power to be generated by gas turbine in the reactor power plant and nuclear heat to be delivered by IHX and piping to the IS hydrogen plant for thermochemical production of hydrogen.



The basic design for the GTHTR300 was initiated in 2001 and has since involved detailed design and engineering to the extent verifiable by tests of new components and systems of appropriate scale. The basic design carries preliminary safety analysis and economical evaluation. In 2003, the design evolved to add two more members including a growth system for enhanced electricity production, thus named the GTHTR300+ and a hydrogen cogeneration system, the GTHTR300C. In the latter system, an intermediate heat exchanger (IHX) is used to transfer a share of reactor thermal power to secondary helium which is delivered in piping as high temperature process heat to a distant IS (iodine-sulfur) hydrogen plant. The electricity need for hydrogen production is met in house from the efficient gas turbine power cogeneration. Thermochemical cracking of water molecules taking place in the IS process yields hydrogen gas product. Figure 1 shows the coupling arrangement of the IS hydrogen plant to the reactor gas turbine power plant. Added finally in this year is the GTHTR300H, a self-reliant hydrogen production system that uses a major share of reactor thermal power for process heat input with the balance used by gas turbine to circulate primary coolant while still co-generating the significant electricity needed by hydrogen production as well as by reactor operations.

The overall goal of the commercial plant design study is to provide a family of system options capable of producing competitive electricity, hydrogen or a mix of both and yet deployable in the near term. The development of the multiple systems simultaneously does not necessarily suggest to have investment and risk multiplied. Rather, the development requirement is minimised thanks to a design philosophy of system simplicity, economical competitiveness and originality, namely the SECO philosophy. There are three major elements to this design philosophy.

The first element is technology simplification. All design variants are built on the premise that they share common system technologies to maximum extent possible. As a result, the design variants share a unified reactor and primary coolant circuit, an aerodynamically and mechanically similar line of helium gas turbines used for electricity production, and the IS process selected to produce hydrogen. This paper shows that the helium gas turbine and the IS process are compatible application systems with the high temperature reactor heat source to enable economically competitive energy production.

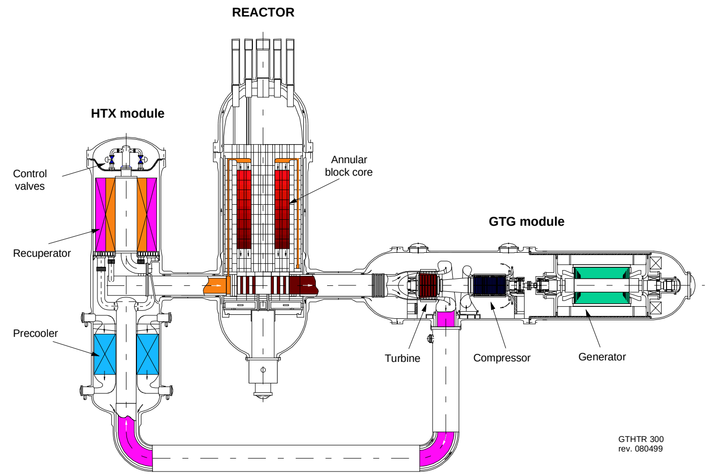
The second element of the SECO design philosophy has been incorporating unique design attributes that are less demanding on the system technologies required. The efforts in this area have resulted in such original design simplification as conventional steel reactor pressure vessel construction, horizontal gas turbine installation, system modular arrangement among others. Sections two and three of this paper discuss the technical design features of the GTHTR300 plant variants in greater detail.

The third element that has been made possible by constant pursuit of technology and design simplification is a focused technological development scope that comes with low risk and investment of overall development. Furthermore, since the technologies to be developed are shared by several systems, the benefit of investing in any one development is increased. On the site where the HTTR is constructed for acquiring the reactor technology, JAEA has also been carrying out research and development on the helium gas turbine and the IS process. Section four of this paper describes the underlying systems and associated research and development activities.

2. GTHTR300 & GTHTR300+: Design variants for electricity production

In addition to being one of the two electric power generation options, the GTHTR300 provides the baseline plant design upon whose reactor and system arrangement all other design variants, including those of hydrogen plants to be described in the next section, are based. As seen in Table 1, the reactor outlet coolant temperature is selected to be 850°C. While the selected temperature is modest comparing with the capability of the present fuel, it is intended to avoid turbine blade cooling with use of conventional blade materials.

Figure 2. Reactor system arrangement in GTHTR300 and GTHTR300+



The GTHTR300+ is a growth system that achieves growth in performance by advancing operational parameters with no change to be made in integrated system design. The reactor outlet temperature is raised to 950°C, matching the top coolant temperature of the HTTR. To retain similar reactor core physics design, fuel burnup period is shortened by half a year from that of the baseline design. Because of the higher reactor outlet temperature the turbine blade is now cooled by compressor bleed cold helium. The blade cooling need may be minimised by adopting advanced heat resistant alloys developed for advanced combustion gas turbines with trace of activating elements removed to suit nuclear service. The growth system also relies on reasonable advancement to be made in gas turbine aerodynamic efficiencies and recuperator effectiveness as indicated in Table 1.

Table 1. GTHTR300 and GTHTR300+ design parameters

	GTHTR300 –– baseline design ––	**GTHTR300+** –– growth system ––
Reactor thermal power	4 x 600 MWt	4 x 600 MWt
Net electric generation	1096 MWe	1200 MWe
Net generating efficiency	45.6%	50%
Plant capacity factor	>90%	90%
Reactor type	graphite moderated, helium-cooled, prismatic block fuel	graphite moderated, helium-cooled, prismatic block fuel
Reactor pressure vessel	SA533 (Mn-Mo) steel	SA533 (Mn-Mo) steel
Core inlet temperature	587 °C	663 °C
Core outlet temperature	850 °C	950 °C
Coolant inlet pressure	6.92 MPa	6.42 MPa
Coolant flow	439 kg/s	401 kg/s
Core power density	5.4 W/cc	5.4 W/cc
Average fuel burnup	120 GWd/ton	120 GWd/ton
Refueling interval	24 months	18 (24) months
Gas turbine cycle type	recuperated, non-intercooled, direct Brayton cycle	recuperated, non-intercooled, direct Brayton cycle
Gas turbine pressure ratio	2.0	2.0
Gas turbine inlet temperature	850 °C	950 °C
Turbine polytropic efficiency	92.8%	93.8%
Compressor polytropic efficiency	90.5%	91.5%
Recuperator effectiveness	95%	96%

As shown in Figure 2, the reactor system is made up of three modular pressure vessel units containing the reactor core assembly, the gas turbine generator, and the heat exchangers, respectively. The units are housed in separate buildings in construction. Partitioning the primary system into properly sized modules and arranging them separately facilitate cost-effective shop construction and parallel site construction. These functionally-oriented modular units are independently accessible in maintenance. The GTHTR300 and GTHTR300+ are characteristic of following design features:

- Fully passive reactor safety.
- High fuel burnup based upon the HTTR type fuel.
- Conventional steel reactor pressure vessel construction.
- Non-intercooled, direct Brayton cycle power conversion.
- Horizontal, single-shaft gas turbine and direct drive of synchronous electric generator.
- Odular system arrangement.

