JAEA-Technology
2008-019

JAEA-Technology

Examination on Small-Sized Cogeneration HTGR for Developing Countries

Nariaki SAKABA, Yukio TACHIBANA, Satoshi SHIMAKAWA
Hirofumi OHASHI, Hiroyuki SATO, Xing YAN
Tomoyuki MURAKAMI, Kazutaka OHASHI, Shigeaki NAKAGAWA
Minoru GOTO, Shohei UETA, Yasuhiro MOZUMI
Yoshiyuki IMAI, Nobuyuki TANAKA, Hiroyuki OKUDA
Jin IWATSUKI, Shinji KUBO, Shoji TAKADA
Tetsuo NISHIHARA and Kazuhiko KUNITOMI

HTGR Cogeneration Design and Assessment Group
Nuclear Science and Engineering Directorate

March 2008

Japan Atomic Energy Agency 日本原子力研究開発機構

JAEA-Technology 2008-019

Examination on Small-Sized Cogeneration HTGR for Developing Countries

Nariaki SAKABA, Yukio TACHIBANA, Satoshi SHIMAKAWA, Hirofumi OHASHI
Hiroyuki SATO, Xing YAN※, Tomoyuki MURAKAMI※, Kazutaka OHASHI※
Shigeaki NAKAGAWA, Minoru GOTO, Shohei UETA, Yasuhiro MOZUMI※, Yoshiyuki IMAI
Nobuyuki TANAKA, Hiroyuki OKUDA, Jin IWATSUKI, Shinji KUBO, Shoji TAKADA
Tetsuo NISHIHARA and Kazuhiko KUNITOMI

Nuclear Applied Heat Technology Division
Nuclear Science and Engineering Directorate
Japan Atomic Energy Agency
Oarai-machi, Higashiibaraki-gun, Ibaraki-ken

(Received January 18, 2008)

The small-sized and safe cogeneration High Temperature Gas-cooled Reactor (HTGR) that can be used not only for electric power generation but also for hydrogen production and district heating is considered one of the most promising nuclear reactors for developing countries where sufficient infrastructure such as power grids is not provided.

Thus, the small-sized cogeneration HTGR, named High Temperature Reactor 50-Cogeneration (HTR50C), was studied assuming that it should be constructed in developing countries. Specification, equipment configuration, etc. of the HTR50C were determined, and economical evaluation was made. As a result, it was shown that the HTR50C is economically competitive with small-sized light water reactors.

Keywords: Cogeneration, HTGR, HTR50C, Developing Country

※Collaborating Engineer

JAEA-Technology 2008-019

発展途上国向け小型コジェネレーション高温ガス炉の検討

日本原子力研究開発機構原子力基礎工学研究部門
核熱応用工学ユニット
坂場　成昭・橘　幸男・島川　聡司・大橋　弘史・佐藤　博之・Xing YAN※
村上　知行※・大橋　一孝※・中川　繁昭・後藤　実・植田　祥平・茂住　泰寛※
今井　良行・田中　伸幸・奥田　泰之・岩月　仁・久保　真治・高田　昌二・西原　哲夫
國富　一彦

（2008 年 1 月 18 日受理）

安全性に優れ、発電のみならず水素製造、地域暖房等に利用できる小型コジェネレーション高温ガス炉は、送電網等のインフラが整備されていない発展途上国に最適な原子炉のひとつと考えられている。

そこで、発展途上国で建設することを想定した小型コジェネレーション高温ガス炉 HTR50C について検討した。HTR50C プラントの仕様、機器構成等を決定し、経済性評価を行った結果、小型軽水炉と経済的に競合できることがわかった。

大洗研究開発センター（駐在）：〒311-1393　茨城県東茨城郡大洗町成田町 4002
※技術開発協力員

Contents

目　　次

1. INDUSTRIAL HYDROGEN DEMAND

The global industrial hydrogen consumptions in the year 1980 are shown in **Fig. 1**[1]. The total hydrogen consumption amounts to 237,300 Mm^3/y, which includes the consumptions of ammonia synthesis of 109,160 Mm^3/y, oil refinement of 87,800 Mm^3/y, methanol synthesis of 23,730 Mm^3/y, and petro-chemistry and others of 16,610 Mm^3/y. More than 80% of the hydrogen was consumed by the two major industries of ammonia synthesis and oil refinement. The present relative hydrogen consumptions by the individual industrial sectors remain almost same as those in 1980.

Figure 2[2] shows the forecast for the global hydrogen demand by 2050 as reported by the International Energy Agency (IEA). The corresponding numerical values are given in **Table 1**. The hydrogen demand for chemical and refinery sectors is projected to increase steadily. After 2020, it is expected that hydrogen will be utilized in the widely-deployed fuel cells. Hydrogen demand for the fuel cells will increase drastically and exceeds the traditional demand for chemicals and refinery in 2050. The total global hydrogen demand in 2050 is estimated at 2,036,400 Mm^3/y, which is more than a four-fold of hydrogen demand comparing with the current hydrogen demand.

The hydrogen cost with a nuclear IS process is estimated to be 1,270 $/ t_H_2 ($1.27/kg) as indicated in **Fig.3**[3] comparing the hydrogen cost with other production methods. A separate study by General Atomics of the USA predicts that the hydrogen produced in a High Temperature Gas-cooled Reactor (HTGR) would cost $1.53/kg [4].

Figure 4 shows potential supplies of hydrogen produced in an HTGR to various industries. Availability of hydrogen product can spur creation of new domestic industries such as petroleum refining, ammonia production and steel making. It is possible to refine the petroleum of 6×10^7 barrels per year of crude oil by using hydrogen generated from one 600 MWt HTGR.

Ammonia has a large global market as a feedstock of the fertilizer production. Not only can HTGR generate hydrogen as such a feedstock, but also HTGR can supply steam and heat needed for the ammonia production ($N_2 + 3H_2 \rightarrow 2NH_3$). Estimated ammonia production rate using one 600 MWt HTGR is approximately 190 kt per year. It is about 0.2% of global ammonia production in 2004.

The developing country with a large iron ore reserve can greatly expand its steelmaking industry to meet the rapidly growing world demand for steels as shown in **Fig. 5**[5]. Hydrogen may be used as a reducing agent in steelmaking while contributing to a substantial reduction of carbon dioxide greenhouse gas emission. Approximately 3.7 Mt/y of iron ore can be processed by using the amount of hydrogen produced in one 600 MWt HTGR.

Figure 6[6] shows the amounts of carbon dioxide gas emitted from various hydrogen production methods.

Nuclear system can reduce carbon dioxide emissions especially when the thermochemical water-splitting IS process hydrogen production system is used. The carbon dioxide emission can be reduced by about 1.75 Mt/y while the steel is manufactured by using the hydrogen supplied from one 600 MWt HTGR.

Automotive energy consumption in the world is 58.5 EJ/y as shown in **Fig. 7**[7]. About 2.5 x 10^{12} Nm^3/y of hydrogen will be necessary when the internal-combustion engine vehicle will replace to the fuel cell vehicle in all over the world. At that time carbon dioxide emission can be reduced by 4,795 Mt/y in total as shown in **Fig. 8**[7] which value corresponds to approximately 21% of global carbon dioxide emission in 2000.

2. THE HTR50C PLANT PRODUCTS

The HTR50C, the HTGR proposed to be built in the developing countries, is designed to be a cascade energy plant that enables highly-efficient cogeneration of electricity, hydrogen and district heating. **Table 2** provides the HTR50C plant specification. **Figure 9** shows the plant cogeneration process including major process parameters.

The plant employs one unit of reactor rated at 50MWt thermal power. The basic energy product of the HTR50C is 15MWe net electricity, which can be produced with or without cogeneration of district heat and hydrogen. Additionally, district heat of 27.4MWt in supplying 260~340t/h water at 100~115^{o}C is co-generated without affecting the nominal production of electricity. The net efficiency of the HTR50C plant for cogeneration of the electricity and district heat is about 84%. Furthermore, hydrogen is co-produced for an output of 25,000 Nm^3/day. When hydrogen is co-produced, about 1MWe electricity is supplied for the in-house hydrogen production, which lowers electricity available for external grid output to 14MWe. In addition, the hydrogen production draws about 7.4MWt thermal power, which reduces district heat output to 20MWt. The net efficiency of the plant, when cogenerating all three energy products including electricity, hydrogen and district heat, is about 75%.

3. DESCRIPTION OF THE HTR50C PLANT

3.1 The system features of the HTR50C

The HTR50C is based on the Generation-IV VHTR nuclear reactor technology that provides significant advances and advantages of nuclear energy in economics, safety, spent fuel management and nuclear non-proliferation. Featuring ceramic coated particle fuel, graphite core structure and helium coolant, the HTR50C provides a core meltdown proof under fully passive and inherent protection and a high temperature coolant capability unmatched by any other nuclear reactors. The coolant heat of 900^{o}C or higher temperature allows efficient electricity generation by using gas turbine, which provides simplified plant construction and reduces electricity cost and the amount of spent fuel per unit of electricity generation. The high temperature capability of the HTR50C enables efficient and economical heat cogeneration with about 80% overall thermal efficiency. The high temperature heat can supply chemical or industrial production such as hydrogen production or ethylene production, iron-making, paper manufacture, cement manufacturing and so on while the low temperature heat can supply process steam, district heating, water distillation or desalination, agricultural and fishery farms and etc.

Specifically, the HTR50C is designed to provide the following plant characteristics:

<u>Plant economics</u>

- 50 MWt unit reactor thermal power and 900^{o}C coolant temperature
- 15 MWe electricity
- 25,000 Nm^3/day hydrogen
- 20-27 MWt district heat
- Generating the above energy products independently and simultaneously

<u>Safety, safeguards and public acceptance</u>

- Fully inherent and passive nuclear safety
- Nuclear proliferation resistance without weapon-grade fuel and spent fuel
- Demonstrable safety as performed and to be shown in the JAEA’s HTTR

<u>Fuel cycles and sustainability</u>

- Ceramic TRISO coated particle fuel
- Once-through low-enriched uranium LEU
- Mixed oxide fuel MOX (optional)
- Direct depository or reprocessing of spent fuel

<u>Near-term deployment</u>

- Deployable from 2010~
- Experience of licensed construction and operations in the HTTR
- Experience of nuclear facility quality assurance in the HTTR project
- Experience of licensed fuel fabrication in the HTTR project

<u>HTR50C technology</u>

- Based on the Generation-IV VHTR reactor technology

3.2 Plant primary system

Figure 10 shows the nuclear primary system layout of the HTR50C Plant. The primary system consists of four pressure vessels containing respectively the reactor, an intermediate heat exchanger, a gas turbine generator unit, and a heat exchangers unit. The pressure vessels are constructed of the conventional steel SA533/SA508, the same steel used in construction of the LWR reactor pressure vessels. The pressure vessels are inter-connected by co-axial pressure pipes as is done in the JAEA's HTTR construction[8]. The whole of the plant primary system is located in underground confinement buildings.

3.3 Reactor

The plant employs a helium-cooled and graphite-moderated reactor of 50 MWt thermal power. The reactor is particularly noted for its ability to produce high temperature helium coolant gas and for its strong safety characteristics. The reactor helium coolant operates at 560°C inlet and 900°C outlet at 4.0 MPa. And the reactor is inherently and passively safe. The core cross section as shown in **Fig. 11** consists of 48 columns of fuel blocks and 19 columns of control-rod guide blocks, and side peripheral columns of replaceable and permanent graphite reflector blocks. Each of the fuel columns is stacked of five fuel element blocks high. As a result, there are a total of 240 fuel element blocks loaded in the core. The fuel design is based on the pin-in-block fuel element of the JAEA's HTTR operating test reactor. The fuel cycle is once through low-enriched uranium with 5.3% average enrichment and fuel cycle length of 900 days with fuel burnup from 30.5 GWd/t in the first fuelled core to 120 GWd/t in the later advanced fuelled cores. The neutronics specification of the HTR50C reactor is listed in **Tables 3 and 4**.

3.4 Fuel

The fuel element of the HTR50C is so-called pin-in-block type, which is made up of fuel rods embedded in a hexagonal graphite block. The configuration of the fuel block element is shown in **Fig. 12**. The data of uranium enrichments of fuel rod and Boron contents of burnable poison in each fuel block are shown in **Tables 5 and 6**.

The coated fuel particle (CFP) is a micro-sphere which confines low enriched UO_2 kernel with TRISO

(Tri-ISOtropic) coating. The CFPs make fuel compacts with graphite matrix. The fuel rod, which is composed of fuel compacts and a graphite sleeve, is contained within a vertical hole of a graphite block. Specifications of the CFPs and fuel compact are shown in **Table 7**. The TRISO coatings consist of 4 layers of a low-density, porous pyrolytic carbon (PyC) buffer layer (60 micro-m) around the fuel kernel (600 micro-m in diameter), high density isotropic PyC layer (30 micro-m), a SiC layer (25 micro-m) and outer PyC coating (45 micro-m). The fuel compact is 10mm in inner diameter and 26 mm in outer diameter.

The higher burnup fuel to be used in the later advanced cores has a thicker SiC layer (40 micro-m) and a thicker buffer layer (130 micro-m) compared with the fuel of the first HTR50C core. These modifications are intended to retain increased quantity of fission products inside the coated fuel particle as the burnup is raised up to 120 GWd/t. The average enrichment of the fuels for use in the advanced cores is approximately 15 %.

3.5 Intermediate heat exchanger

The intermediate heat exchanger (IHX) is a vertical helically-coiled counter flow type heat exchanger in which the primary helium gas flows on the shell side and the secondary helium gas in the tube side as shown in **Fig. 13**. The primary helium is contained only in the primary coolant system by keeping the pressure in the secondary helium circuit slightly higher than the pressure of the primary system circuit.

The primary helium enters the IHX through the inner tube of the primary concentric hot-gas-duct. It is deflected under a hot header and discharged around the heat transfer tubes to transfer the heat to the secondary helium coolant. The secondary helium enters the IHX through the top tube sheet headers and flows downward in the heat transfer tubes while being heated. Being collected in the bottom hot header, the hot secondary helium flows upward in the central hot-gas-duct to exit the IHX.

The insulation is applied onto the inner shell and the central hot-gas-duct to control the metal temperatures. The tube support assemblies hold the heat transfer tubes. Both the central hot-gas-duct and heat transfer tube support assemblies are hung from the vessel top so that the thermal expansion is not constrained. Material of the heat transfer tubes and hot header is Hastelloy XR, and the inner and outer shells are made of Mn - Mo steel.

3.6 Gas turbine and generator

Figure 14 depicts the 15MWe class helium gas turbine design for the HTR50C. The gas turbine is of a single-shaft and axial-flow design including a six-stage turbine and a twenty-stage compressor. The gas turbine drives a synchronous generator on the cold end of the shaft at 10,000 rpm. The commercial grid frequency is achieved by power electronics frequency converter. A flexible shaft diaphragm couples the gas turbine rotor to the generator rotor and makes alignment and vibration of each rotor group effectively independent of the other. Each of the rotors is supported by bearings at two rotor ends.

The turbine design is based on reaction stages with the tip speed and stage loading similar to those employed in modern turbine designs. In addition, advanced design techniques are employed to optimize aerodynamic performance such as the 3D blading used to optimize the secondary flows in the turbine flow path. The turbine uses uncooled blades made of directionally solidified alloy. The maximum rotor diameter is 0.82 meter. The polytropic efficiency of the helium turbine is estimated to be 90%.

The compressor design is based on the advanced helium compressor flowpath design that has been proven in the recent JAEA helium compressor development and test program[9)]. The flowpath design incorporates a number of advanced blading techniques including the blade-end bends to eliminate flow separation and the blade over-camber to compensate for flow distortion near the endwall. These advanced design features are combined with optimum blade row solidity and aspect ratio to balance the operational requirements of efficiency and flow stability. CFD optimizations of inlet and outlet geometries are performed to control pressure losses in these usually loss-intensive locations. The rotor maximum diameter is 0.59 meter. The compressor performance is estimated of 87% polytropic efficiency with a 20% design point surge margin.

3.7 Heat exchangers

The major heat exchangers of the HTR50C include a He-to-He recuperator and a He-to-water precooler. Both heat exchangers are installed in the same HTX pressure vessel. The recuperator rated at 60 MWt is made up of three compact plate-fin heat transfer units that operate in parallel and is located in the upper HTX pressure vessel.

Figure 15 shows a unit design of the recuperator. The effective heat exchanger core volume of the recuperator is about 1m^3. The surface material is stainless steel of Type 316SS. The precooler rated at 26 MWt is the heat exchanger equipment used for district heating. It supplies 160^{o}C water to be circulated in an intermediate water circulating loop. The precooler is a helically-coiled tube bundle with water circulating in the tubes and helium in the shell. Tubing is fabricated of carbon steel STB410. The tube bundle is placed in the lower HTX pressure vessel section. Essential technologies employed in the recuperator and pre-cooler designs have been developed in Japan[9)].

3.8 Helium purification system

Two separate helium purification systems are used to purify the primary and secondary helium circuits, respectively, by removing the chemical impurities such as hydrogen, carbon monoxide, water vapour, carbon dioxide, methane, oxygen and nitrogen. The primary helium purification system is mainly composed of a pre-charcoal trap, an inlet heater, two copper oxide fixed beds, coolers, two molecular sieve traps, two cold charcoal traps and gas circulators. The helium purification system has three kinds of traps for reducing the chemical impurities. Each trap has two identical systems for high reliability of the plant operation. The first trap is a copper oxide fixed bed where hydrogen and carbon monoxide are oxidised to water vapour and carbon dioxide, respectively. It is kept at a temperature of 280°C during its operation. The second trap is a molecular sieve trap where water vapour and carbon dioxide are removed by adsorption. The third trap is a cold charcoal trap where oxygen, nitrogen, methane and noble gases are removed by adsorption; it is kept at a temperature of -195°C. The flow rate in the primary helium purification system is 200kg/h. The flow rate through the cold charcoal trap is 50kg/h with a bypass flow for the rest of the gas.

3.9 Instrumentation and control system

The instrumentation and control system is based on the same practice of the JAEA's HTTR operating reactor[8)]. The system consists of instrumentation, control, safety protection systems as well as a control room. The instrumentation system consists of reactor and process instrumentations to provide information for operation, monitoring and reactor protection.

(1) Reactor instrumentation

The reactor instrumentation monitors the major parameters in the operation condition of the HTR50C such as the neutron flux, position of control rods (CRs), differential pressure in the core, coolant temperature at the hot plenum and fission products (FPs) from failed fuel.

The instrumentation system, such as nuclear instrumentation, CR position instrumentation and differential pressure instrumentation, is used as a safety protection system. The requirements for the system are as follows.

a) The channel of the instrumentation is multiple so as not to lose the safety protection function even if a single failure occurs or one of channels is detached during the operation.
b) The multiple channels are separated physically as reasonably achievable.
c) The safety protection function is not lost in the event of a loss of off-site electric power or isolation of the system.
d) In case that the signal from the channel is used for the reactor control system, etc., the safety protection function is not lost because of a malfunction in the reactor control system.
e) The instrumentation system is inspected periodically during reactor operation and the function of the system must be confirmed not to be lost.
f) For instrumentation wiring, the incombustible and flame-resistant material is used as reasonably achievable.
g) The power source for the instrumentation system is avai1able in the power suspension.

The fuel failure detection (FFD) system and hot plenum coolant temperature instrumentation are installed for monitoring the core state during reactor operation.

- Nuclear instrumentation

Two types of neutron detectors are installed for the HTR50C. One is a fission counter which is prepared for the wide range monitoring system (WRMS) and is used under a high temperature environment at the top of a permanent reflector, the other an uncompensated ionization chamber which is prepared for the power range monitoring system (PRMS) and can detect a low neutron flux level outside the RPV. The WRMS and PRMS are used in the power range from 10^{-8}% to 35% and from 0.1% to 120%, respectively. In the HTR50C, the temperature around the wide range detector becomes about 600ºC and the neutron flux level around the power range detector becomes about 10^7n/cm^{2}s during the rated power operation of 50MW. It was confirmed that the WRMS could be used under a high temperature environment of 600ºC and the PRMS could detect a flux level of 10^7n/cm^{2}s. **Figure 16** shows the arrangement of neutron detector for WRMS and PRMS.

- CR position instrumentation

The CR position instrumentation is prepared to monitor the vertical position of 19 pairs of CRs. The position of CR is measured by the encoder sensor in the control rod drive mechanism (CRDM) and the signal from this instrumentation is used for the reactor control system and the safety protection system.

- Core differential pressure instrumentation

The core differential pressure instrumentation is prepared to detect a decrease in primary coolant flow in the reactor core. The core differential pressure instrumentation measures the differential pressure between the inlet and outlet of the core, and the signal from this instrumentation is used for the safety protection system.

- Fuel failure detection system

It is very important to prevent the FPs from being released abnormally into the primary coolant during the normal operation. The FFD system detects the failure of a CFP by detecting short life FPs, such as Kr-88 and Xe-138, which are gathered with precipitating wiring. The conceptual block diagram is shown in **Fig. 17**. The helium gases of the primary cooling system from the seven regions in the hot plenum are transferred to the precipitating wiring, and the K-88 and Xe-138 in the gases are detected. The FFD system has such sufficient and high sensitivity to detect a 0.02% fuel failure.

- In-core temperature monitoring system

Four thermocouples are arranged at each hot plenum block in order to monitor the primary coolant temperature. The N-type thermocouples are used because the deviation of thermo-electromotive force is small compared with other types of thermocouple under a high temperature environment.

(2) Process instrumentation

The process instrumentations of temperature, pressure, flow rate, radioactivity, etc., are required to monitor the plant parameter during the reactor operation. There are about 4000 sensors in the HTR50C, and the signals from the sensors are centralized by the plant computer.

The process instrumentation is used to measure process parameters. The signals of process instrumentation are transferred to the safety protection system, reactor control system and others. Major signals are indicated and recorded at the central control room. The process instrumentations used for the reactor protection system and the engineered safety features actuating system consist of three identical channels. The post accident monitoring instrumentation designed with safety protection grade is required to monitor the parameters during an accident.

(2) Control system

The control system controls the plant major operating parameters such as reactor power in the case of the ordinary change of the reactor power and the disturbance postulated during the normal operation, to prevent the abnormal event from escalation, and to actuate the interlock before reactor scram. The main control systems of the HTR50C are described as follows.

- Turbine bypass valve control system

The turbine bypass control system is used in the power range from 30 to 100%. In the case that there is a deviation between the power generator output and the set value, the primary coolant flow rate in the reactor core and the turbine is controlled by adjusting the opening of a turbine bypass valve to make the generated power output follow the desired set value. In the case that the unbalance between the power output and the load following such as in a loss of load event, the interlock of the control system makes the turbine bypass valve fully open to bring the reactor and plant to an equilibrium state of idle running in which the nominal turbine rotational speed is maintained to continue the idle plant operation.

- Reactor outlet coolant temperature control system

The reactor outlet coolant temperature control system is used in the power range from 10 to 100%. In the case that there is deviation, this control system gives a demand to the reactor power control system and controls the reactor outlet coolant temperature by controlling the position of CRs.

- Reactor power control system

The reactor power control system is used in the power range from 10 to 100%. In the case that there is a deviation between the reactor power and set value, some CRs are inserted or withdrawn to dissipate the deviation.

- Primary helium pressure control system

The primary helium pressure control system is used in the power range from 10 to 100%. The primary helium pressure control system controls the primary helium pressure by actuating the valves of the helium storage and supply system.

- Recuperator inlet coolant temperature control system

The recuperator inlet coolant temperature control system is the equipment to maintain the recuperator inlet helium temperature by actuating a control valve in the case that the recuperator inlet helium temperature deviates from the set value.

(3) Safety protection system

The safety protection system consists of the reactor protection system and engineered safety features actuating system. The reactor protection system ensures the integrity of the core and reactor coolant pressure boundary under the abnormal operating conditions. The engineered safety features actuating system prevents the FPs from being released into the environment in case of an accident such as a rupture in the primary concentric hot-gas-duct.

- **Reactor protection system**

The reactor protection system inserts the CRs into the core to ensure the integrity of fuel and protect the reactor coolant pressure boundary under abnormal operating conditions. This system has logic circuits having two trains which receive the signals from the reactor and process instrumentation systems, and sends the signals in case of a reactor scram.

- **Engineered safety features actuating system**

The engineered safety features actuating system sends the signals actuating the engineered safety features. The engineered safety features protect the reactor, the reactor coolant pressure boundary and the reactor building boundary, and prevent large amounts of FPs from being released outside the reactor facility. This system consists of the logic circuits having two trains which receive the signals from the reactor and process instrumentation, and actuates the engineered safety features.

3.10 Plant auxiliary facilities

(1) Fuel handling and storage systems

The new fuels and the spent fuels should be handled and stored safely and reliably by the fuel handling and the fuel storage systems. These facilities are located in the operating floor in the reactor building.

- **Fuel handling system**

The fuel handling system is utilized to install and remove fuel elements, replaceable reflector blocks, top shielding blocks, CR guide blocks and CRs. The fuel handling system consists of a fuel handling machine, attached equipment and auxiliary equipment.

The fuel handling machine consists mainly of a shielded cask, a gripper, a fuel handling unit drive system, a rotating rack and a door valve as shown in **Fig 18**. The fuel handling machine has a shield sufficient for fuel handling personnel and gas-tight boundary. The gripper handles the fuel element. The gripper is suspended by a pair of wires, and the gripper tip consists of six fingers to prevent the core element from dropping during refueling. The rotating rack has four discharge holes located circularly, and has the capacity to contain a top shielding block and one column of core component. Even if the fuel blocks are stored to capacity, the fuel handling machine maintains sub-criticality. The door valve, which is connected with the bottom of the fuel handling machine, has a gas-tight and shield structure along with a reactor isolation valve.

The attached equipment used during refueling consists of a reactor isolation valve, a connecting pipe and the CR handling machine. A maintenance pit is provided for the maintenance of the fuel handling machine.

- **Fuel storage system**

The fuel storage system consists of fresh and spent fuel storage systems. After cooling in the spent fuel storage pool in the reactor building, the spent fuels are transferred to the spent fuel storage system in the spent fuel storage building.

The functions of the fresh fuel storage system are to inspect fresh fuel rods which are transported to the reactor building, to assemble fuel elements and to store fresh fuel elements. The fresh fuel storage system consists of the fuel assembling and testing equipment, the fresh fuel storage cell and the inert gas replacement equipment. The fresh fuel storage cell is fabricated of ferroconcrete. The storage rack forms a vessel of a vertical cylinder with a plug and has sufficient distance to the adjacent storage racks not to become critical. The inert gas replacement equipment evacuates the air in the rack and replaces it with pure helium gas to keep fuel elements in a dry condition.

The spent fuel storage system stores spent fuel elements, CR guide blocks, replaceable reflector blocks. This system consists of a spent fuel storage pool, pool water cooling and purification system, and an irradiated material storage pit. The spent fuel storage pool is fabricated of ferroconcrete and has sufficient shielding for personnel as shown in **Fig. 19**. The spent fuel storage pool is lined inside the pool with stainless steel to prevent pool water leakage. When pool water leaks, the leakage can be detected by monitoring the water from the leakage check ditch which is located within the lining. The storage rack forms a vessel of a vertical cylinder with a shielding plug and has sufficient distance to the adjacent storage racks not to become critical even if the inside of the storage rack is filled with water. The pool water cooling and purification system removes the decay heat from spent fuel elements by coolers. The irradiated material storage pit stores and cools down spent CRs and irradiated samples.

(2) Radioactive waste treatment systems

The concept of radioactive waste management involves examination of all potential pathways of a radioactive release into the environment and provisions for appropriate processing and treatment equipment to ensure that any release of radioactivity into the environment is kept as low as possible. There are three radioactive waste treatment systems in the HTR50C: the radioactive waste treatment systems for gaseous, liquid and solid. All potentially radioactive gases, liquids and solids are collected and processed according to their physical and chemical properties and radioactive concentrations. Considerations are also taken in the design to minimize any mechanical leakage paths in these systems in order to limit unprocessed leakage.

- **Gaseous radioactive waste treatment system**

The gaseous radioactive waste treatment system collects and monitors all potentially radioactive gases discharged from the plant. **Figure 20** shows the schematic diagram of the gaseous radioactive waste treatment system. This system consists of the high and low activity gaseous radioactive waste treatment lines.

The high activity gaseous waste treatment line consists of a buffer tank with $0.5m^3$ capacity, two compressors and two decay tanks with $10m^3$ capacity each. Gases are stored temporarily up to 30 days in the decay tanks to reduce the activity for the release. The major sources of high activity gaseous wastes derive from the regeneration off-gas of the primary helium purification system. The low activity gaseous radioactive waste treatment line consists of two filtering units and exhaust blowers each. Gas which enters the system via the low activity inlet header flows through filtering units. Each filtering unit contains three kinds of filters: coarse-filter, metallic FP removal filter and radioactive iodine removal filter. The major sources of low activity gaseous wastes derive from the fuel handling system.

- **Liquid radioactive waste treatment system**

The liquid radioactive waste treatment system collects and monitors all aqueous radioactive waste discharged from the plant. **Figure 21** shows the diagram of the liquid radioactive waste treatment system. The system contains washing waste liquid drain, component drain, floor drain and spent fuel storage building drain lines.

Liquid radioactive waste from the washing waste liquid drain, component drain and floor drain lines are classified according to level of the activity in solutions. Liquid with high activity is transferred to the radioactive waste treatment facility. Leakage detectors are installed on each tank to detect any leakage from the tanks at an early stage.

- **Solid radioactive waste treatment system**

The solid radioactive waste treatment system collects, classifies, packages and tentatively stores all solid waste discharged from the plant. The beta and gamma emitting high level solid radioactive wastes such as spent replaceable reflector blocks and so on are temporarily stored in the storage pool to reduce their radioactivity. The spent CRs are stored in the irradiated material storage pit or storage pool. Solid radioactive waste is packed for shipment in the radioactive waste treatment facility according to their radioactive levels. The wall thickness on the solid radioactive waste treatment system is designed to control the equivalent dose rate around the site at a level as low as is reasonably achievable.

(3) Radiation management system

The protection and safety of all plant personnel and the general public against the radiation exposure, under all plant operating conditions, are ensured by the radiation monitoring system, adequate shielding design and access control procedures, supplemented by periodic radiation surveys and radiochemical analyses. Radiation protection is provided to prevent exposure of the public and employee beyond the limits. Radiation shielding and plant layout for the HTR50C are designed so that the plant can be operated, maintained, and refueled without operating personnel receiving radiation doses beyond the limits. Appropriate access control should be provided throughout the plant. For the access control, the plant layout should be divided into zones for normal operational and refueling conditions.

The function of the radiation monitoring system is to protect the employee and the public, and to safeguard plant equipment by providing measurement and alarm if the radiation level or activity release rate reach preset or maximum allowable levels. Permanent area radiation monitors are provided to warn the operating personnel of off-normal radiation levels in operating areas most subject to accidental irradiation from equipment or pipelines or from activity released into the building. Normally, high activity areas or shielded special areas are not provided with permanent monitors. Health physics procedures under administrative control call for special monitoring measures (with aid of portable instruments) when working at such locations. The area monitors are connected to redundant power source such that loss of single power supply will not disable the whole system. The radiation levels are indicated and recorded in the control room in order to provide a history of radiation in a given area in case of accidental over-radiation.

Additionally, alarms both in the control room and near the detector are provided to warn the operators. The operation of a monitor may be checked periodically from the control room by means of a check source at the detector.

(4) Electric facility

The electric facility of the HTR50C consists of a commercial power line, two emergency power lines and two constant-voltage and constant-frequency (CVCF) power lines.

A commercial high-voltage bus is made of only one which supplies power to gas turbine and four power centers. Two of the power centers are supplied only from the commercial power line and the others are from the commercial power line and/or the emergency power lines. Four power centers are connected to a high-voltage line through transformers.

The emergency power lines consist of two independent emergency power feeders with equal capacity. The emergency power feeders have gas turbine generators which are composed of gas turbine engines, generators and current breakers. The gas turbine generators are selected as an emergency power supply because it is possible to operate without cooling water and to supply the rated power instantly. The gas turbine generator starts up automatically when commercial power is lost and supplies emergency power to CVCF, safety equipments. One of the gas turbine generators is capable of supplying enough power to keep the reactor shutting down safely.

The CVCF power lines are classified into three systems, i.e., DC power systems, uninterruptible AC power systems and a power providing system for the computers. These power systems are designed to adopt static type power conversion equipment. DC power systems are composed of the two battery units of the same capacity. When off-site electric power is available, the power is charged in the DC battery units and supplied to safety equipment through rectifiers. When off-site electric power is lost, the DC battery units are discharged for providing electricity to the safety equipment. Uninterruptible AC power systems are composed of the same size of three inverter-converter units. When off-site electric power is available, electrical power is supplied to the safety instrumentation channels through the inverter-converter units. When the off-site electric power is lost, the power is switched to DC power systems. The computer power providing system is connected with non-safety equipment such as plant computers, plant control units, reactor power control units, instrumentations and other control panels. When one of the emergency power lines fails, the line is automatically switched to the other emergency power line.

(5) Other auxiliary facilities

The auxiliary plant facilities consist of systems for ventilation and air conditioning, fresh water supply, purified water supply, auxiliary component cooling water, general cooling water, solution injection, nitrogen supply, compressed air supply, steam supply, fire-extinguish and general drainage.

- **Ventilation and air conditioning system**

The ventilation and air conditioning system is available to supply fresh air to ventilate and regulate the temperature and humidity in the buildings. The ventilation and air conditioning system for reactor building consists of the air supply system and two exhaust systems. The air supply system is composed of two air conditioners, two blowers and three air supply filtering units. The system supplies air to the controlled area by regulating the automatic damper located downstream to the blower. The exhaust system A is composed of a filtering unit including a coarse and fine dust filter to purify the gas from each room in the controlled area. The exhaust system B is composed of two filtering units including coarse and fine dust fi1ters and an active charcoal filter to purify the gas from the spent fuel inspection room.