Figure 3 shows a schematic of the direct Brayton cycle employed. Cycle intercooling is ruled out, even though it yields two-percentage points higher efficiency, because the added complexities and costs in construction and operations offset the marginal efficiency gain, resulting in no net benefit in cost of electricity [4]. On the other hand, cycle recuperation, that recovers significant turbine exhaust heat, offers substantial efficiency gain and thus a compelling economical case for design choice. A 95-96% effective recuperator is feasible by employing compact plate heat exchangers operating in high pressure benign helium gas streams.

Figure 3. Recuperative direct Brayton cycle

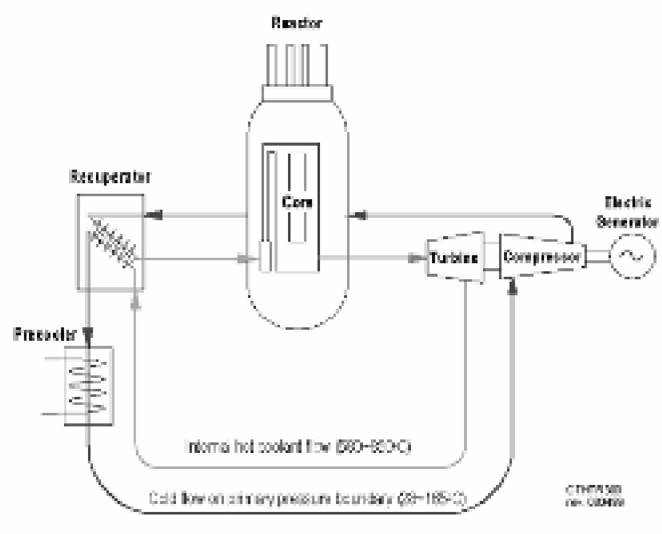
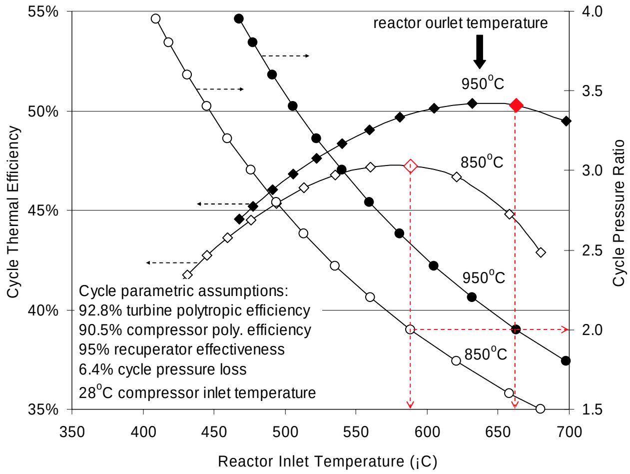


Figure 4 helps explain methodical selection of several other important cycle parameters. As stated earlier, the reactor outlet coolant temperature is set to 850°C for the GTHTR300 cycle and increased to 950°C in the GTHTR300+ cycle due in part to whether the turbine blade cooling is warranted. For each of these given core outlet temperatures, core inlet coolant temperature has been selected as appropriate for arriving at peak cycle thermal efficiency. As seen, the core inlet temperature is 587°C for the 850°C core outlet temperature cycle and 663°C for the 950°C cycle. The resulting relatively high core inlet temperatures in both cycles offer design benefit important to reactor core, which is a topic of more detailed discussion in Section 4 of this paper.

Figure 4. Brayton cycle characteristics



The gas turbine cycle pressure ratio corresponding to peak thermal efficiency remains nearly identical at around 2.0 for both the 850°C and 950°C core outlet temperature cycles. This is the basis for the baseline and growth cycles to employ a similar line of gas turbines, which is another topic to be discussed later in Section 4.

A commercial plant will consist of four reactor primary system units (4 x 600 MWt) operating in parallel, each of which is housed in its own underground confinement structure, but shares most other operations and maintenance facilities and functions. The power plant rating is 1 096-1 200 MWe busbar output at a net efficiency of 45-50%. The estimated cost of electricity is less than 3.5¢/kWh, about 30% below the cost of existing LWRs in Japan.

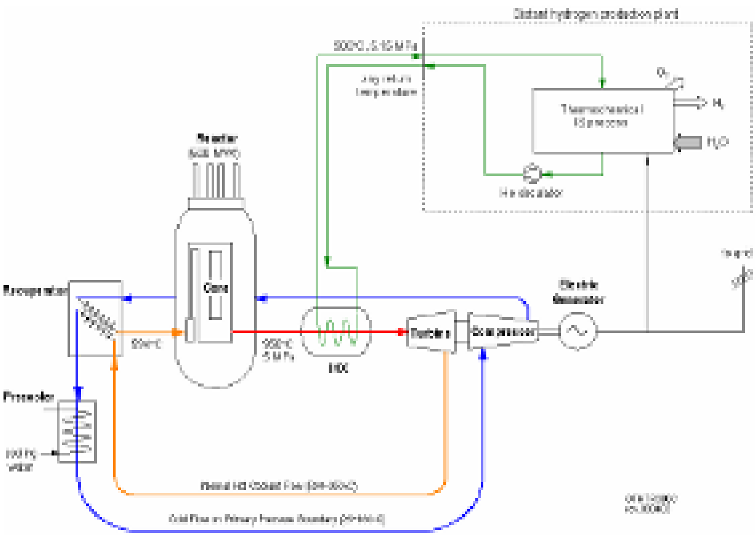
3. GTHTR300C & GTHTR300H: Design variants for hydrogen production

The two design variants, GTHTR300C and GTHTR300H, add variable hydrogen production capability in the GTHTR300 plant family. Like the power plant design variants, the hydrogen production plants are based on identical integrated system design and the variable hydrogen production is met by adjusting operating parameters only. The GTHTR300C produces hydrogen using effectively one-third of reactor thermal power with the balance of the reactor power going to electric power production. The GTHTR300H is designed to be a self-reliant hydrogen production system. Not only it yields massive hydrogen production using effectively 85% of reactor thermal power but also it has the ability to co-generate the significant electric power needed to support hydrogen production and reactor operations. In all GTHTR300 plant variants, the direct cycle gas turbine circulates reactor coolant directly, thereby obviating development need for a dedicated coolant circulation system.

The cogeneration cycle shown in Figure 5 evolves from the power-only production cycle, shown previously in Figure 3, by adding an intermediate heat exchanger (IHX) in serial between reactor and gas turbine. The particular serial arrangement makes the logarithmic mean temperature difference as large as 150°C between the primary and secondary fluids, creating a design condition for compact IHX. A secondary loop circulates hot helium from IHX to the distant hydrogen plant and completes necessary environmental separation between the nuclear facility from the chemical plant [5].

In GTHTR300C a nominal 170 MWt of the total 600 MWt per reactor thermal power, is extracted through the IHX as process heat input to the hydrogen process and the balance of reactor thermal power is used for gas turbine electric power generation. The reactor outlet helium gas of 950°C enters the shell side of the IHX and heats the tube-side secondary helium to 900°C. The helium gas of 850°C exiting the shell side of the IHX enters the gas turbine power conversion cycle. A gross of 202MWe electricity is generated at an estimated 46.8% efficiency. About 12% of the electricity generated is used in hydrogen plant operations to power electrolyzers, circulators, pumps and other utilities. Combining the process heat and the thermal equivalence of electricity gives a 219 MWt effective thermal input to hydrogen production.

Figure 5. Electricity and hydrogen cogeneration cycle of GTHTR300C and GTHTR300H



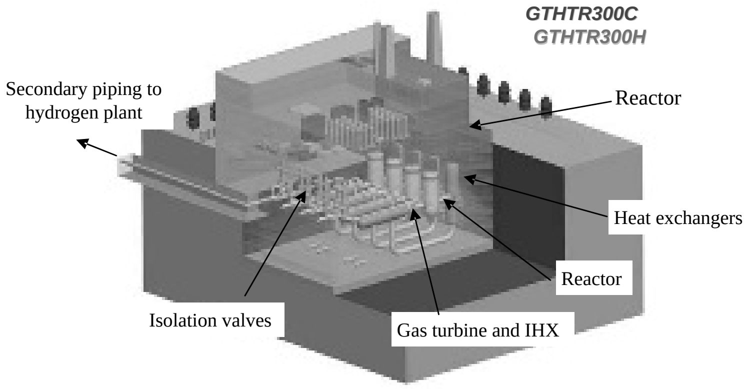
In the case of GTHTR300H, a major fraction of the total reactor thermal power, 371 MWt, is extracted from the IHX. The reactor outlet helium gas of 950°C enters the shell side of the IHX and heats the tube-side secondary helium to 900°C. Due to the significant IHX heat extraction, the primary helium gas that leaves the shell side of the IHX is now at 730°C. This temperature is still high enough to power the highly-recuperative gas turbine to generate 87.6 MWe at 38.3% cycle efficiency in addition to circulating reactor coolant. A majority of the generated electricity is used to meet the electricity demand in hydrogen production. Combining the process heat and thermal equivalence of electricity consumption gives 505 MWt effective thermal input to hydrogen production process.

The primary coolant pressure is lowered to 5 MPa from 7 MPa for the power-only reactor for two design considerations. The first is to reduce the design pressure loads on a host of high temperature heat exchangers, including IHX and chemical reactors, to secure sufficient life of these usually costly components. The second consideration is to maintain design and performance similarity of the gas turbines to the baseline unit of the GTHTR300. The gas turbine design approach will be revisited in detail in the next section. Although the lowered primary pressure increases specific cost of gas turbine equipment, the benefits gained in the heat exchanger life cost saving and for gas turbine technology simplification offer more compelling design advantage.

The commercial plants of the GTHTR300C and GTHTR300H are depicted in Figure 6 to each consist of four reactors operating in parallel, adapting the same system arrangement described earlier for the electricity-only generating plants. Table 5 provides the design parameters and the rated electricity and hydrogen product rates from the four-reactor commercial plants. The nuclear produced heat is transported by the secondary helium circulation loop over a safe distance to the hydrogen plant inside a coaxial hot gas piping, which is a proven component of the HTTR.

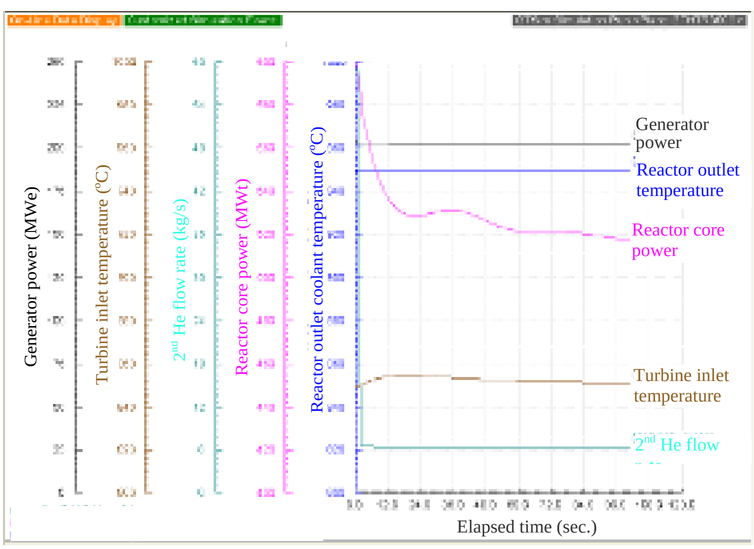
The layout for a commercial plant is depicted in Figure 6 to consist of four reactors operating in parallel, adapting the same system arrangement described earlier for the electricity-only generating plants. The nuclear produced heat is transported by the 2nd helium circulation loop over a safe distance to the hydrogen plant inside a coaxial hot gas piping, which is a proven component of the HTTR. Table 5 provides the design and production specification of the four-reactor commercial plants.

Figure 6. GTHTR300C and GTHTR300H commercial plant arrangement



Although a cogeneration system, the GTHTR300C may operate with one production in partial or full absence of the other, ensuring operational flexibility and stability in scheduled or forced outage. A simulated response to a hydrogen plant load upset is shown in Figure 7. Reactor operating parameters are shown to undergo orderly transient while maintaining stable production of electricity. The reactor outlet coolant temperature remains essentially constant due to large thermal capacity of the graphite core whereas the reactor power is brought down by the negative temperature coefficient of reactivity of the inherent core design. The turbine inlet temperature is returned, following a modest rise, to the rated value, by bypassing 10% compressor discharged cold gas to the fore of turbine to mix with the rising temperature gas there. Though not explicitly shown in Figure 7, the water cooled precooler acts as a passive thermal shock absorber that prevents thermal excursion from occurring anywhere in primary coolant circuit. Should the hydrogen plant load remains off in extended time, core outlet temperature would be brought down gradually from 950°C to 850°C by insertion of reactor power control rods.

Figure 7. GTHTR300C plant response to 100% to 10% loss of IS hydrogen plant heat load



Likewise, the simulation of the cogeneration system to a loss of electricity load showed that stable production of hydrogen could be maintained in the IS process plant.