At the time of an accident, the ventilation and air conditioning system is shut down and connected to the active charcoal filter to protect employees from radiation exposure. The ventilation system is so designed as to allow air to flow through the lower region of radioactive level to the higher region while taking in fresh air. The ventilation and air circulating system contains a recirculation cooler and a depressurization apparatus. The recirculation cooler consists of an air conditioner including two cooling coils and two blowers to cool and circulate air in the reactor building during normal condition as well as accidents and loss of off-site electric power. It is of great importance in supplying air to the stand pipe room so as to keep CRDM temperature below the limit. The depressurization apparatus suppresses any pressure increase during normal conditions. Then, it leads the air to the ventilation stack through the fine dust filter and active charcoal filter.

- **Miscellaneous facilities**

The auxiliary component cooling water system consists of a cooling tower, a circulation pump and piping. During normal condition as well as accidents and loss of off-site electric power, temperature increase of water used in some cooling systems is reduced by the air of the cooling tower, and the water is restored by the circulation pump.

In the hydrazine injection system, it is necessary to remove dissolvent oxygen by controlling the hydrogen exponent of pH and preserve the plant components and related pipes from corrosion by injecting inadequate amount of hydrazine into the cooling water. The hydrazine injection is carried out independently of the cooling system and is regulated by related valves.

3.11 IS process hydrogen production system

Table 8 shows the major specification of the IS process to be coupled with the HTR50C. The heat produced by the reactor is supplied to the IS process by the secondary helium. The thermal duty of the IS process is approximately 7.4MW. Hydrogen production rate is estimated to be about 25,000 Nm^3/day.

- Flow sheet diagram

Figure 22 shows the simplified flow sheet diagram of the IS process. The IS process is split into three procedures; Bunsen reaction procedure (Bunsen PROC), H_2SO_4 decomposition procedure (H_2SO_4 PROC), and HI decomposition procedure (HI PROC). H_2SO_4 solution and HIx solution (solution of HI, I_2 and H_2O) obtained in the Bunsen reactor are separated at H_2SO_4/HIx separator. Each of the solutions is concentrated, vaporized and decomposed in H_2SO_4 PROC and HI PROC, respectively. H_2 and O_2 are obtained as products and other compounds are returned into the Bunsen reactor. A three stage multiple-effect vaporizer is used as H_2SO_4 concentrator. A direct contact heat exchanger (DCHX) is installed upper stream of the H_2SO_4 vaporizer to recover unreacted H_2SO_4 in the SO_3 decomposer with efficient direct heat exchanging. An Electro-Dialyzer is used to increase the HI concentration of the HIx solution to over pseudo-azeotropic. While the concentrated HIx solution is fed to the HI distillation column, HI-rich vapor is obtained from the top. I_2 is removed from the reaction field by reaction with Cobalt in HI decomposition reactor.

(1) Major specifications of main components

- H_2SO_4 PROC

Main components in H_2SO_4 PROC are H_2SO_4 concentrator, H_2SO_4 decomposer and SO_3 decomposer. **Table 9** provides the major specification of the H_2SO_4 concentrator. For the internal structures, ceramic tray and carbon steel coated with glass lining are adapted for the pressure vessels and for piping and other equipment, respectively, to ensure structural integrity in the corrosive working fluid environments. **Table 10** shows the major specification of the H_2SO_4 decomposer. H_2SO_4 is decomposed into SO_3 and H_2O at the H_2SO_4 decomposer. The H_2SO_4 decomposer is constructed of SiC heat transfer blocks which are corrosion resistant to the evaporating H_2SO_4 environment. **Table 11** shows the major specification of the SO_3 decomposer. The SO_3 decomposer is installed downstream of the H_2SO_4 decomposer and SO_3 is decomposed into SO_2 and O_2. Pt catalysts are loaded inside the flow path in the heat transfer blocks to enhance the SO_3 decomposition.

- HI PROC

Main components in HI PROC are HI distillation column, Electro-Dialyzer, HI decomposer. **Table 12** provides the major specification of the HI distillation column. HI-rich vapour is obtained from the top and azeotropic HIx solution is obtained from the bottom. The heat from the secondary helium and regenerated heat in the HI PROC are used as the heat source of the re-boiler. **Table 13** shows the major specification of the Electro-Dialyzer. HIx solution is concentrated up to 13 mol-HI/kg-H_2O by using the graft-type polymer electrolyte membrane prepared by radiation processing developed by JAEA[10]. **Table 14** shows the major specifications of the HI decomposer. HI vapor is heated using regenerated heat in the HI PROC and then decomposed into H_2 and I_2 at HI decomposer. Decomposition is enhanced by Pt catalysts and I_2 absorption using Cobalt system. Absorbed I_2 is separated by the secondary helium.

- Bunsen PROC

Main components in Bunsen PROC are Bunsen reactor and H_2SO_4/HIx separator. **Table 15** provides the major specification of the Bunsen reactor. The H_2SO_4 solution and HIx solution are obtained in the Bunsen reactor. Tantalum or other lining materials are utilized for corrosion resistance. **Table 16** shows the major specification of the H_2SO_4/HIx separator. The H_2SO_4 solution and HIx solution obtained in the Bunsen reactor are separated into H_2SO_4-rich phase and HIx-rich phase by detention in the separator. Tantalum or other lining materials are utilized to ensure the structural integrity in the corrosive working environments.

3.12 The HTR50C plant buildings

The HTR50C plant consists of a reactor building, a hydrogen production area and a district heat building. **Figure 23** shows the arrangement of the HTR50C plant. The layout was designed by sizing the main components installed in the HTR50C plant. The hydrogen production system is not enclosed in a building in order to minimize the possibility of a hydrogen explosion accident. The hydrogen production area and the district heat building are separated over an adequate distance from the reactor building. The adequate distance will be defined by considering the structural integrity of the safety equipment, reactor control room, etc. from a possible hydrogen explosion and a possible toxic gas leakage from the IS hydrogen production system. The spent fuel storage area which is not mentioned in the figure is also required.

The reactor building made of reinforced concrete is divided into a reactor building section, an auxiliary building section and a service building section. The plan views of the reactor building are shown in **Fig. 24, 25, and 26.** **Figure 24** shows the elevated reactor building which includes a reactor section and a service section. The height of the building is 21m above the ground and 30 m underground. The height of stacks above the ground is about 30m. The width of the building is about 57m. **Figure 25** shows the side view of the reactor building with a width of about 27m. **Figure 26** shows the plan view of the reactor building.

In the reactor building section, the reactor pressure vessel (RPV), the gas turbine generator (GTG) vessel, the heat exchangers (HTX) vessel and the intermediate heat exchanger (IHX) vessel are installed. Fuel handling machine and control rod handling machine are located at the operation floor on the ground level. The reactor confinement made of concrete, rather than the reactor containment steel vessel, provides the safety of the HTR50C. The building pressure is reduced by the stacks during a depressurization accident. The advantage of the fully inherent and passive safety features of the HTR50C can significantly improve the HTR50C plant cost and economics.

4. THE HTR50C ECONOMIC ASSESSMENT

4.1 Economic assessment of the reactor system

(1) Plant construction cost

Plant construction cost of the HTR50C was estimated. The estimations of major systems, which are similar to those of the Japanese HTTR[8)], were carried out based on the construction cost data of the HTTR. On the other hand, the estimations of some systems, which are similar to those of the GTHTR300, were based on the previous estimation results of the GTHTR300[11)].

The result of the HTR50C construction cost estimate is shown in **Table 17**. The total plant construction cost was estimated as 466.8 M$. This value is based on the assumption that all equipments are provided by the Japanese vendors and the HTR50C is constructed in the Japanese site.

It should be noted that escalation of metallic material prices is not taken into consideration.

(2) Power generating and heat supply costs

Power generating and heat supply costs of the HTR50C were estimated with the similar calculation method used in the power generating cost estimates of the GTHTR300 in Japan[11)].

(a) Major assumption

(i) General conditions

- Plant life time 40 year
- Plant capacity factor 90%
- Discount rate 3%

(ii) Capital cost

- Depreciation cost
  - Declining balance method
  - Durable years: 40years (the same as operating lifetime of reference plant)
  - Residual book value: 5% at the last year of the operation
- Decommissioning cost per unit reactor power is assumed to be same to that of the GTHTR300.
- Interest cost and fixed property cost are neglected.

(iii) Operating & Maintenance cost

- Total of the maintenance cost rate and the miscellaneous cost rate are assumed to 5.0 % based on the operating experience of the HTTR.
- Personnel cost: Number of the employees are assumed to be 28 persons per unit as same as the estimation of the GTHTR300.
- Head office cost and business tax are neglected.

(iv) Fuel Cycle cost

Unit price of each item used in the fuel cycle cost calculation are shown in **Table 18**. The unit price of the fuel fabrication cost is assumed as twice higher as that of the GTHTR300's estimation so that the FOAK (First Of A Kind) cost should be obtained from the NOAK (Number Of A Kind) cost of the GTHTR300. The fuel cycle cost estimated in the GTHTR300 includes the reprocessing cost and the resulting waste disposal cost. However, in this HTR50C estimation, the spent fuel are assumed to be directly disposed and the unit price of the final direct disposal cost is assumed to one forth of that of the reprocessing cost based on the example of the LWR cost estimations. Other unit price data in **Table 18** are same as that used in the GTHTR300.

(b) Estimation results

Based on the assumptions explained above, the total amount of the necessary annual expenditures during the plant operation is calculated as **Table 19**.

The power generating cost and the heat supply cost should be determined to compensate this expenditure. However, each share of the power generating cost and the heat supply cost cannot be defined, the heat supply cost necessary to compensate the annual expenditure for given power generating cost is calculated parametrically. The result is shown in **Fig. 27**. The cost profile of the HTR50C shown in **Fig. 27** is apparently higher than those of the Russian ABV-6 reactor[12)].

(3) Revised cost estimates using Russian labour cost data

Russian labour cost data is compared to Japanese labour cost in order to minimize the cost of power generation and heat supply.

(a) Russian labour cost data information

According to the database of the ILO website[13)], labour cost of the machine and electrical machinery fabrication of the year 2005 in Russia is about 340 JPY/h. On the other hand, the Japanese labour cost of the year 2001 is about 3,600 JPY/h, which is about 10.6 times higher than that of Russia. Therefore it can be assumed that the all Russian personnel costs are ten times lower than the relevant Japanese personnel costs.

(b) Fraction of the personnel cost to the total plant construction cost

Here it is assumed roughly that two third of the total plant construction cost depends upon the personnel cost and the remaining one third is the material cost.

(c) Revised estimates case and their results

- Case 1 : All systems are provided as the Japanese personnel cost condition.
  (This case is essentially the same one to the case estimated in the previous section.)
- Case 2 : Major systems (reactor internals, IHX, gas-turbine system, secondary helium system and fuel handling and storage system) are provided as the Japanese personnel cost condition and all remained systems are provided as the Russian personnel cost condition.
- Case 3 : All systems are provided as the Russian personnel cost condition.

The estimation results of the plant construction cost and the annual expenditures for each case above are shown in **Table 20**.

In the estimation of the annual expenditures of the case 2 and 3 shown in **Table 20**, following assumptions are adopted.

- The unit price of the personnel cost of the operation and maintenance cost are as the Russian personnel cost condition.
- The two third of the fuel cycle cost are assumed to depend on the personnel cost and the Russian personnel cost condition is adopted.

According to the total annual expenditures of the each case, the cost profile on the power generating cost and the heat supply cost are calculated in the same manner, and the results are shown in **Fig. 28.** The cost profile of the case 2 and 3 shown in **Fig. 28** is much lower than those of the Russian ABV-6 reactor[12)]. Especially, in the case 3, if the power generation cost are set to slightly higher than 10 c/kWh, the heat supply cost is lower than the energy price of the coal and this suggests that the case 3 cost has a possibility to be competitive to the present heat supply cost of the conventional plant.

5. RESEARCH AND DEVELOPMENT

5.1 Major technologies for HTGR system developed by JAEA

JAEA has been developing the HTGR technologies through the design, construction and operation of the HTTR since 1969. In order to design and construct the HTTR, R&Ds were carried out with large numbers of test apparatuses.

Representing tests using large-scale test apparatuses are OGL-1, HENDEL, VHTRC and material test machines. Irradiation tests of HTTR fuels were performed with the OGL-1 installed in the Japan Materials Testing Reactor (JMTR)[14]. Thermal-hydraulic performance of HTTR core and durability of core structure were verified with the real scale mock-up model, HENDEL, under high-pressure and high-temperature conditions simulating the HTTR operation[15)-17]. Helium circulation and high-temperature helium transfer technologies were established through the HENDEL tests[18]. Reactor criticality was examined in a system consisting of graphite fuel blocks using the VHTRC[19]. Mechanical strength including creep fatigue performance was examined in high-temperature helium gas conditions up to 950 °C using the material test machines[20,21].

Major technologies for HTGR system developed by JAEA are listed in **Tables 21 and 22**.

The fabrication technology for unique and high quality coated fuel particles has been developed by establishing the fluidization and continuous coating technologies, and hot pressing technique for fuel compact. The data base and inspection standard of fuel particles has been established. Fine-grained isotropic nuclear graphite, IG-110, has been developed for core graphite components of the HTTR. The IG-110 has quite excellent mechanical and irradiation-resistant properties. IG-110 is only the high quality nuclear graphite in the world. The irradiation database of IG-110 has already been established[22]. For the metallic material for the components under high-temperature condition, i.e., heat transfer tube of IHX and hot-gas duct, super alloy Hastelloy XR has been developed. The Hastelloy XR is the Hastelloy X based superalloy enhancing corrosion resistant and high-temperature mechanical performances. The Hastelloy XR showed no corrosion under the HTTR coolant condition of 10,000 hr long-term corrosion test[23].

First criticality of the HTTR was attained in 1998, and the reactor outlet temperature of 950 °C with full power of 30MWt was achieved in 2004[24] based on these technologies. The excellent reactor safety characteristics of HTGRs have been demonstrated by the safety demonstration tests using the HTTR[25]. The excellent FP-retention ability of Japanese coated fuel particle has been demonstrated through the long-term HTTR operation. The experimental results obtained with the HTTR showed much lower FP release than that observed with AVR in Germany or FSV in US[26]. The technical know-how for the reactor construction and the reactor operation were also established by the HTTR.

R&Ds for the next generation HTGR, GTHTR300C[27)], have been also conducted including R&Ds on the helium gas compressor[9)], magnetic bearing[9)], high-temperature isolation valve[28)], and IS process hydrogen production system[29)].

5.2 Necessary R&Ds for HTR50C

R&Ds for HTR50C in the future are none or to be minimized because KHTR will be built on the basis of the above-mentioned technologies for HTGR system developed by JAEA.

6. CONCLUDING REMARKS

The small-sized and safe cogeneration reactor, HTR50C, which is a cascade energy plant that enables highly-efficient cogeneration of electricity, hydrogen and district heating, was studied assuming that it should be constructed in developing countries. Specification, equipment configuration, etc. of the HTR50C were determined, and economical evaluation was made. As a result, it was shown that the HTR50C is economically competitive with small-sized light water reactors.

REFERENCES

1) The Japan Development Bank (1987).
2) International Energy Agency : "Prospects for hydrogen and fuel cells", IEA/OECD (2005).
3) B.C.R. Ewan, et al., : "A figure of merit assessment of the routes to hydrogen", Int. J. Hydrogen Energy, 30, 8, pp.809-819 (2005)
4) L.C. Brown, et al., : "High efficiency generation of hydrogen fuels using nuclear power", GA-A24285, pp.3-37 - 3-38 (2003).
5) International Iron and Steel Institute : World crude steel production, 1950 to 2006 (online) available from <http://www.worldsteel.org/>(accessed 2008-01-08).
6) Central Research Institute of Electric Power Industry : "Life cycle evaluation of CO_2 emissions for power generation technology", CRIEPI annual report (2000).
7) L. Fulton, et al., : "IEA/SMP Model Documentation and Reference Case Projection", WBCSD, (2004).
8) S. Saito, et al., : "Design of High Temperature Engineering Test Reactor (HTTR)", JAERI 1332, Japan Atomic Energy Res. Inst. (1994).
9) T. Takizuka, et al., : "R&D on the power conversion system for gas turbine high temperature reactors", Nucl. Eng. Des. 233, 1-3, pp.329-346 (2004).
10) T. Yamaki, et al., : "Preparation of Proton Exchange Membranes Based on Crosslinked Polytetrafluoroethylene for Fuel Cell Applications", Polymer, 45, pp.6539-6573 (2004).
11) M. Takei, et al., : "Economical Evaluation on Gas Turbine High Temperature Reactor 300 (GTHTR300)", Transactions of the Atomic Energy Society of Japan, 5, 2, pp.109-117 (2006) (in Japanese).
12) Private communication.
13) International Labour Office : International Labour Office database on labour statistics, (online) available from <http://laborsta.ilo.org/>(accessed 2008-01-08).
14) H. Nakata, et al., : "VHTR Fuel Irradiation Tests by the In-pile Gas Loop,OGL-1 at JMTR", JAERI-M, 86-068 (1986).
15) S. Maruyama, et al., : "Experimental studies on the thermal and hydraulic performance of the fuel stack of the VHTR, Part I; HENDEL single-channel tests with uniform heat flux", Nucl. Eng. Des., 102, pp.1-9 (1987).