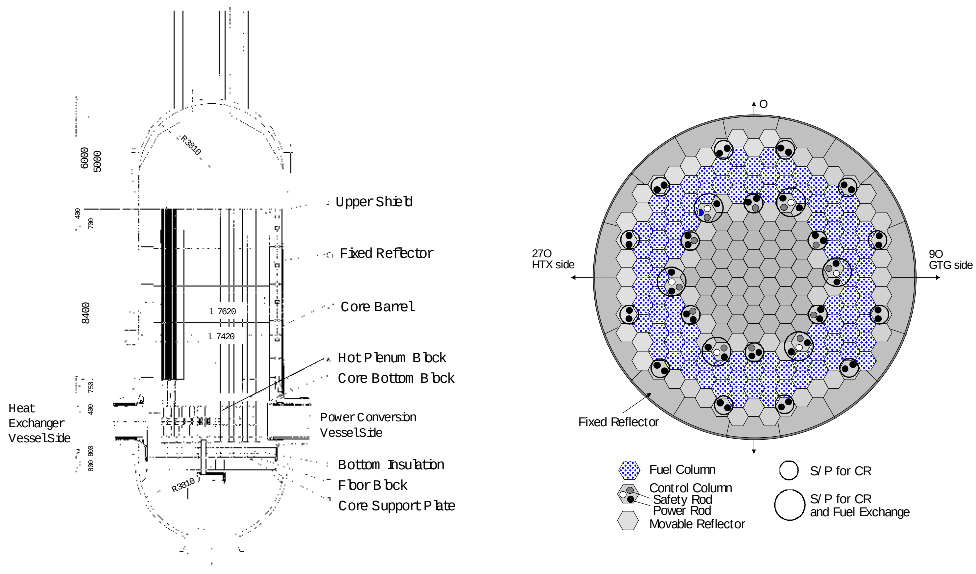
4. Systems and related R&D

The family of the GTHTR300 plant variants are based on three shared system technologies including reactor, helium gas turbine and, in the case of hydrogen production, the IS process system. This section discusses the underlying system designs and related research and development activities.

4.1 Reactor system

A unified reactor system design, including structural, thermal and physics designs, is employed by the GTHTR300 design variants. Table 2 summarises the overall reactor design parameters. As shown in Figure 8, a steel reactor pressure vessel (RPV) contains the graphite-moderated, helium-cooled prismatic core assembly. A unique reactor coolant circuit incorporates a pair of horizontal coaxial ducts providing the inner passage to channel hot helium gas into and out of the central core and the outer passage for cold helium gas to envelope the inner surface of the RPV. As a result, the RPV is maintained without active cooling in an operating temperature range that qualifies the 371°C design limit of conventional steel (SA533/508) for reactor pressure vessel construction. Details of this intrinsic RPV cooling scheme has been reported elsewhere [4].

Figure 8. The reactor design



The reactor active core consists of an annular ring of fuel columns surrounded by inner and outer replaceable reflector columns that partly contain control rod insertion channels. The core is embraced by outer permanent graphite reflector and enclosed in a steel core barrel. Each fuel column is stacked of eight hexagonal fuel blocks high and capped at top and bottom with reflector blocks. Dowels are used to align fuel blocks securely in a column. The fuel rods are located in the coolant holes of a fuel block. Burnable poisons are stored in three full-length holes. As shown in Figure 8, the coolant gas enters the reactor via the inner pipe of the horizontal coaxial duct on the left and travels upwards the gas channels embedded in the side reflector, turns in the top gas plenum to flow downward in the active core, and exits through the inner pipe of the horizontal coaxial duct on the right.

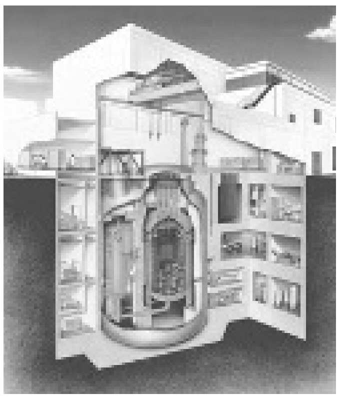
Table 2. Reactor design parameters

	GTHTR300 - power plant - baseline design	GTHTR300+ - power plant - growth design	GTHTR300C - cogeneration - GTHTR300H H₂ plant
Reactor rating	600MWt @850°C	600MWt @950°C	600MWt @950°C
Reactor design	Prismatic annular core	← same	
Fuel design	SiC TRISO particles	← same	
Reactor pressure vessel steel	SA533/508 (370°C)	← same	
Reference fuel cycle	LEU	← same	
Refueling method	2 batch axial shuffle	← same	
Core physics design			
Fuel columns	90	← same	
Inner reflector columns	73	← same	
Outer reflector columns	48	← same	
Core height (m)	8.4	← same	
Average power density (MW/m³)	5.4	← same	
Average burnup (GWd/t)	120	← same	
Fuel rods per block	57	← same	
Fuel rod diameter (cm)	2.6	← same	
Enrichment count	8	7	← same
Average enrichment (%)	14.3	14.2	← same
Burnable poison (BP) count	4	5	← same
BP pin diameter (m)	4.8	2.6	← same
Refueling interval (months)	24	18	← same
Max. fuel power peak factor	1.16	1.10	← same
Core thermal design			
Coolant (helium) flow rate (kg/s)	439	403	322
Coolant inlet temperature (°C)	587	663	594
Coolant outlet temperature (°C)	850	950	950
Coolant inlet pressure (MPa)	7.0	6.4	5.1
Core coolant pressure drop (kPa)	58	50	35
Min. fuel coolant flow fraction	0.88	.88	.88
Max fuel temperature (normal) (°C)	1108	1205	1244
Max. fuel temperature (LOCA) (°C)	1546	1554	1535

The fuel burnup averages 120GWd/ton. Several enrichment zones averaging about 14% enrichment are chosen to make as less as possible power peaking factors, which are limited to less than 1.16 through a burnup period. This in combination with large coolant flow checks fuel operating temperatures in a range expected to result in low fission product activity in the primary circuit to ease equipment maintenance.

The GTHTR300 reactor system has been designed based on the technologies and design codes developed and validated on the test reactor HTTR shown in Figure 9 and with further technical base for high burnup fuel [6] to allow specification of a modified TRISO coated particle fuel to meet commercial system objectives [7].

Figure 9. The HTTR test reactor



The characteristic design of low power density and peaking factor limits the maximum fuel temperature that could be reached during passive conduction cooldown following accidents. Figure 10 shows the transient temperatures of fuel and RPV in a loss of coolant accident (LOCA), in which decay heat is conducted from the central graphite core to the reactor pressure vessel and then removed by thermal radiation off the external wall of pressure vessel to surrounding reactor cavity cooling panels. The maximum temperatures reached in this as well as other bounding safety events satisfy the design limits of the fuel and pressure vessel

The IHX is a critical barrier component of the reactor pressure boundary. The present design selects a helical tube and shell heat exchanger because the same type is used in constructing the HTTR as shown in Figure 11. The Ni-base Hastelly-XR was developed for this application as heat-resistant helium-service tubing material. A high temperature structural guide was established in design and licensing. The IHX structural integrity and thermal performance are demonstrated in operations at 950°C in the HTTR. Figure 11 compares the IHX designs for the GTHTR300C and HTTR. Similar operating conditions are observed and the same tubing material and similar stress limits are followed in both designs. Because of GTHTR300C IHX having a large LMTD, a rather compact tube bundle is sized and placed within the cylindrical envelope provided by the gas turbine horizontal pressure vessel (refer to Figure 6). Further study of the placement will be in order to optimise installation, including consideration for alternative arrangement following the HTTR IHX installation practice [8] and new designs such as the one under independent industrial study on plate IHX to develop fabrication, ISI methods and a design standard for gas reactors [9]. A proven plate IHX would make it simpler to integrate IHX into the gas turbine vessel unit.

Figure 10. Reactor maximum temperatures in LOCA passive conduction cooldown

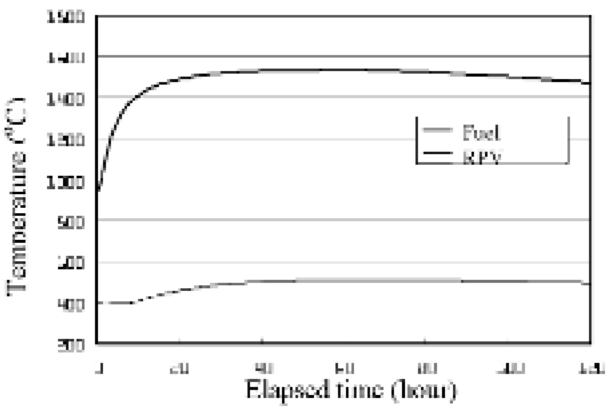
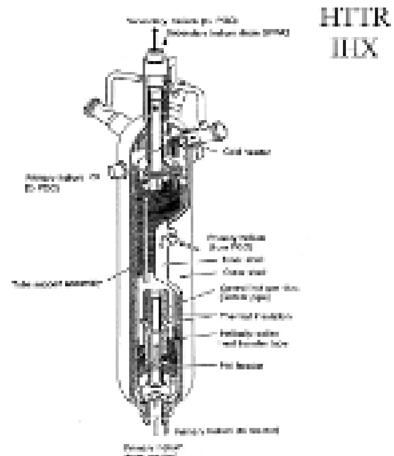


Figure 11. The IHX design comparaison

	GTHTR300C IHX	HTTR IHX
Thermal rating (MWt)	168	10
Primary inlet/outlet temperature ( )	950/650	950/389
Secondary inlet/outlet temperature ( )	500/900	237/869
Primary side pressure (MPa)	5.02	4.06
Secondary side pressure (MPa)	5.15	4.21
LMTD ( )	154	113
Heat transfer tubing	Hastelloy XR	
OD x t (mm)	45× 5	31.8× 3.5
Ave. length (m)	14	22
Tube number	724	96
Helical tube bundle sizing		
OD x L (m)	4.57× 2.97	1.31× 4.87
Weight (ton)	51	5.4
Design lifetime (yr)	20	20

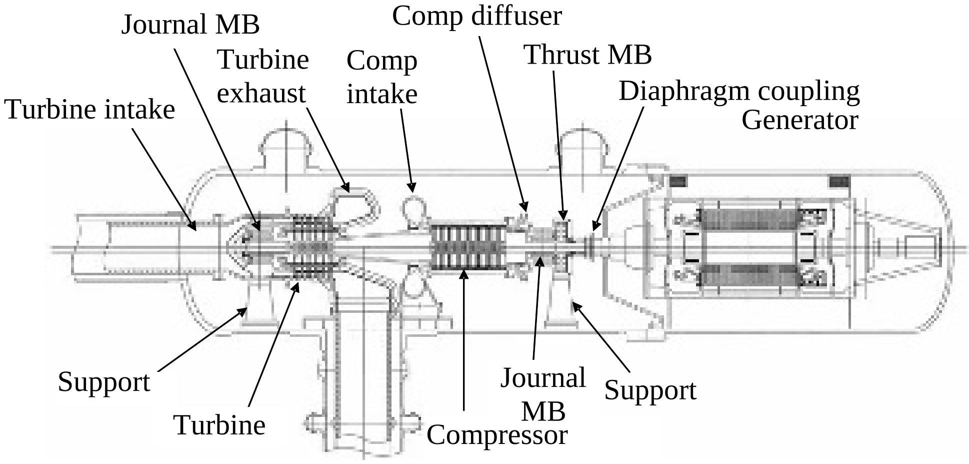


4.2 Helium gas turbine

High aerodynamic efficiency, reliability and serviceability are key performance requirements for helium gas turbine to qualify for nuclear power generation service. Besides little practical experience exists in the area, development of helium gas turbine to meet these performance goals presents a technical challenge, the extent of which proves to depend heavily on design choices made. The design approach for the GTHTR300 helium gas turbine has been to take advantage of successful experience in combustion gas turbines, while incorporating new design elements when must [4].

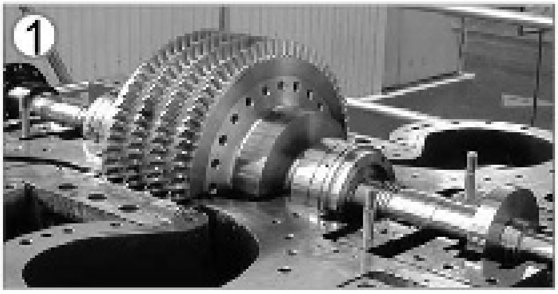
As shown in Figure 12, the baseline design of helium gas turbine is a single-shaft, axial-flow design having six turbine stages and twenty non-intercooled compressor stages. The gas turbine rated at 300 MWe and 3 600 rpm drives a synchronous generator from shaft cold end by a diaphragm coupling. The machine is placed horizontally to minimise bearing loads. These design features have been chosen in consistence with the established industrial practice in combustion gas turbines. The new gas turbine elements incorporated in the baseline unit are the narrow compressor flowpath, which is the result of working in helium, and the use of rotor magnetic bearings (MB) to avoid large pressure boundary penetration or potential lubricant contamination to reactor system. The development and test programs have been carried out to validate the new technology components uniquely present in this application.

Figure 12. Baseline design of GTHTR300 horizontal helium gas turbine in pressure vessel



Shown in Figure 13 is 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 baseline gas 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.

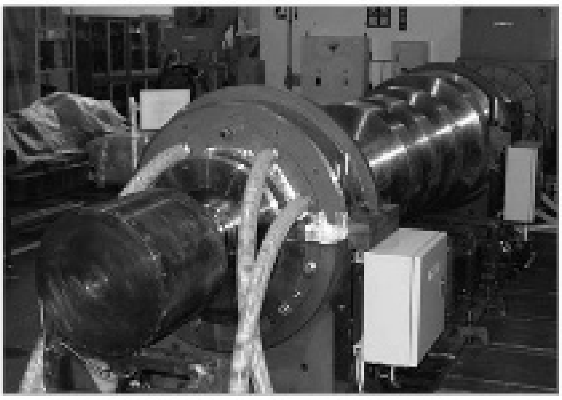
Figure 13. Test compressor of 1/3 full scale



The multi-year compressor development and test programme has just been concluded. The programme 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 programme is focused on evaluating optimal rotor-bearing clearance control method and developing magnetic bearing control algorithm to operate rotor above the 2nd bending critical speed. A test rig has been constructed and is presently undergoing commissioning. As shown in Figure 14, 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 will be test calibrated.