16) S. Maruyama, et al., : "Experimental studies on the thermal and hydraulic performance of the fuel stack of the VHTR, Part II; HENDEL multi-channel test rig with twelve fuel rods", Nucl. Eng. Des., 102, pp.11-20 (1987).
17) K. Kunitomi, et al., : "Thermal and hydraulic tests in HENDEL T supporting the development of the core bottom structure of the High Temperature Engineering Test Reactor (HTTR)", Nucl. Eng. Des., 108, pp.359-368 (1988).
18) Y. Miyamoto, et al., : "Thermal and hydraulic tests of test sections in the helium engineering demonstration loop", Nucl. Eng. Des., 120, 2-3, pp.435-445 (1990).
19) N. Fujimoto, et al., : "Validation of the nuclear design code system for the HTTR using the criticality assembly VHTRC", Nucl. Eng. Des., 233. 1-3, pp.155-162 (2004).
20) Y. Kurata, et al., : "Creep properties of base metal and welded joint of Hastelloy XR produced for high-temperature engineering test reactor in simulated primary coolant helium", J. Nucl. Sci. Technol, 36, 12, pp.1160-1166 (1999).
21) Y. Kurata, et al., : "Long-term creep properties of Hastelloy XR in simulated high-temperature gas-cooled reactor helium", J. Nucl. Sci. Technol, 32, 11, pp.1108-1117 (1995).
22) T. Oku, et al., : "Lifetime evaluation of graphite components for HTGRs", Nucl. Eng. Des., 227, 2, pp.209-217 (2004).
23) Y. Muto, et al., : "Development of high temperature structural materials for the HTGR", Nucl. Eng. Des. 144, 2, pp.305-315 (1993).
24) S. Fujikawa, et al., : "Achievement of Reactor-Outlet Coolant Temperature of 950 °C in HTTR", J. Nucl. Sci. Technol., 41, 12, pp.1245-1254 (2004).
25) S. Nakagawa, et al., : "Safety demonstration tests using high temperature engineering test reactor", Nucl. Eng. Des. 233, 1-3, pp.301-308 (2004).
26) K. Sawa, et al., : "Research and development on HTGR fuel in the HTTR project", Nucl. Eng. Des. 233, 1-3, pp.163-172 (2004).
27) K. Kunitomi, et al., : "JAEA's VHTR for Hydrogen and Electricity Cogeneration : GTHTR300C", Nuclear Engineering and Technology., 39, 1, pp.9-20 (2006).
28) T. Nishihara, et al., : "Development of High Temperature Isolation Valve for the HTTR Hydrogen Production System", Transactions of the Atomic Energy Society of Japan, 3, 4, pp.381-387 (2004) (in Japanese).
29) S. Kubo, et al., : "A demonstration study on a closed-cycle hydrogen production by the thermochemical water-splitting iodine–sulfur process", Nucl. Eng. Des. 233, 1-3, pp.347-354 (2004).

List of tables

List of figures

Table 1 Forecast of the global hydrogen demand (Mm^3/y)[2)]

Year	2000	2010	2020	2030	2040	2050
For energy use (fuel cell)	0	0	27,900	303,100	655,200	1,147,800
For chemical and refinery	462,800	548,000	633,100	718,300	803,400	888,600
Total	462,800	548,000	661,000	1,021,400	1,458,600	2,036,400

Table 2 Major plant specification of the HTR50C

Plant	Reactor unit(s) / unit power	1 unit / 50 MWt
	Electricity output (when H_2 is co-produced)	15 (14) MWe
	Hydrogen (H_2) output	25,000 Nm^3/day
	District heat (when H_2 is co-produced)	27 (20) MWt 100~115°C water
	Plant efficiency (when H_2 is co-produced)	84% (75%)
	Plant capacity factor	>90%
Reactor	Reactor pressure vessel	SA533/SA508 (Mn-Mo) steel
	Reactor safety system	no active emergency system
	Radioactive nuclide retention	confinement
	Coolant inlet/outlet temperature	560 / 900°C
	Coolant pressure	4 MPa
	Coolant flowrate	28 kg/s
	Fuel operating temperature	1350 °C
	Average power density	2.5 W/cc
	Fuel element	pin-in-block prism
	Fuel cycle	LEU once through
	Fuel average enrichment	5.3%
	Average burnup	30.5 GWd/ton
	Shutdown refueling	once per 3 years
	Refueling duration	30 days
Gas Turbine Generator	Design type	single-shaft horizontal unit
	Shaft speed	10,000 rpm
	Turbine inlet temperature/pressure	850°C / 3.87 MPa
	Turbine mass flow	28 kg/s
	Turbine expansion ratio	1.87
	Number of turbine stages	6
	Turbine maximum rotor diameter	0.82 m
	Turbine polytropic efficiency	90%
	Compressor inlet temperature	28°C
	Compressor pressure ratio	2.0
	Number of compressor stages	20
	Compressor maximum rotor diameter	0.59 m
	Compressor polytropic efficiency	87%
	Generator drive	high-speed synchronous
	Frequency conversion	Power electronics
Heat exchangers	Recuperator design type	plate-fin
	Recuperator thermal rating	60 MWt
	Recuperator effectiveness	88%
	Recuperator total pressure loss	1.7%
	Recuperator construction material	Type 316SS
	Precooler design type	helical-coiled finned tube bundle
	Precooler thermal rating	26 MWt
	Cooling water inlet temperature	22°C
	Cooling water outlet temperature	160°C
	Precooler tubing material	carbon steel (STB410)

Table 3 The neutronics specification of the HTR50C reactor (Part 1/2)

Items		HTR50C preliminary	HTTR
Thermal power(MWth)		50	30
Fuel block kinds :radial direction		6	4
:axis direction		4	4
U enrichment(%)	max.	9.9	9.9
	min.	3.0	3.4
	average	5.3	5.8
Enrichment kinds		13	12
Burnable poison content kinds		1	2
U loading(t)		1.48	0.9
Fuel block columns		48	30
Fuel block layers		5	5
Total fuel blocks		240	150
Fuel suffling during a cycle		0	0
Cycle length (Effective full power days)		900	660
Burnup average(GWd/t)		30.5	22.0
Burnup max.(GWd/t)		43.4	33.0
Integral power average(GWd)		45.0	19.8
Averaged column power(MW/Column)		1.04	1.00
Power density(W/cc)	ave.	3.2	3.0
	max.	7.0	6.6
Control rod block column		19	16
Fuel region diameter(m)		3.0	2.3
Active core height(m)		2.9	2.9

Table 4 The neutronics specification of the HTR50C reactor (Part 2/2)

Items		HTR50C preliminary	HTTR
Excess reactivity(%Dk/k)			
Cold clean state	limit	16.5	16.5
	evaluated	9.7	13.5
Power operation state		1.8	3.2
Control rod worth(%Dk/k)	summation	23.0	18.0
	evaluated	63.5	66.5
Shutdown margin(%Dk/k)	limit	1.0	1.0
	evaluated	32.0	45.0
Temperature coefficient of fuel ($x10^{-5}$ %Dk/k/°C)	max.	-4	-2
Temperature coefficient of Refl ($x10^{-5}$ %Dk/k/°C)	max.	-2	1
Power coefficient ($x10^{-4}$ %Dk/k/MW)	max.	-2	-4
Prompt neutron generation time	max.	0.88	0.85
	min.	0.80	0.81
Delayed neutron fraction	max.	0.0067	0.0067
	min.	0.0046	0.0049
Fuel temperature(°C)	max.	1492	1492

Table 5 Uranium enrichment for fuel blocks

radius / axis	F1	F2	F3	F4	F5	F6
1	6.2	6.2	7.0	8.6	8.6	9.9
2	5.0	5.0	5.5	6.7	6.7	7.9
3	4.0	4.0	4.5	5.5	5.5	6.2
4	3.0	3.0	3.4	4.0	4.0	4.8
5	3.0	3.0	3.4	4.0	4.0	4.8

U235wt% average = 5.3

Table 6 Boron content for fuel blocks

radius / axis	F1	F2	F3	F4	F5	F6
1	5.4	5.4	5.4	5.4	5.4	5.4
2	5.4	5.4	5.4	5.4	5.4	5.4
3	5.4	5.4	5.4	5.4	5.4	5.4
4	5.4	5.4	5.4	5.4	5.4	5.4
5	5.4	5.4	5.4	5.4	5.4	5.4

B-wt% average = 5.4

Table 7 Comparative fuel specifications for the first and advanced cores of the HTR50C

	First core	Advanced cores
Fuel type	Rod	Rod
Fuel coating type	TRISO	TRISO
Diameter of particle(micro m)	920	990
Fuel kernel Materials Density(%TD) Diameter(micro m)	 UO_2 95 600	 UO_2 95 550
Materials and thickness (micro m) of coatings 1st layer 2nd layer 3rd layer 4th layer	 Low density PyC 60 High density PyC 30 SiC 25 High density PyC 45	 Low density PyC 130 High density PyC 25 SiC 40 High density PyC 25
Enrichment (wt %)	3-10 (Average 5)	11-16 (Average 15)
Burnup (GWd/t)	30.5	120
Specification of fuel compact		
Type Materials Packing fraction of coated fuel particles (Volume %) Dimensions Outer/inner diameter(mm) Height of compact(mm)	Hollow cylinder Coated fuel, binder, graphite 30 26/10 39	Hollow cylinder Coated fuel, binder, graphite 22 26/9 83

Table 8 Major specification of the IS process to be coupled to the HTR50C

Item	Value
IS process thermal duty	7.4 MW
Hydrogen production rate	25,000 Nm^3/d
Electrical power consumption	703 kW
IS process inlet helium temperature	835 °C
IS process outlet helium temperature	460 °C
Secondary helium pressure	4.0 MPa (gauge)
Secondary helium flow rate	3.6 kg/s
H_2SO_4 procedure pressure	1.2 MPa (gauge)
HI procedure pressure	1.2 MPa (gauge)
Bunsen procedure pressure	0.2 MPa (gauge)

Table 9 Major specification of H_2SO_4 concentrator

Item	Specification
Number	1
Type	Three-stage multiple-effect vaporizer + Direct contact heat exchanger (DCHX)
Design pressure	0.28/0.28/0.28/1.4 MPa (gauge)
Design temperature	110/120/180/450 °C
Structure material	Carbon steel + Glass lining

Table 10 Major specification of H_2SO_4 decomposer

Item	Specification
Number	1
Type	SiC heat exchanger
Design pressure	Helium : 4.0 MPa (gauge) Process : 1.2MPa (gauge)
Design temperature	Helium : 600 °C Process : 500 °C
Structure material	SUS316

Table 11 Major specification of SO_3 decomposer

Item	Specification
Number	1
Type	Catalytic packed SiC heat exchanger
Design pressure	Helium : 4.0 MPa (gauge) Process : 1.2MPa (gauge)
Design temperature	Helium : 880 °C Process : 850 °C
Structure material	Alloy800

Table 12 Major specification of HI distillation column

Item	Specification
Number	1
Type	Packed tower
Design pressure	1.4MPa (gauge)
Design temperature	250 °C
Structure material	Carbon steel + Glass lining

Table 13 Major specification of Electro-Dialyzer

Item	Specification
Number	1
Type	Electrolyte cell
Design pressure	0.3 MPa (gauge)
Design temperature	140 °C
Structure material	Carbon steel + Tantalum or other lining
Membrane	Graft type polymer electrolyte membrane prepared by radiation processing (Developed by JAEA)

Table 14 Major specification of HI decomposer

Item	Specification
Number	1
Type	Catalytic packed bed reactor
Design pressure	1.4MPa (gauge)
Design temperature	600 °C
Structure material	MAT21

Table 15 Major specification of Bunsen reactor

Item	Specification
Number	1
Type	Shell & tube reactor
Design pressure	0.6 MPa (gauge)
Design temperature	100 °C
Structure material	Carbon steel + Tantalum or other lining

Table 16 Major specification of H_2SO_4/HIx separator

Item	Specification
Number	1
Type	Cylindrical container
Design pressure	0.6 MPa (gauge)
Design temperature	100 °C
Structure material	Carbon steel + Tantalum or other lining

Table 17 Plant construction cost of the HTR50C

System	Specification	Weight (t)	Cost (1000USD)
1. Reactor			
(1) Core Element	CR Block 19 columns Removal Reflector 24columns	57	12,828
(2) Core internal structure	ϕ4,930×H8,000		57,252
・ Graphite Structure		210	
・ Metalic Structure		116	
(3) Reactivity control system	19 systems	-	29,735
2. Main Cooling System			
(1) Primary Cooling System			
・ Reactor Pressure Vessel	ϕ5.2×H13.2×t120、SA-533	395	25,249
・ Intermedeate Heat Exchanger	ϕ1,630H,9300、7.4MWt	-	10,564
・ Turbine	6 stages, 34 MWt	-	49,124
・ Compressor	20 stages, 16.5MWt	-	incld. above.
・ Generator	10,000rpm, 15MWe	-	incld. above.
・ Power Conversion Vessel	ϕ3,000×L15,000	-	incld. above.
・ Heat Exchanger			
Recuperator	plate-fin, 60 MWt	-	incld. above.
Pre-Cooler	helical coile, 26 MWt	-	incld. above.
・ Heat Exchanger Vessel	ϕ3,000×L15,000	-	incld. above.
・ Primary Piping	Co-axial Double Piping	-	incld. above.
(2) Secondary Helium Cooling System	7.4MWt	-	17,113
3. Engineering Safety Features			
(1) Reactor Cavity Cooling System	Natural Draft Air Cooling Panel	550	5,445
4. Reactor Auxiliary Systems		122	7,440
5. Auxiliary Helium Systems			40,820
(1) Shutdown Cooling System	5.8MWt	-	
(2) Primary Helium Purification System	purification flow rate 200kg/h	-	
(3) Primary Helium Storage System	$90m^3$×8.8MPa	-	
(4) Primary Helium Sampling System	Humidity detector, Radiation detector,etc.	-	
(5) Secondary Helium Purification System	purification flow rate10kg/h	-	
(6) Secondary Helium Storage System	$16.5m^3$×7.9MPa	-	
(7) Secondary Helium Sampling System	Humidity detector, etc.	-	
6. Fuel Handing and Strage System			49,408
New Fuel Storage System	Equivalent to 1.5 core	200	
New Fuel Fabrication System		-	
Fuel Handling System	Fuel Exchange Machine, Fuel transport Machine	255	
Spent Fuel Storage System	Equivalent to 2 core	360	
Auxiliary Equipments		-	
7. Instrumentation and Control System		-	32,677
8. Electric Facility		-	18,673
9. Radioactive Waste Treatment System		-	4,080
10. Radiation Management System		-	9,600
11. Auxiliary Plant Facilities		-	17,502
12. Buildings	Horizontal Cross Sectional Area $1,500m^2$	-	79,310
Total Plant Construction Cost		-	**466,820**

Table 18 Unit price of fuel cycle

Item	Value	Unit	Loss factor
Uranium purchase, conversion	6	1000 JPY/kg-U	
Enrichment	13	1000 JPY/kg-SWU	0.5 %
Fabrication	1,124	1000 JPY/kg-U	1.0 %
Storage	176	1000 JPY/kg-HM	
Final direct deposal	266	1000 JPY/kg-HM	
Other items for HTR50C			
Uranium inventory	1.48 t-U		
Fuel average enrichment	5.3wt %		
Tails assay for enrichment	0.25 wt%		

Table 19 Annual expenditures

(Unit M$/y)

Item	Cost
Capital Cost	16.6
Operating & Maintenance cost	4.2
Fuel Cycle cost	10.1
Total	30.9

Table 20 Revised plant construction costs and annual expenditures

	Case 1	Case 2	Case 3
Plant construction cost (M$)	466.8	322.3	186.7
Annual expenditures (M$/y)			
Capital cost	16.6	11.5	6.7
Operation and maintenance cost	4.2	1.8	1.1
Fuel cycle cost	10.1	4.1	4.1
Total	30.9	17.4	11.9

Table 21 Technologies developed by JAEA (1/2)

Category	Item
Fuel	• Development of fabrication technology for unique and high quality coated fuel particles (low failure fraction, irradiation resistance) • Establishment of data base of fuel particles • Establishment of inspection standard for fuel particles
Graphite	• Development of high grade graphite, IG-110 (high strength, corrosion and irradiation resistance) • Establishment of irradiation database of IG-110 • Establishment of graphite structural design guideline • Establishment of code/ standard for in-core components
Metallic Materials	• Development of heat and corrosion resistant super alloy, Hastelloy XR (~1000°C, corrosion resistance) • Establishment of strength data base of $2^1/_4$Cr - 1Mo steel • Establishment of high temperature structural design guideline
Instrumentation equipments	• Development of fission counter for the wide range monitoring system under high temperature environment • Development of uncompensated ionization chamber for the power range monitoring system • Development of fuel failure detection system • Development of in-core temperature monitoring system
Other components	• Development of intermediate heat exchanger • Development of high-temperature isolation valve • Development of hot-gas duct • Establishment of helium purification technology • Development of fuel handling system
Technical know-how for reactor construction	• Transit and installation of king-size components • Weld and assembly technology of piping and equipments • Prefab construction of building and piping

Table 22 Technologies developed by JAEA (2/2)

Safety evaluation	• Establishment of seismic characteristics of in-core components • Establishment of evaluation technology for the plate-out behavior of fission product • Establishment of evaluation technology for the lift off behavior of fission product • Establishment of evaluation technology for reaction rate of oxidization of core graphite
Numerical code	• Development and verification of various codes (neutronics, thermal hydraulics, seismic behavior, FP plate-out and transport, safety analysis, heat balance of plant during normal operation, plant dynamics, integrity of high temperature components)
Gas turbine	• Development of helium compressor • Development of magnetic bearing

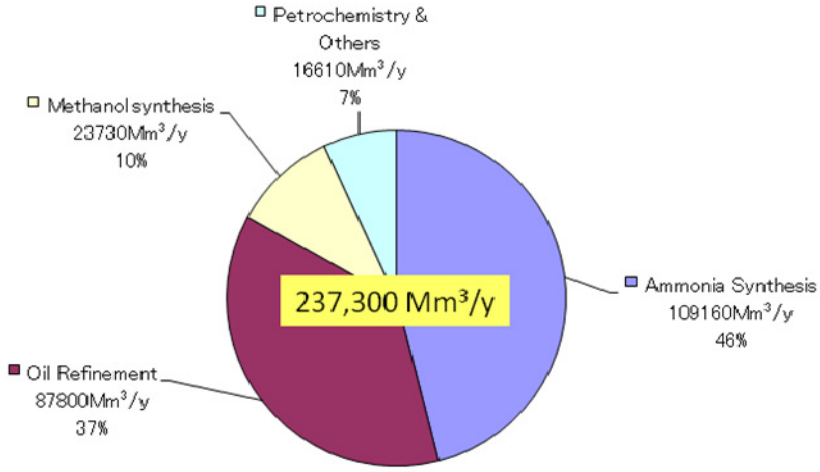


Fig. 1 The global hydrogen consumptions in 1980[1)]

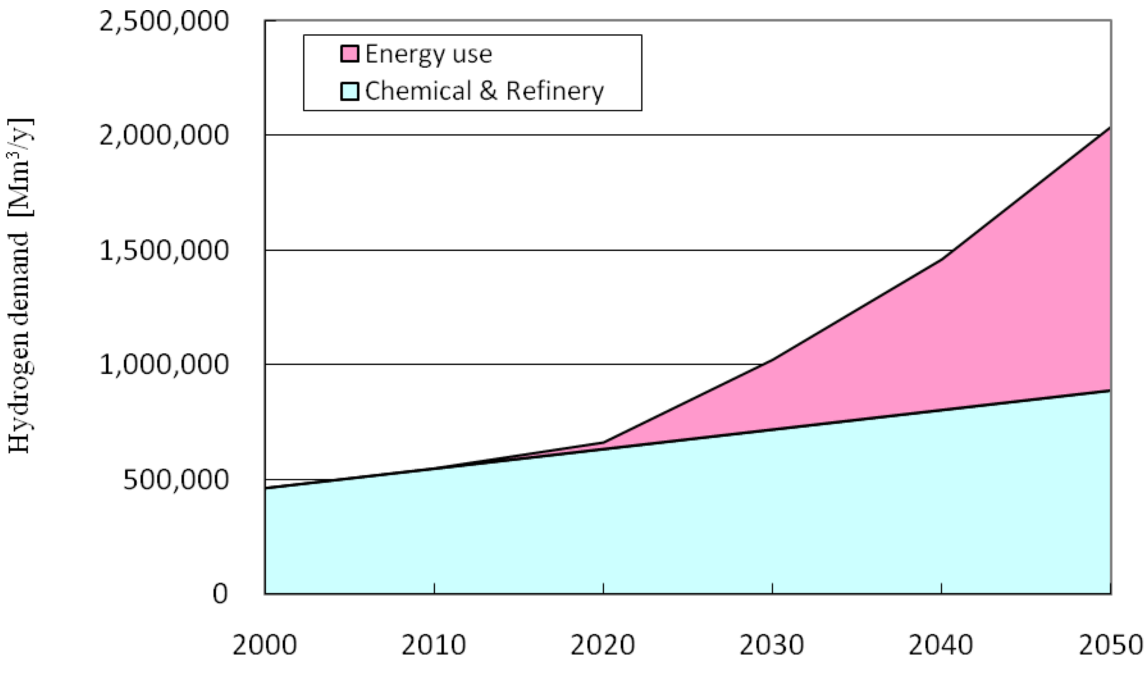


Fig. 2 Forecast of the global hydrogen demand[2)]

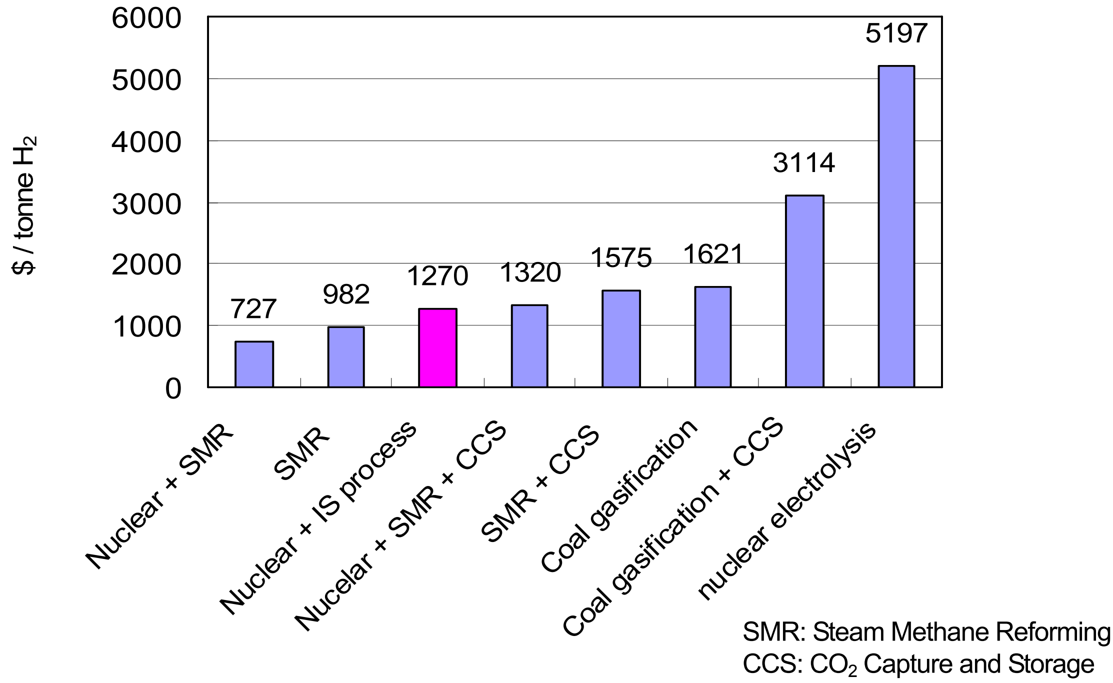


Fig. 3 Hydrogen production cost[3)]

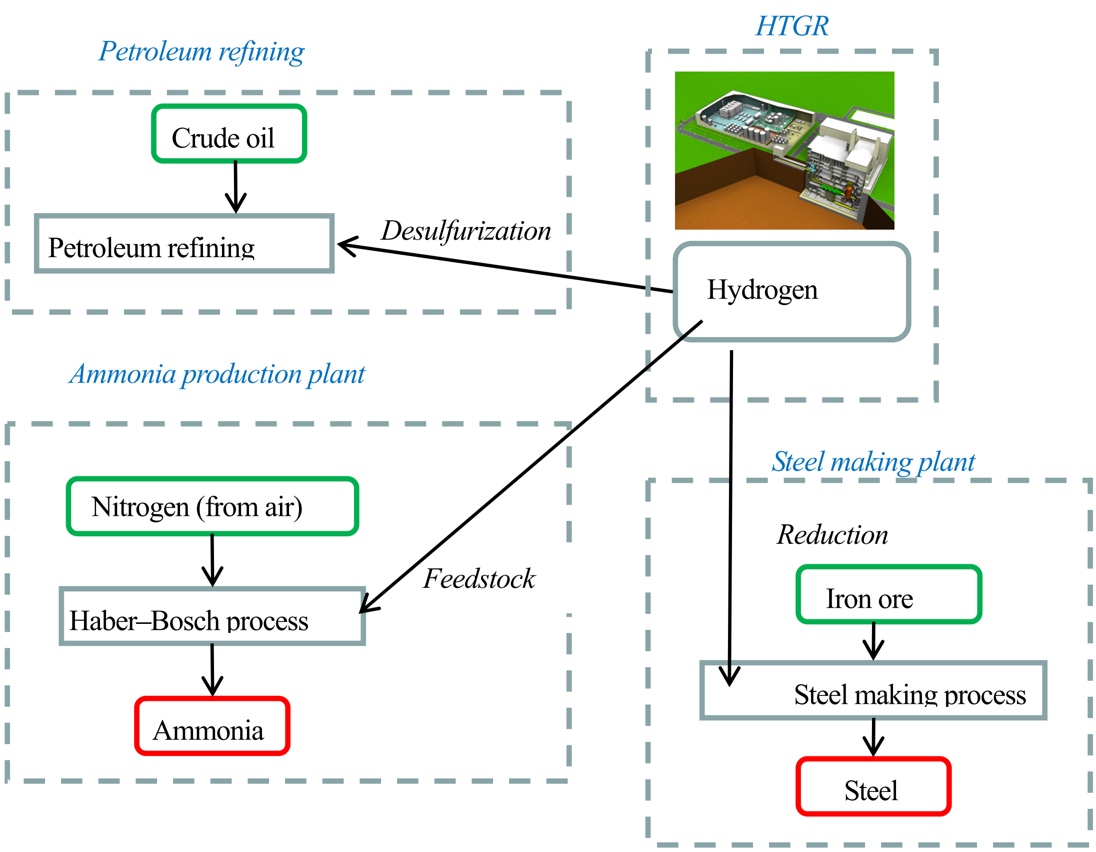


Fig. 4 Usage of nuclear produced hydrogen

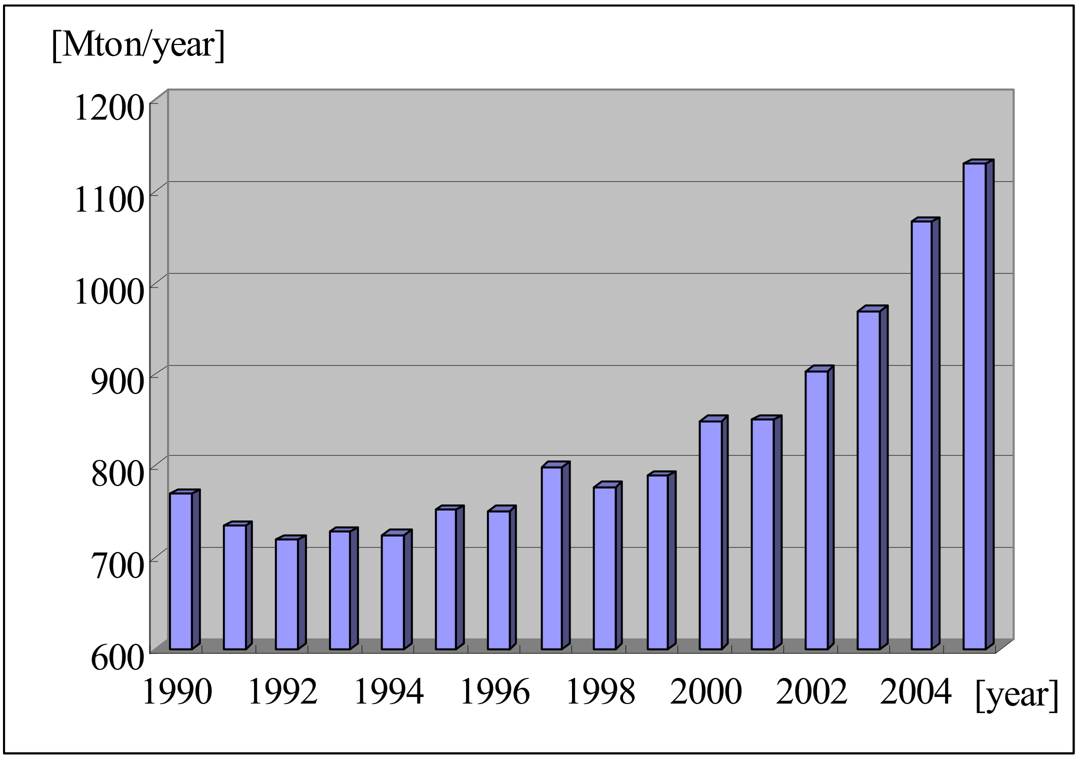


Fig. 5 Crude steel production in the world[5)]

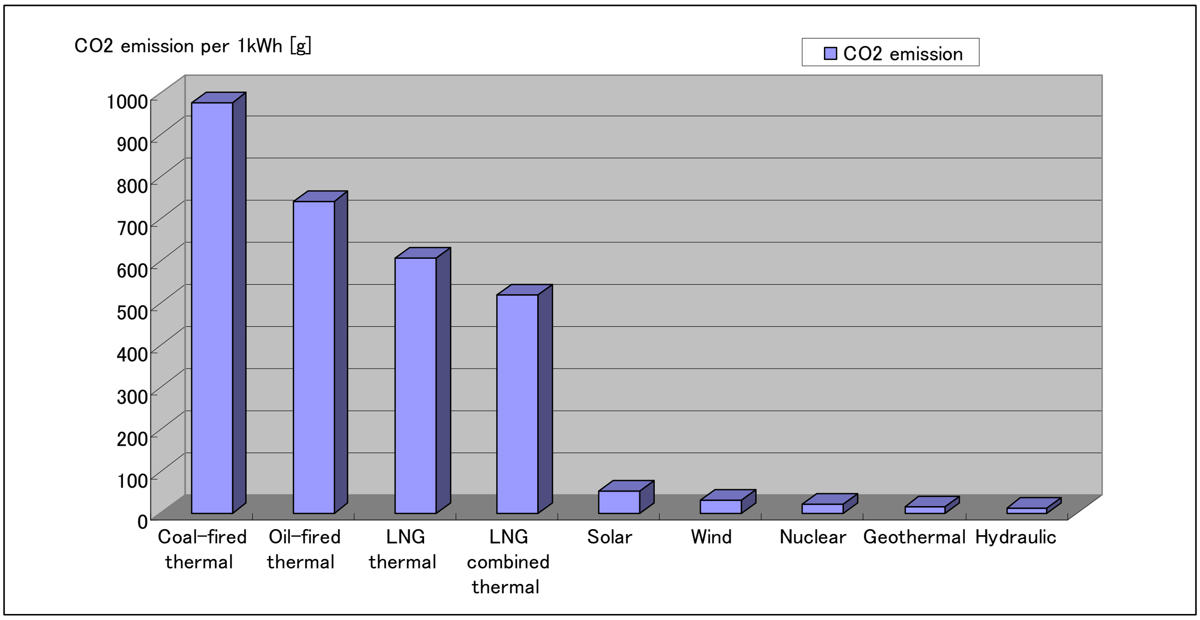


Fig. 6 CO_2 gas emissions from various hydrogen production systems[6)]

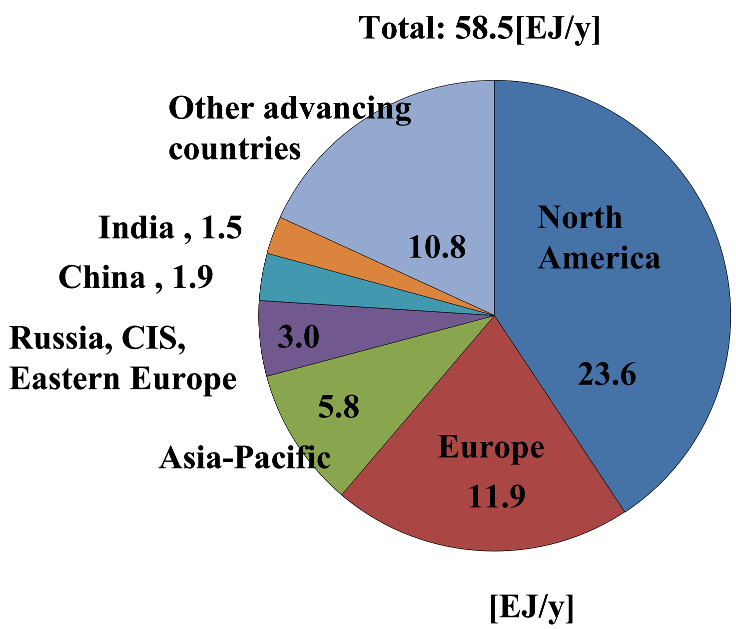


Fig. 7 Automotive energy consumption in the world[7)]