Figure 14. MB rotor test rig of 1/3 full scale

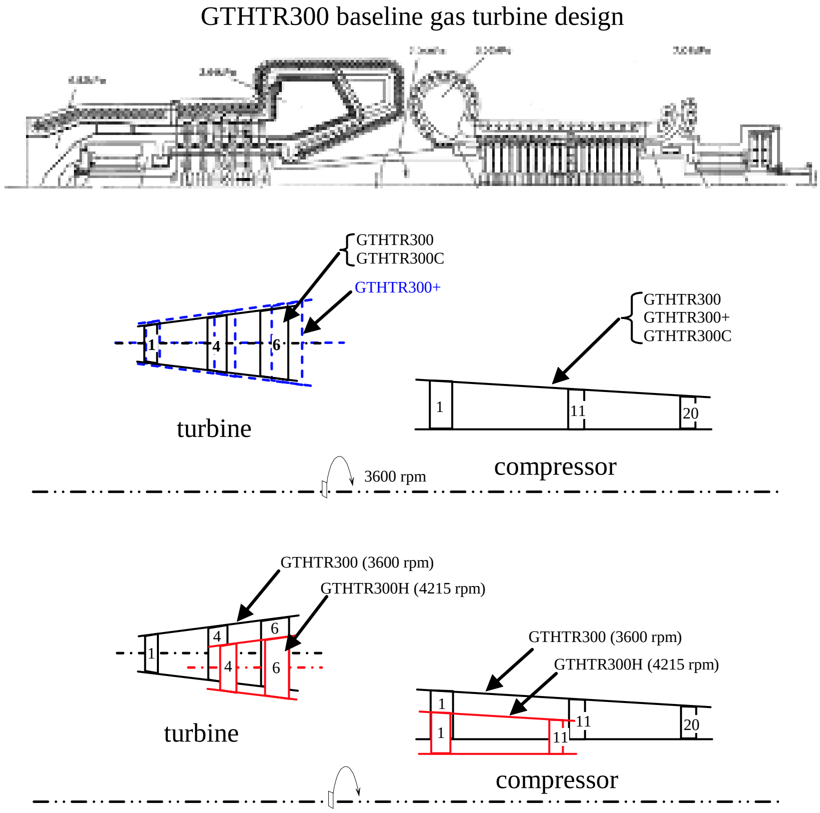


The baseline helium gas turbine design with its component development described so far is the unit in use in the power plant design variant, the GTHTR300. For the units used in other plant variants, geometric scaling from the baseline design has been applied to achieve design and technology simplification in accordance with the SECO design philosophy.

The scaling method is based on the principle that one can increase or decrease system pressure and alternatively or simultaneously increase or decrease the rotor diameter while holding the speed constant to produce aerodynamically and mechanically similar gas turbines of larger or smaller unit capacity. The complex blade airfoils, such as those obtained in the helium compressor development, become simply scalable from one machine to the other and the resulting aerodynamic working conditions and efficiencies are unchanged. The centrifugal stresses remain also unchanged in discs and blades. This makes the technologies developed for the baseline unit also applicable in other units.

Figure 15 depicts the scaling method and Table 3 lists the base scaling parameters used. Starting from the GTHTR300 baseline gas turbine design, the compressors of GTHTR300+ and GTHTR300C retain the baseline flowpath and airfoils by a reduction in compressor inlet pressure to adjust to their respective through flow capacity. The reduction in compressor inlet pressure also achieves the corresponding effect of invariable basic geometry for the turbines of GTHTR300+ and GTHTR300C. Because the GTHTR300+ turbine operates in 100°C higher than the 850°C baseline turbine inlet temperature, its flowpath is widened by 9% around the mean pitch line. The number of compressor and turbine blade rows is the same due to the same pressure ratio specified in the underlying cycles.

Figure 15. Gas turbine scaling for the family of GTHTR300 plants



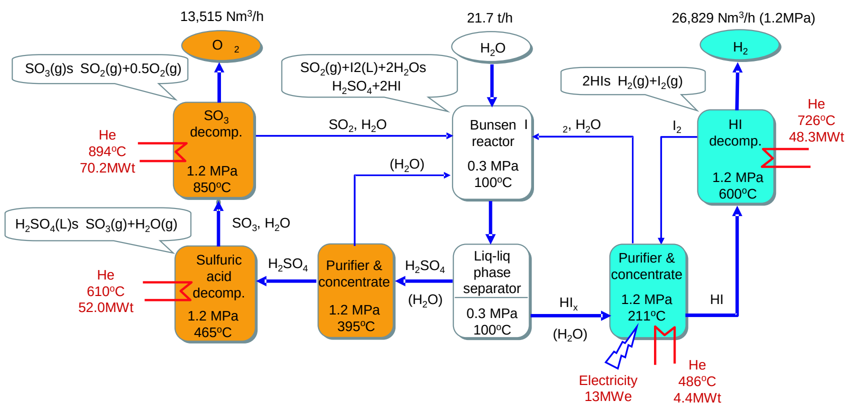
Relative to the GTHTR300 baseline gas turbine unit, the GTHTR300H unit has 1.47, instead of 2.0, compressor pressure ratio and 730°C, rather than 850°C, turbine inlet gas temperature. Because of the lower pressure ratio, the number of turbine and compressor stages necessary for the GTHTR300H is reduced. The GTHTR300H turbine adopts the rear three stages (4-6 stages) and the compressor the front eleven stages (1-11 stages) from the GTHTR300 baseline turbine and compressor, respectively. Furthermore, the diameter is reduced while holding rotor speed constant, to adjust to the reduced through flow of the GTHTR300H gas turbine while retaining similar aerodynamic conditions and mechanical stresses. The diameter reduction calls for increase in rotational speed from 3 600 to 4 215 rpm for the GTHTR300H. The asynchronous speed is acceptable because the generated electric power, 85 MWe, is meant mainly for in house consumption by hydrogen plant to power helium circulators, variable speed pumps, and to convert to direct current power source for use in process electrolysers. The GTHTR300H gas turbine is significantly shorter and more compact. So is the downsized electric generator of a reduced duty. The entire rotor train becomes considerably stiffened, making magnetic bearing suspension less challenged.