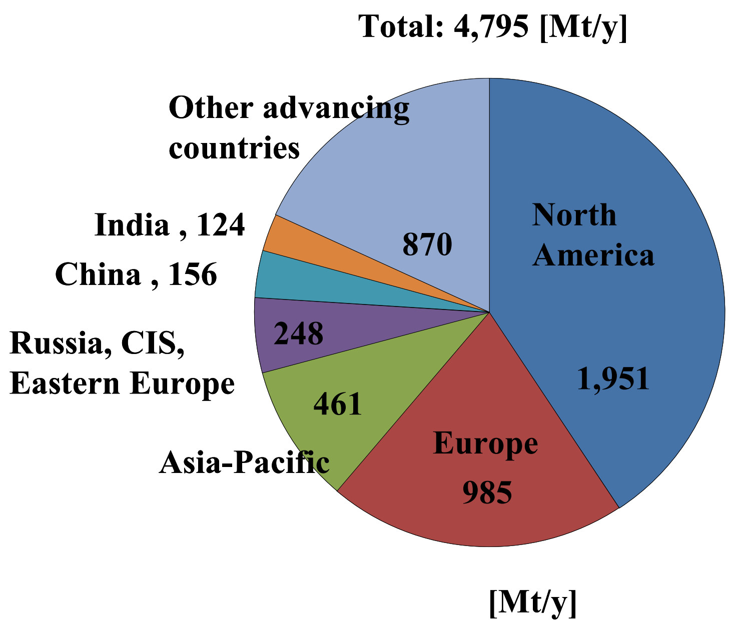


Fig. 8 Potential reduction quantity of carbon dioxide when the internal-combustion engine vehicle will replace to the fuel cell vehicle in all over the world[7)]

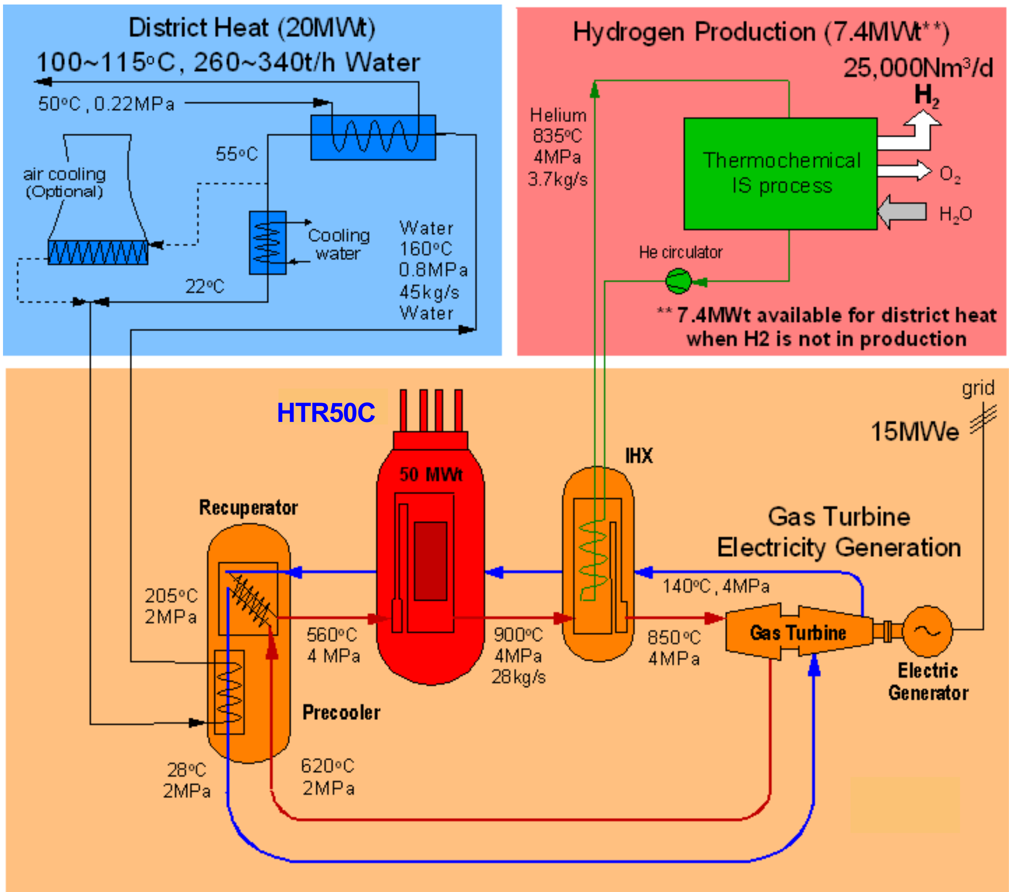


Fig. 9 Cascade energy plant cogeneration process parameters of the HTR50C

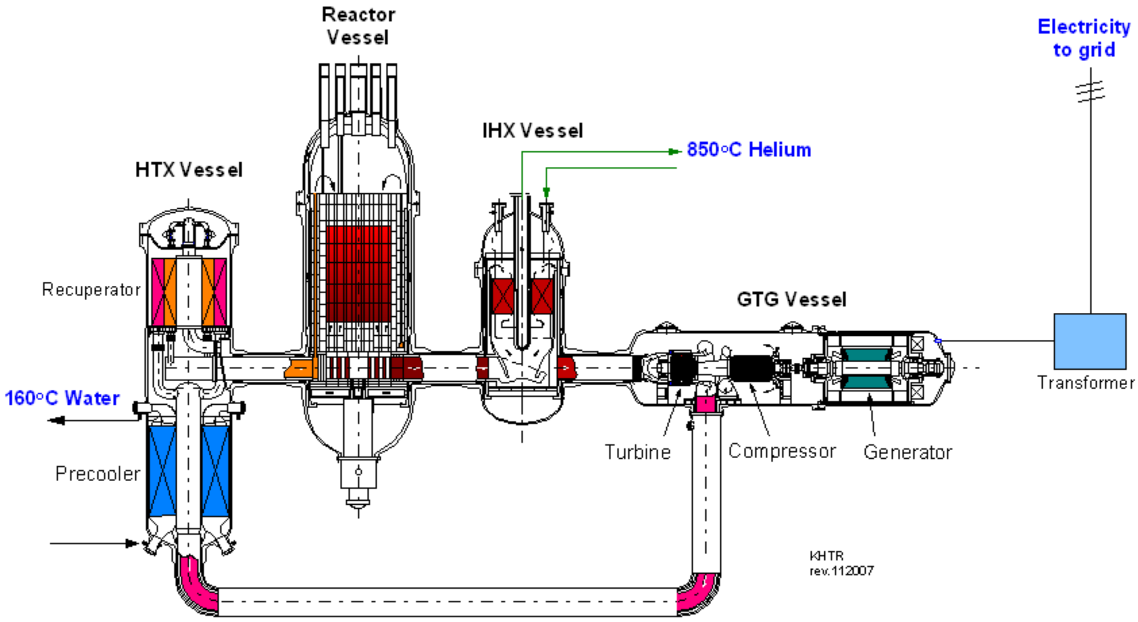
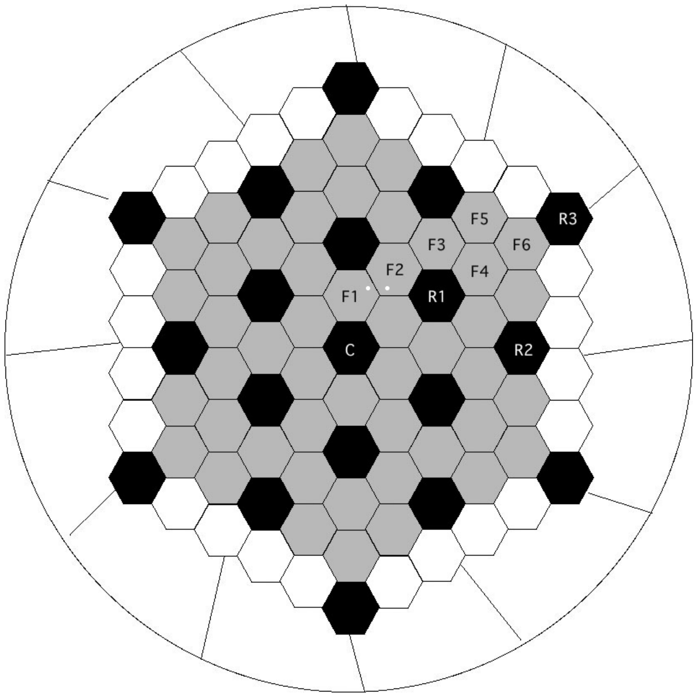


Fig. 10 The primary system layout of the HTR50C Plant



Fuel Columns: 48 (6 groups: F1-F6)

Control Rod Columns: 19 (4 groups: C. R1-R3)

Reflector Columns: 24

Fig.11 The core cross-section view of the HTR50C reactor

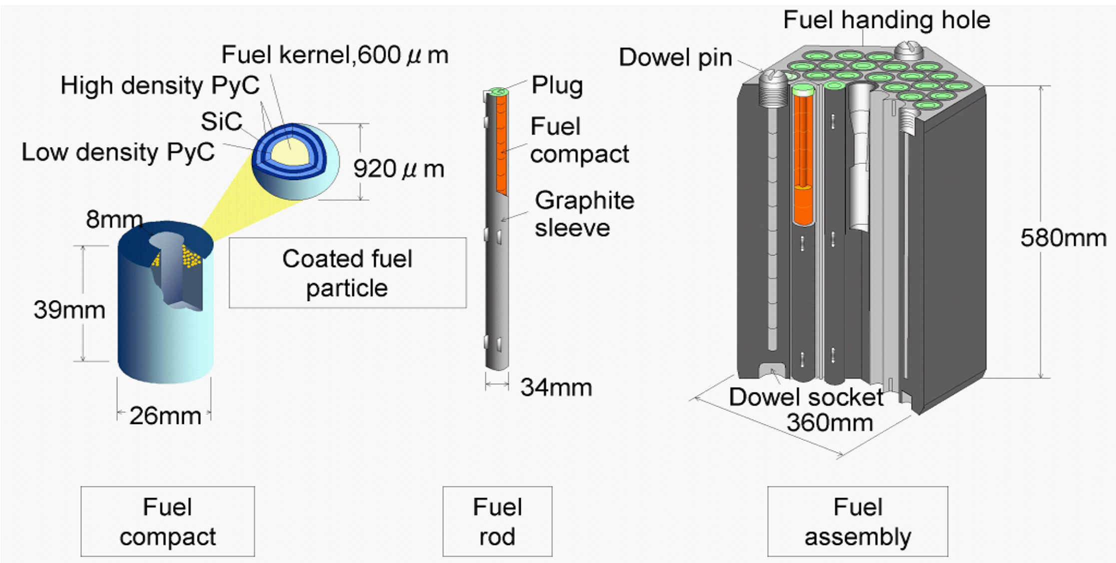


Fig. 12 The fuel element design for the first core of the HTR50C

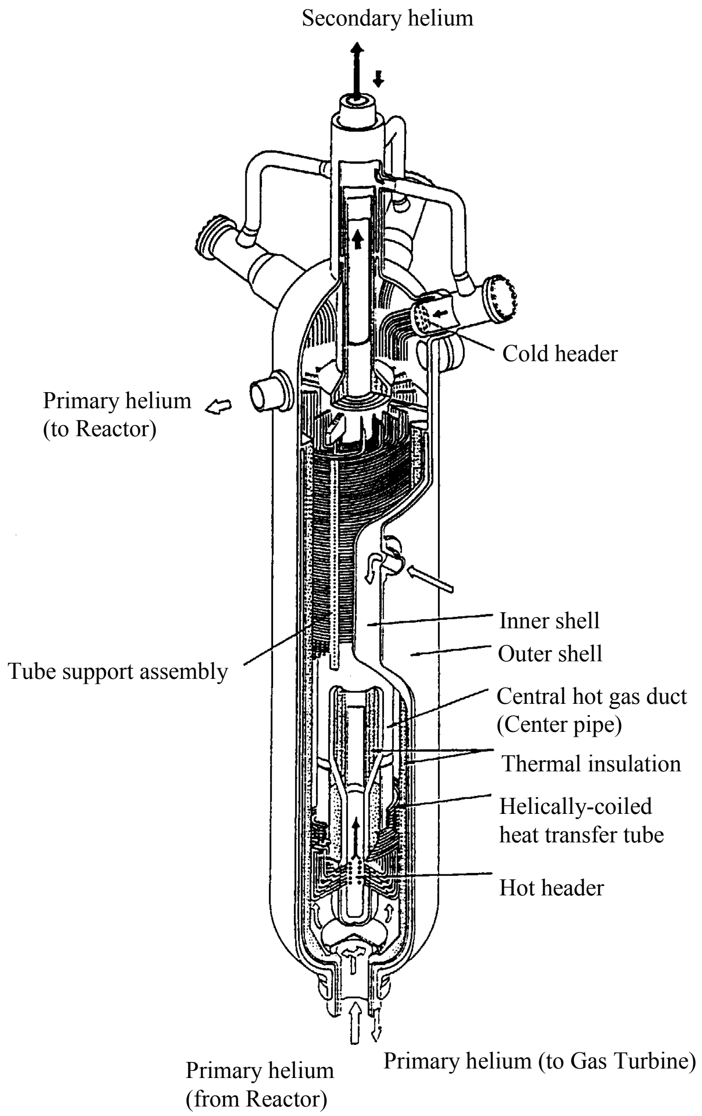


Fig. 13 Conceptual view of the IHX of the HTR50C

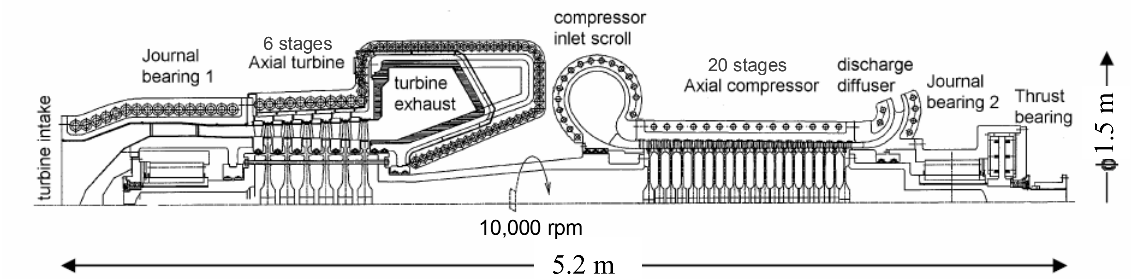


Fig. 14 15MWe class helium gas turbine for the HTR50C

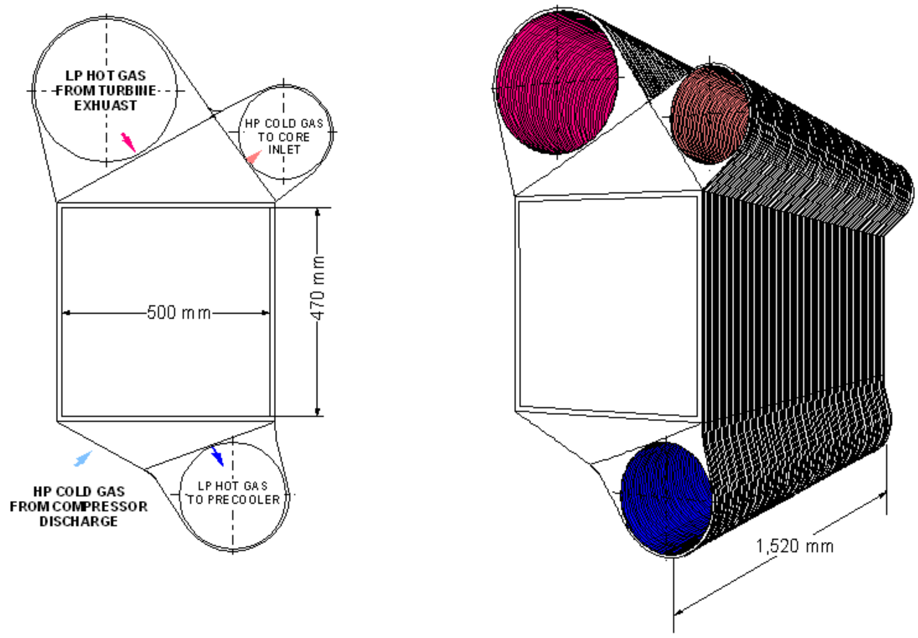


Fig. 15 One recuperator unit

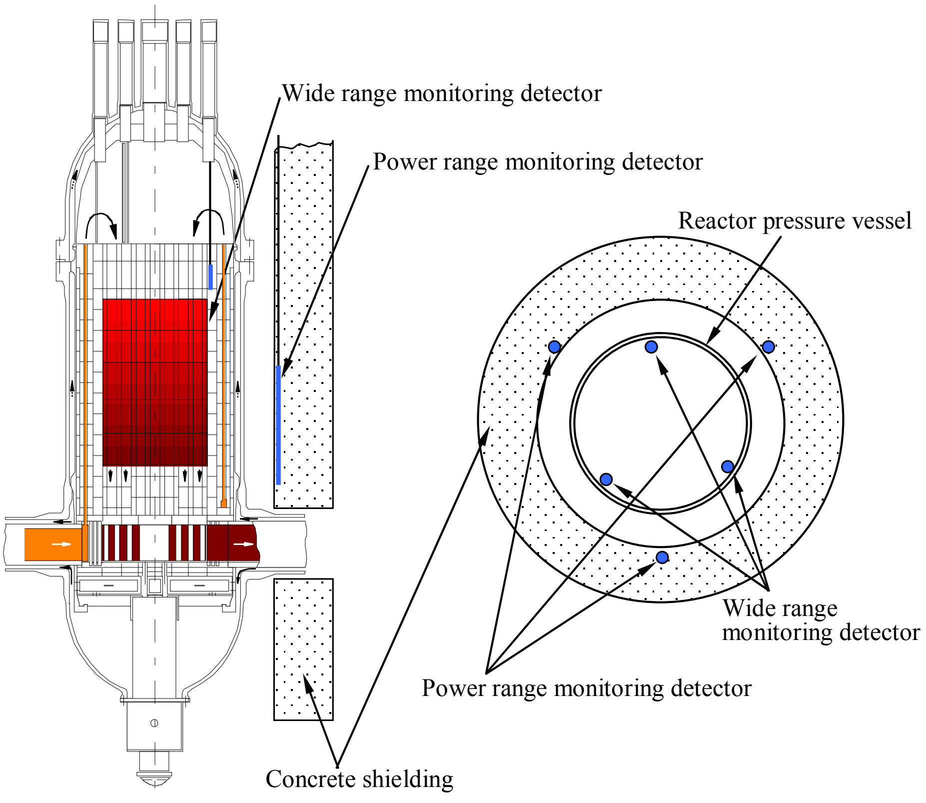


Fig. 16 Neutron detector arrangement

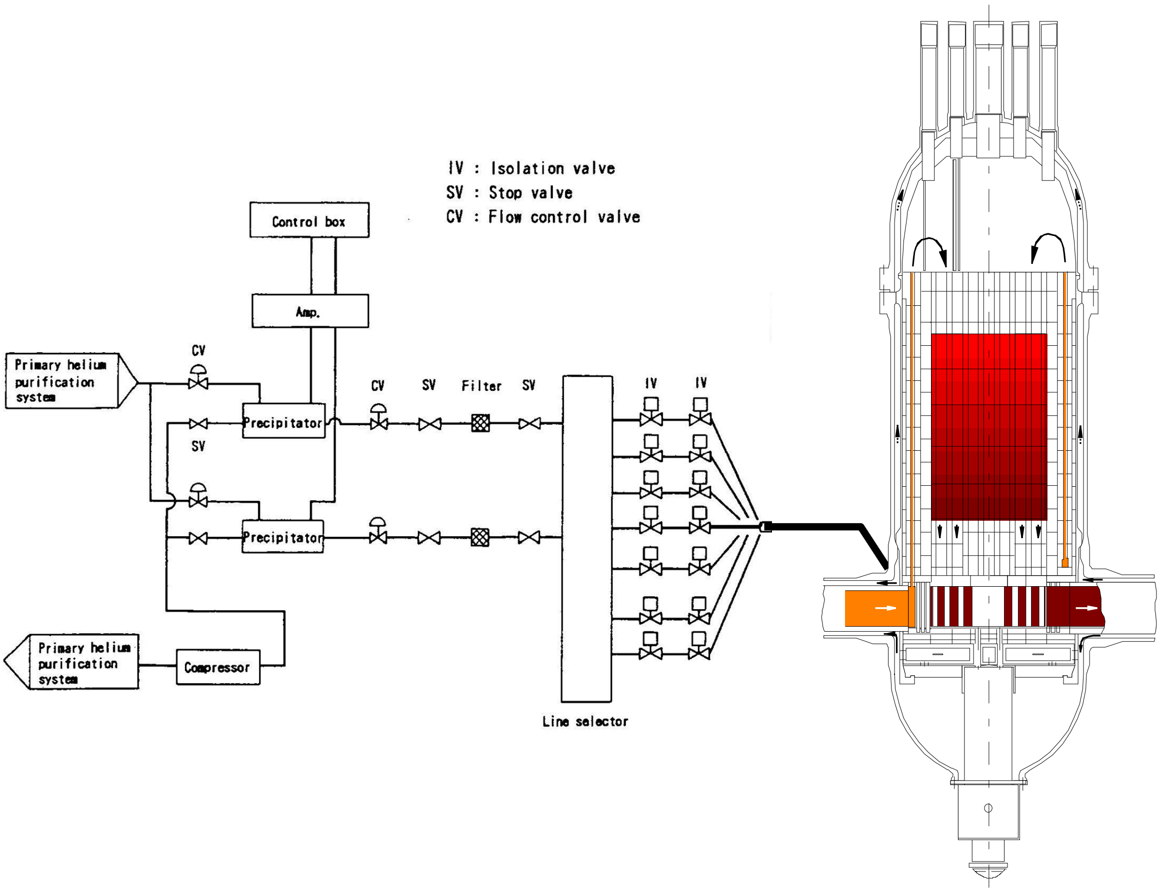


Fig. 17 Fuel failure detection system

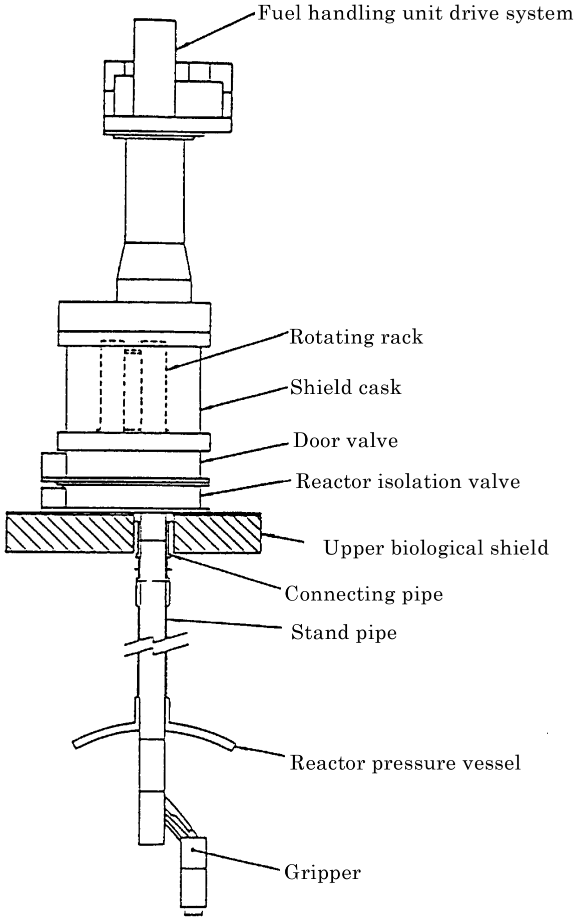


Fig. 18 Schematic diagram of fuel handling machine

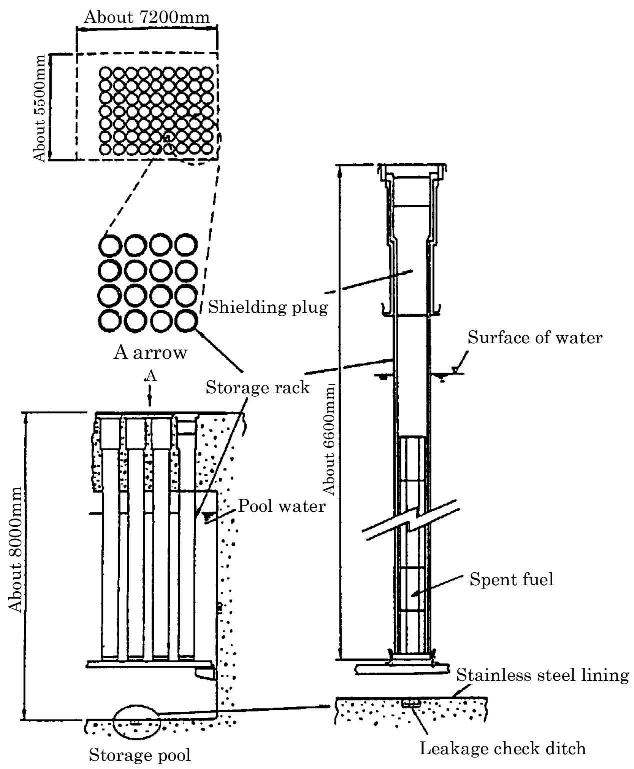


Fig. 19 Schematic diagram of spent fuel storage system in reactor building

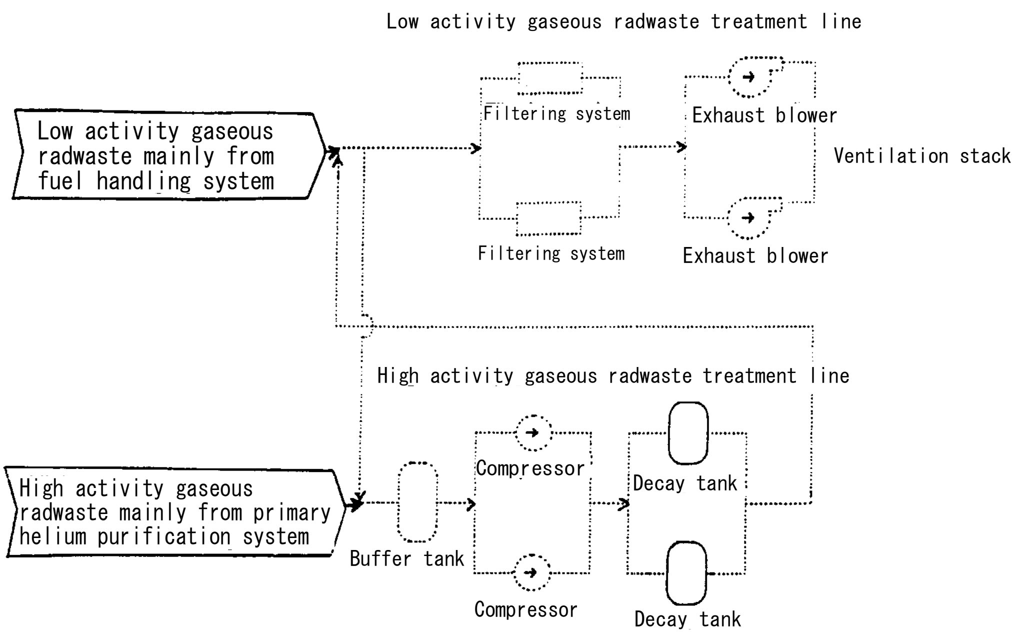


Fig. 20 Schematic diagram of the gaseous radioactive waste treatment system

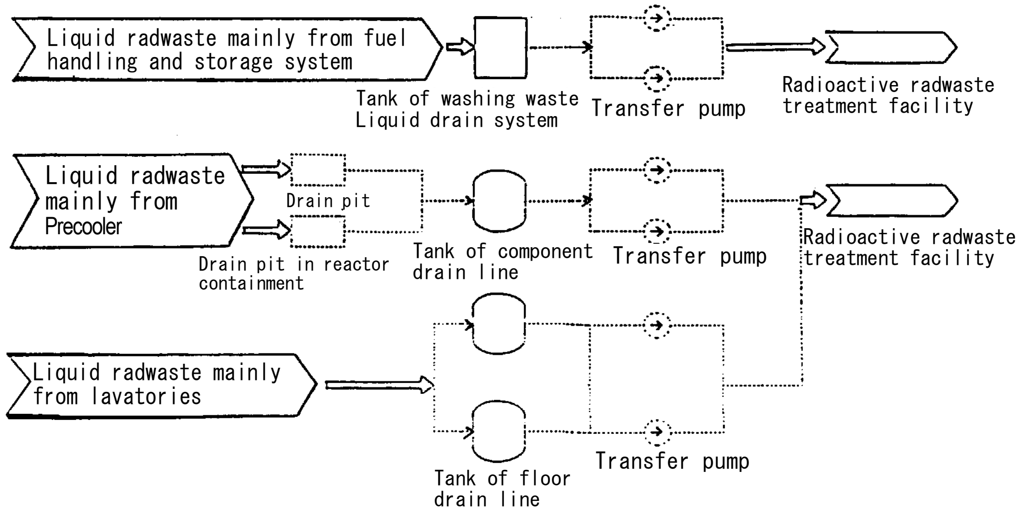


Fig. 21 Schematic diagram of the liquid radioactive waste treatment system

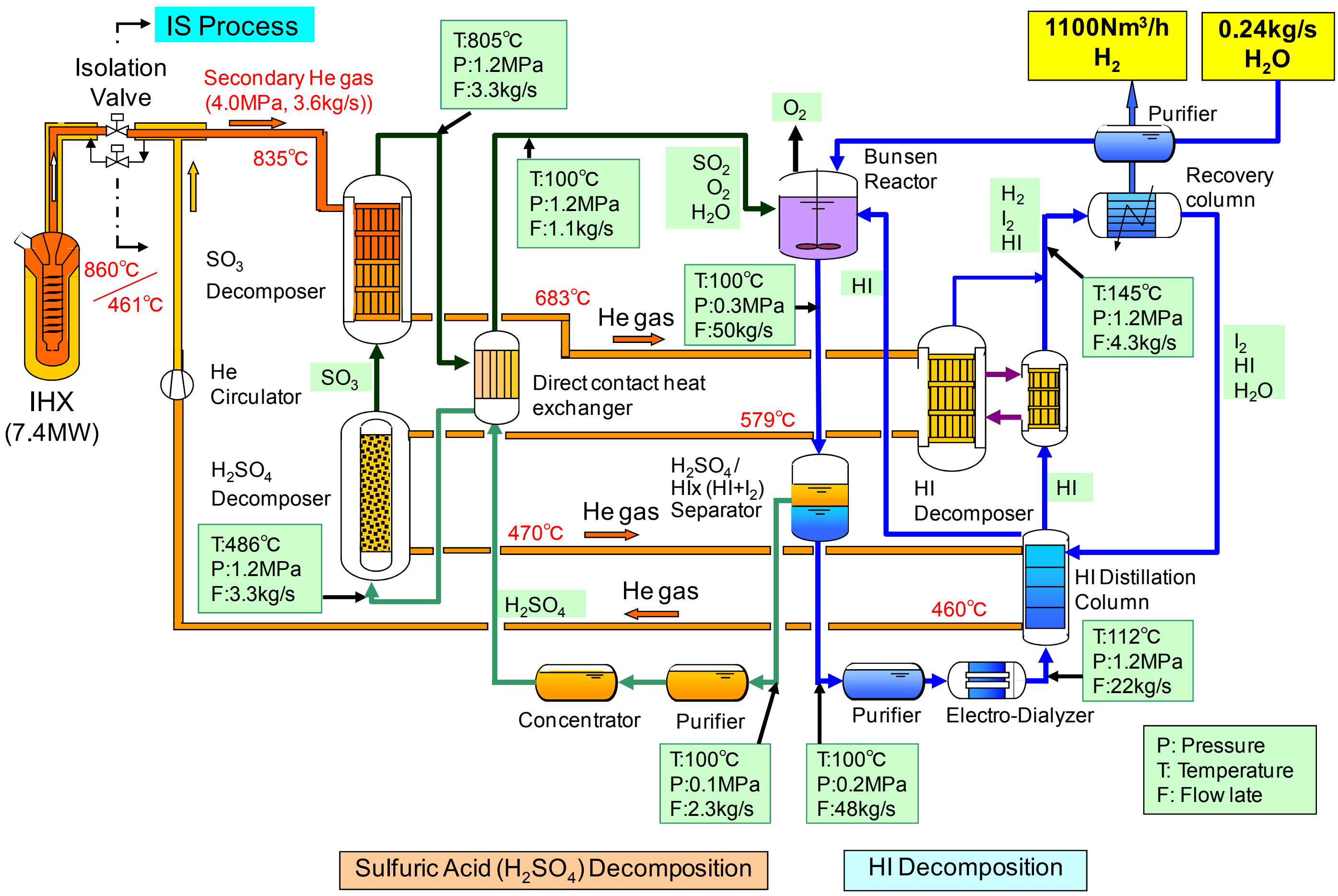


Fig. 22 Flow sheet diagram of the IS process coupled with the HTR50C

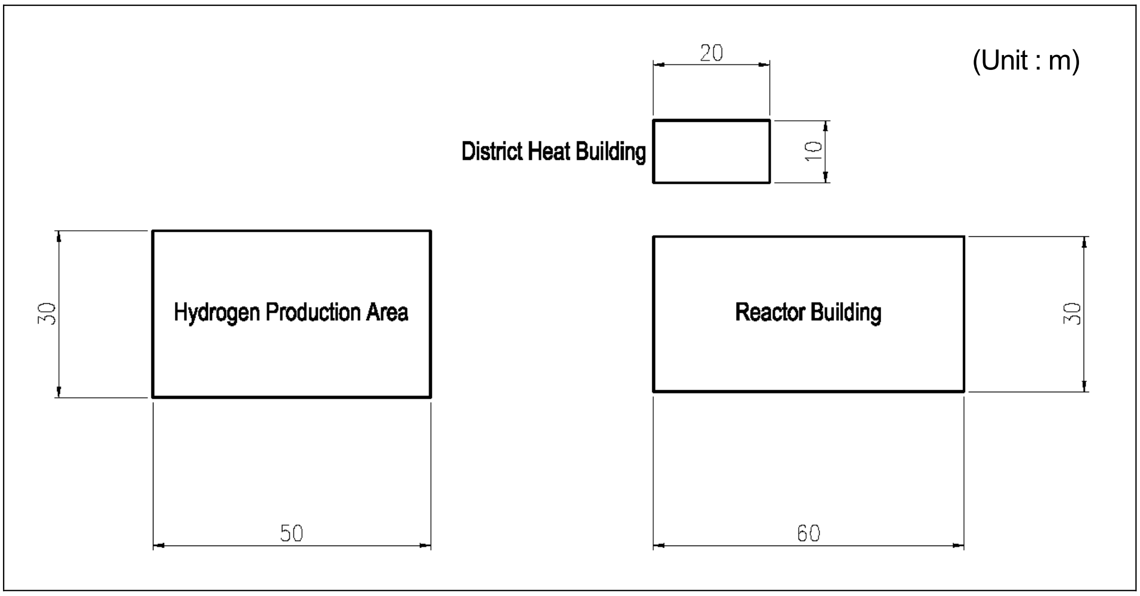
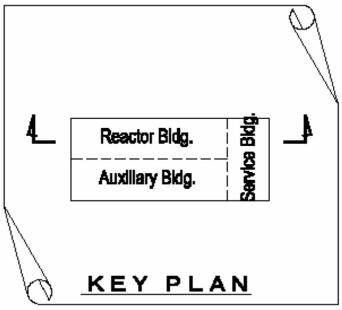