Table 3. Gas turbine scaling parameters

Unit	Gas turbine			Compressor section				Turbine section			
	Rotation speed [rpm]	pressure ratio	Mass flow [kg/s]	Inlet temperature [°C]	Inlet pressure [MPa]	rim speed [m/s]	Number of stages	Inlet temperature	Inlet pressure [MPa]	mean speed [m/s]	Number of stages
GTHTR300	3,600	2.00	445	28.0	3.5	282	20	850	6.8	377	6
GTHTR300+	3,600	2.00	408	28.0	3.2	282	20	950	6.2	377	6
GTHTR300C	3,600	2.00	327	26.2	2.6	282	20	850	5.0	377	6
GTHTR300H	4,215	1.47	327	26.2	3.5	282	11	730	5.0	377	3

4.3 IS process system

Figure 16. IS process heat and mass balance

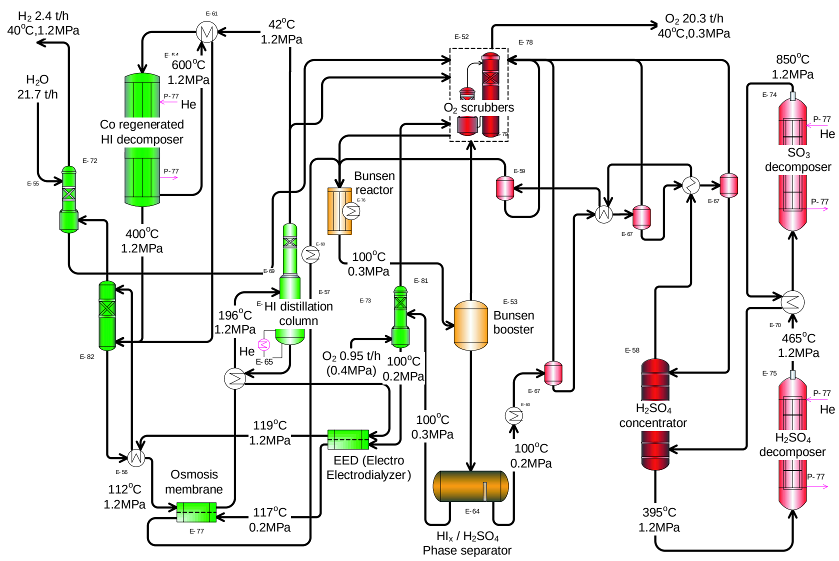


The IS process shown in Figure 16 involves three inter-cyclic thermochemical reactions to dissociate water molecules into hydrogen and oxygen gas products with heat and minor electricity as required energy input and with water as the only material feed. All process materials other than water are reagents. The nuclear generated heat in form of hot helium gas is used in various steps of process stream concentration and decomposition. The electric energy is used to power process electrolysers, gas circulators, pumps and other utilities. The energy and material balance provided in Figure 16 is representative of the GTHTR300C IS process corresponding to a nominal thermal input of 175MWt from the secondary helium circulation loop. For the GTHTR300H, the balance of energy and materials needs to be adjusted to the actual thermal rate while the marked process temperature and pressure conditions remain applicable to both systems.

The process flowsheet as presently developed is shown in Figure 17. The exothermic Bunsen reaction produces two aqueous solutions of sulfuric acid and hydriodic acid from material feeds of water, sulfur dioxide and iodine. The reaction favors presence of excess water and iodine to make it spontaneous and with iodine rich hydriodic acid (HIx) formed to facilitate subsequent phase separation. The excess of water and iodide, however, imposes heavy process stream loads upon subsequent reactions, particularly so in the HI reaction steps. Though not yet reflected in the present flowsheet, improved reaction conditions are being studied with the goal of significantly reducing excessive reactants in order to simplify overall process and production cost.

In the endothermic sulfur reaction, sulfuric acid H_2SO_4 from Bunsen reaction is purified and concentrated before being decomposed in steps into H_2O and SO_3 and then to SO_2 and byproduct oxygen gas, involving heat temperatures up to 850°C. The sulfur reaction is relatively well established and the main technical issues are concerned with having decomposers that are sufficiently heat and corrosion resistant. These practical problems are being tackled in industrial trial fabrication of the key component elements completed with strength and performance evaluation.

Figure 17. GTHTR300C IS process flowsheet



In the endothermic HI reaction, hydriodic acid HIx from Bunsen reaction is concentrated in a number of steps and the resulting hydrogen iodide concentrate is decomposed into reagent iodine and product hydrogen gas. The HI reaction steps appear to have the largest room for process improvement, for which several innovative process techniques have been incorporated in the present flowsheet. The HI concentration steps combine electro-electrodialysis cell and carbonized osmosis membrane to reduce excess iodine and water prior to final distillation. An iodine absorber is integrated into the HI decomposer to improve decomposition ratio in a newly proposed Co- regenerated process:

(1) $2HI \rightarrow H_2 + I_2$ (400°C)

(2) $Co + I_2 \rightarrow CoI_2$ (400°C)

(3) $CoI_2 \rightarrow Co + I_2$ (600°C)

---

(4) $2HI \rightarrow H_2 + I_2$

Table 4. GTHTR300C IS process efficiency

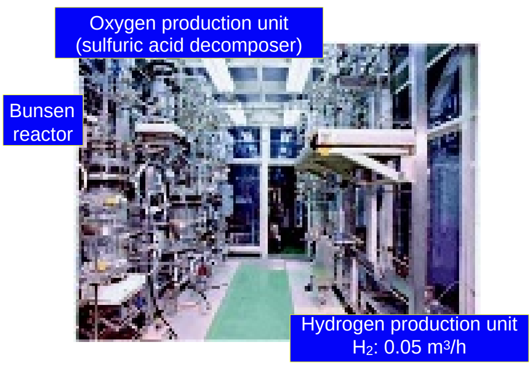
Thermal heat (MWt)	Electricity consumed (MWe)	Electricity cogeneration efficiency	IS plant net efficiency (HHV)
170.0	21.7	40	42.4%
		45%	43.6%
		50%	44.6%

By absorbing product I_2 from reaction (1) in the presence of reaction (2), as high as 80% once-through HI decomposition ratio is achievable in net reaction (4) as has experimentally been observed. The cobalt and iodine are regenerated in endothermic reaction (3).

The IS process efficiency has been estimated from a detailed flowsheet and best known process database. An overall process efficiency is defined as high heating value of total hydrogen produced against total thermal energy consumed. The total thermal energy consumption includes both the heat input and the thermal equivalent of electricity input needed to sustain hydrogen production operations. As presented in Table 4, the GTHTR300C delivers 170 MWt heat through IHX, which is distributed to several endothermic reactions (refer to Figure 16), and supplies additionally 21.7 MWe electricity mostly consumed by the process electrolyser (about 13MWe), and next by helium circulator (about 5MWe). The electricity supplied is co-generated in hous by gas turbine at 47% gross efficiency. The overall efficiency is about 44% net with a hydrogen production rate of 26,829 Nm^3/h or 2.4 ton/h.

JAEA continues long-term basic studies to identify heat and corrosion resistant materials suited for constructing demanding acid reactors, propose innovative process techniques to improve efficiency [10], and develop techniques of closed-cycle operations and automation [11]. Figure 18 shows a bench scale test apparatus used in process automation study. The results of the basic studies have allowed the efforts now being made to address practical issues in appropriate scales. A pilot plant to test 30 m3/h hydrogen production is being implemented. The technical and engineering data bases to be acquired in the pilot plant will enable JAEA to move forward with the final R&D goal of demonstrating nuclear production of hydrogen at 1000 m^3/h in an HTTR coupled test plant.

Figure 18. Bench scale IS process test apparatus



5. Summary

The SECO design philosophy of system technology sharing, design simplification, and focused R&D has enabled evolution of the GTHTR300 design variants that allow a flexible range of electricity and hydrogen products per reactor as indicated in Figure 19. Table 5 provides product ratings of commercial plants combining four reactors per plant. The ability to produce or co-produce hydrogen and electricity in a range of system options makes the GTHTR300 plant family strongly adaptable to market needs.

Moreover, the commonality of the technologies used in the family of the GTHTR300 plants makes any one of the plants suited to prototypical demonstration and initial deployment. The GTHTR300C being a substantial cogeneration system may be best suited in this role because it covers a full spectrum of the technologies used in the GTHTR300 plant family. The demonstration using the GTHTR300C may be phased to focus on electricity generation first and, once the reactor and gas turbine system is confirmed, proceed to second phase of overall cogeneration system demonstration by coupling with the hydrogen plant.

Figure 19. Electricity and hydrogen products per reactor

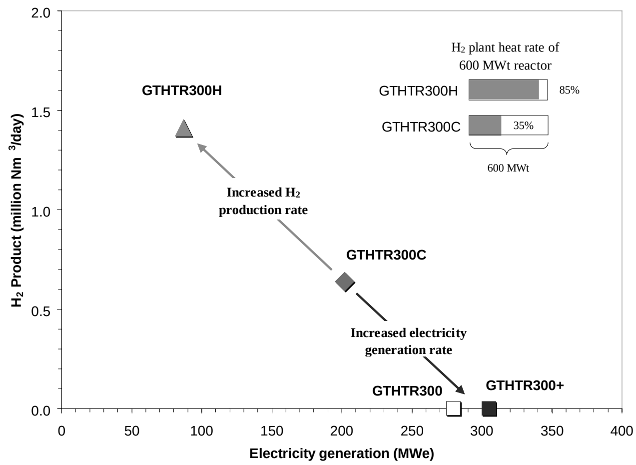


Table 5. GTHTR300 commercial production rates

		GTHTR300 - power plant -	GTHTR300+ - power plant -	GTHTR300C - cogen. plant -	GTHTR300H - H_2 plant -
Reactor thermal power	MWt	**4 x 600**	**4 x 600**	**4 x 600**	**4 x 600**
Net electricity rate	MWe	**1096**	**1200**	**697**	**137**
Hydrogen production	Mm^3/d	—	—	**2.6**	**5.6**
Plant net efficiency	**%**	**46**	**50**	**45**	**40**
Reactor outlet temperature	°C	850	950	950	950
Reactor inlet temperature	°C	587	663	594	594
Reactor coolant flow	kg/s	440	401	327	327
Reactor coolant pressure	MPa	7.0	6.4	5.0	5.0
Gas turbine heat rate per reactor	MWt	600	600	430	229
Turbine inlet temperature	°C	850	950	850	730
Gas turbine pressure ratio	æ	2	2	2	1.5
Gross electricity generation	MWe	280	305	202	87
Generating efficiency	%	47	51	47	38
IS process heat rate per reactor	MWt	æ	æ	170	371
IS process effective heat rate	MWt	æ	æ	219	505
IS process top temperature	°C	æ	æ	850	850
IS process efficiency	%	æ	æ	43	41

The government of Japan plans to introduce five million fuel cell vehicles (FCVs) by 2020 and fifteen millions by 2030, againt a backdrop of seventy five million total cars on road today. The plan envisions 100% FCVs in the later half of the century. The GTHTR300 plant family has the potential to play a significant role in supplying both emerging and matured hydrogen economy in Japan. Six GTHTR300C plants consisting of four reactors per plant, can fuel 7.5 million FCVs accounting 10% of the total number of cars. If deployed in time, these plants can simultaneously provide replacement power for the as many LWRs expected to retire by the year 2030 while co-producing the new hydrogen fuel on the existing sites. In longer term, adding either ten more plants of GTHTR300C or five plants of GTHTR300H could meet more than a quarter of the hydrogen fuel demand from a transportation sector that would become wholly hydrogen driven in a full-fledged hydrogen economy. In Japan, sustainability of HTGR energy production is being addressed by alternative fuel cycle and waste schemes such as the one outlined recently for an HTGR and FBR (fast breeder reactor) synergy to solve long-term issues of resources and wastes [12].

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REFERENCES

[1] Saito, S., *et al.*, (1994), Design of High Temperature Engineering Test Reactor (HTTR), JAERI 1332

[2] Shiozawa, S., *et al*., (2004), Overview of HTTR design features. Nucl. Eng. Des. 233, 11-21

[3] Yan, X., *et al.*, (2000), Design innovations in GTHTR300 gas turbine high temperature reactor, Proc. ICONE8, Baltimore, MD, USA, 2-6 April .

[4] Yan, X., *et al.*, (2003b), Cost and performance design approach for GTHTR300 power conversion system. Nucl. Eng. Des. 226, 351-373.

[5] Nishihara, T., *et al.*, (2004), Development of high temperature isolation valve for the HTTR hydrogen production system. AESJ Transaction. (2004) Vol. 3, No. 4.

[6] Sawa, K., *et al.*, (2002), Investigation of irradiation behavior of SiC-coated fuel particle at extended burnup. J. of Nucl.Tech. 142, 250-259.

[7] Nakada, T., *et al.*, (2002), Nuclear design of the gas turbine high temperature reactor (GTHTR300). JAERI-Tech 2002-066.

[8] Kunitomi, K., *et al.*, (2004), Deployment of GTHTR300 cogeneration for hydrogen and electric generation. Proc. ICAPP '04, Pittsburgh, PA, USA, 13-17 June .

[9] Tokunaga, K., *et al.*, (2005), Technology development of high efficiency and high capacity gas to gas heat exchanger which is necessary to practical application of gas-cooled reactor. To appear in Proc. Global 2005, Tsukuba, Japan, 9-13 Oct .

[10] Onuki, K., *et al.*, (2001), Electro-electrodialysis of hydriodic acid in the presence of iodine at elevated temperature, J. of Membrane Society, 192, 193-199.

[11] Kubo, S., *et al.*, (2004), A demonstration study on a closed-cycle hydrogen production by thermochemical water-splitting iodine-sulfur process," Nucl. Eng. Des. 233, 347-354.

[12] Shiozawa, S., (2005), Future plan on environmentally flriendly hydrogen production by nuclear energy, Proc. of this meeting.

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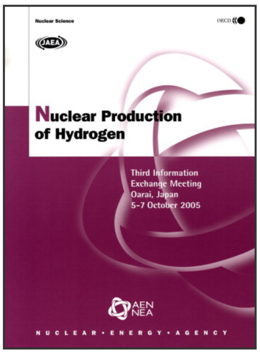

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