Fig. 23 Plant layout of the HTR50C



(Unit : m)

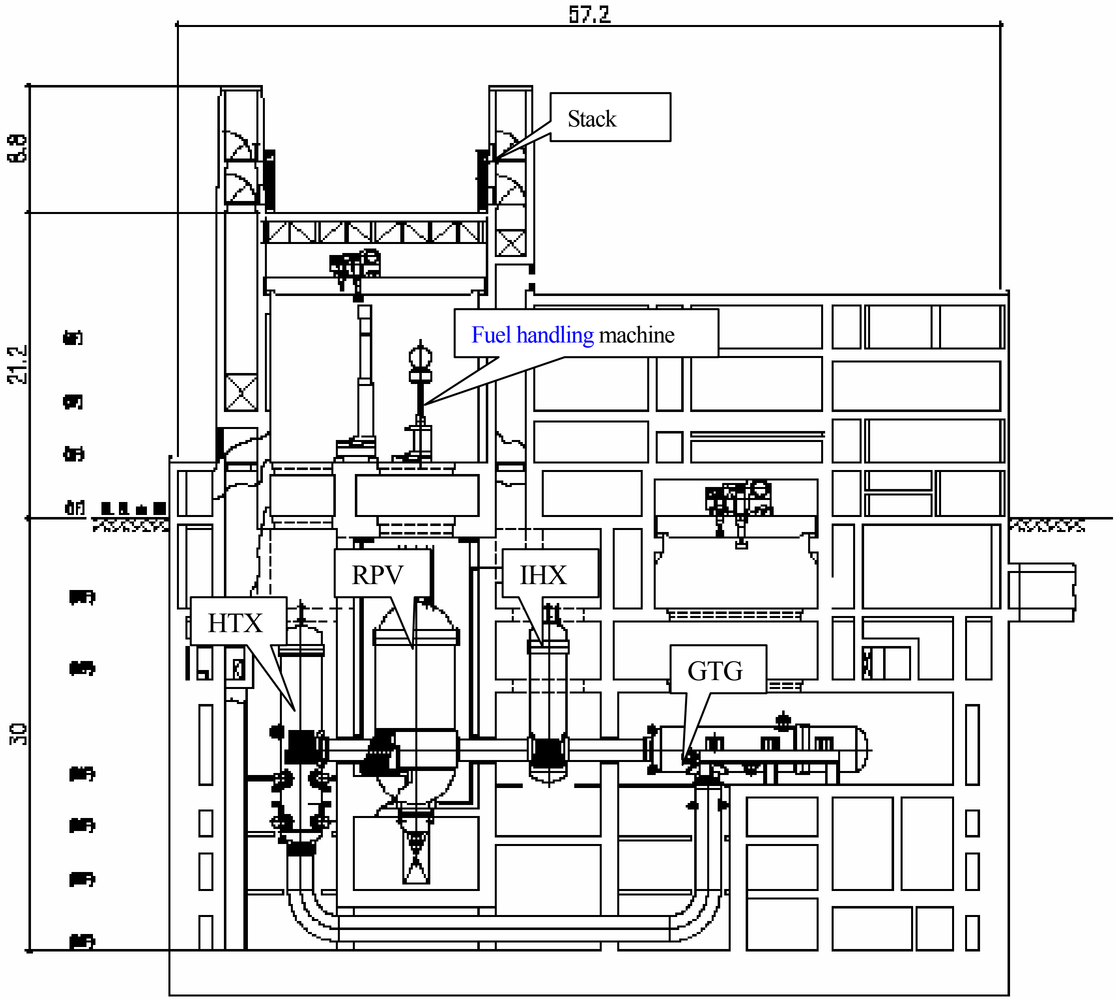
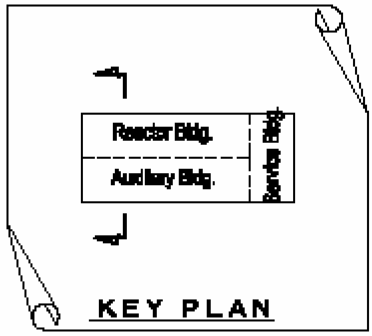


Fig. 24 Elevation of the reactor building



(Unit : m)

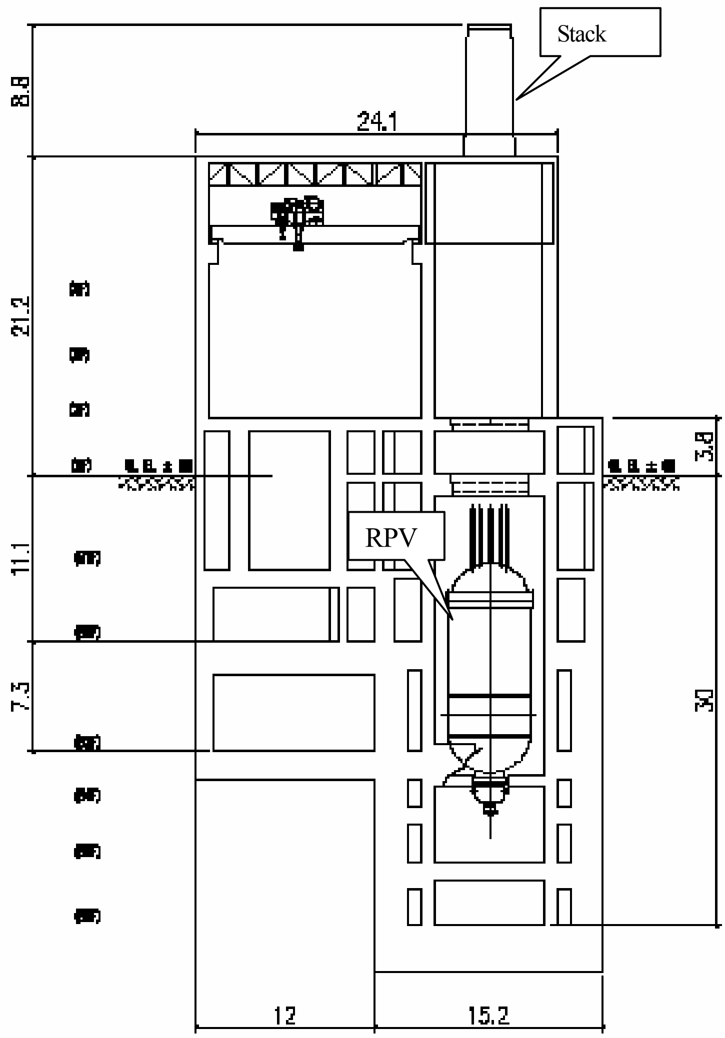
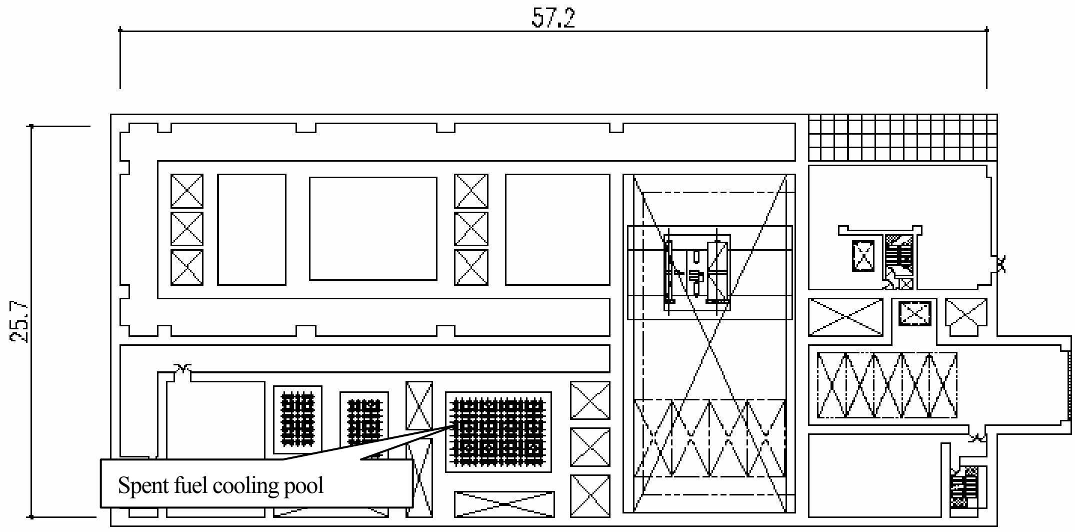
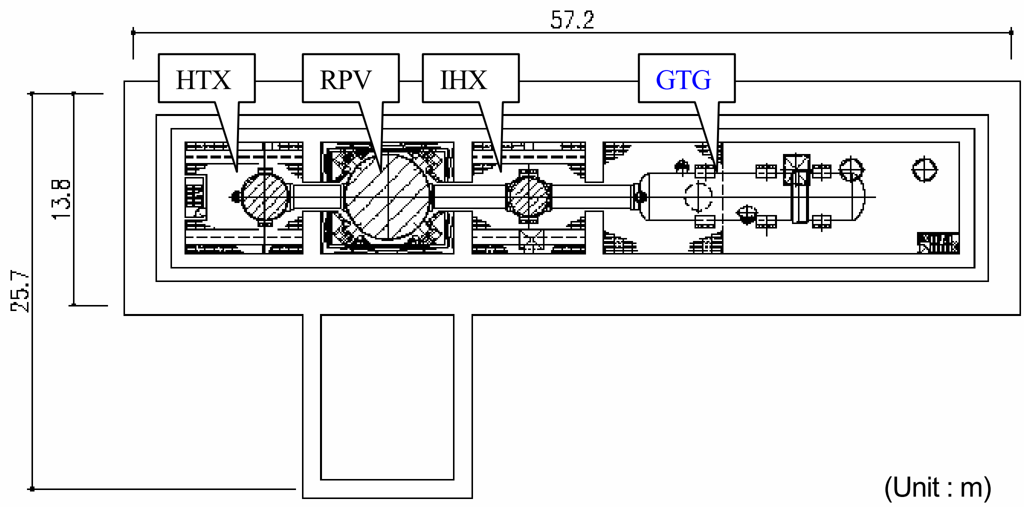


Fig. 25 Side view of the reactor building



(Ground floor)



(B3F)

Fig. 26 Plan view of the reactor building

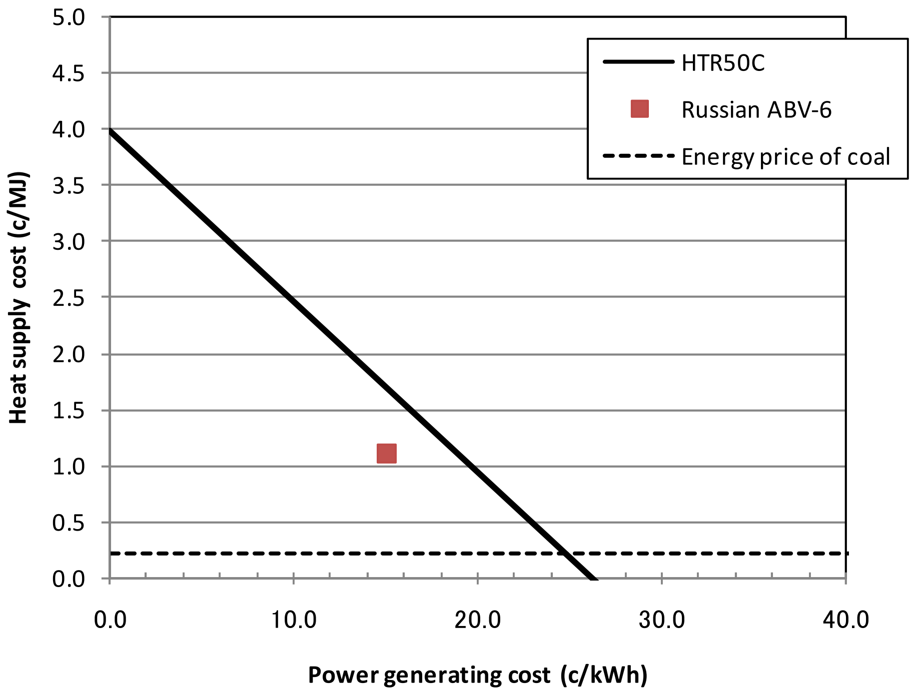


Fig. 27 The power generating cost and the heat supply cost of the HTR50C

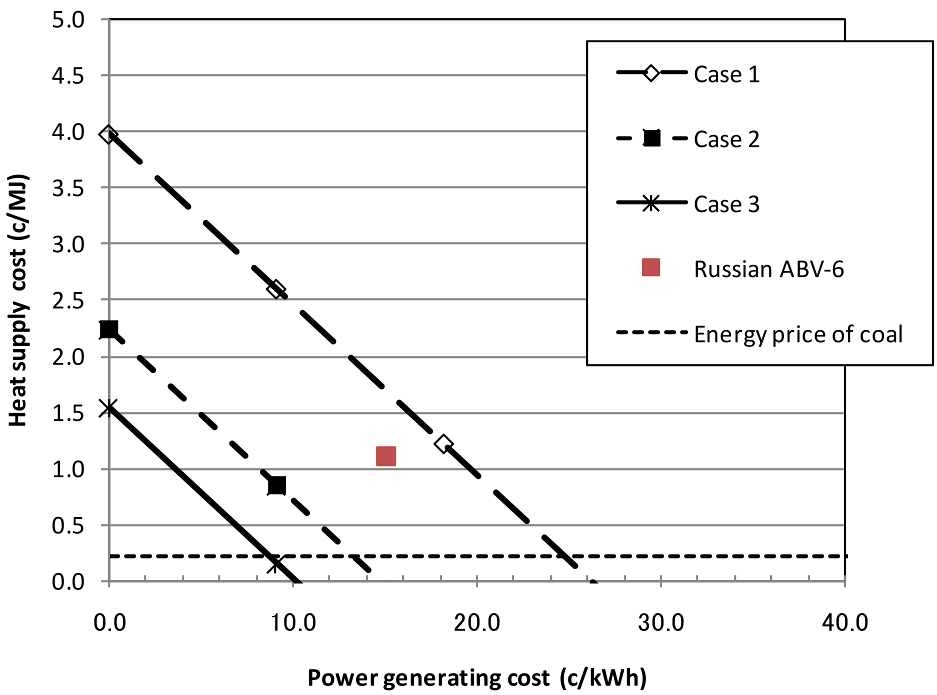


Fig. 28 The revised power generating cost and the heat supply cost of each case

This is a blank page.

国際単位系（SI）

表１．SI 基本単位

基本量	SI 基本単位	
	名称	記号
長さ	メートル	m
質量	キログラム	kg
時間	秒	s
電流	アンペア	A
熱力学温度	ケルビン	K
物質量	モル	mol
光度	カンデラ	cd

表２．基本単位を用いて表されるSI組立単位の例

組立量	SI 基本単位	
	名称	記号
面積	平方メートル	m^2
体積	立法メートル	m^3
速さ，速度	メートル毎秒	m/s
加速度	メートル毎秒毎秒	m/s^2
波数	毎メートル	m-1
密度（質量密度）	キログラム毎立法メートル	kg/m^3
質量体積（比体積）	立法メートル毎キログラム	m^3/kg
電流密度	アンペア毎平方メートル	A/m^2
磁界の強さ	アンペア毎メートル	A/m
（物質量の）濃度	モル毎立方メートル	mol/m^3
輝度	カンデラ毎平方メートル	cd/m^2
屈折率	（数の）１	1

表５．SI 接頭語

乗数	接頭語	記号	乗数	接頭語	記号
10^{24}	ヨタ	Y	10^{-1}	デシ	d
10^{21}	ゼタ	Z	10^{-2}	センチ	c
10^{18}	エクサ	E	10^{-3}	ミリ	m
10^{15}	ペタ	P	10^{-6}	マイクロ	μ
10^{12}	テラ	T	10^{-9}	ナノ	n
10^{9}	ギガ	G	10^{-12}	ピコ	p
10^{6}	メガ	M	10^{-15}	フェムト	f
10^{3}	キロ	k	10^{-18}	アト	a
10^{2}	ヘクト	h	10^{-21}	ゼプト	z
10^{1}	デカ	da	10^{-24}	ヨクト	y

表３．固有の名称とその独自の記号で表されるSI組立単位

組立量	SI 組立単位			
	名称	記号	他のSI単位による表し方	SI基本単位による表し方
平面角	ラジアン[(a)]	rad		$m \cdot m^{-1}=1$[(b)]
立体角	ステラジアン[(a)]	sr[(c)]		$m^2 \cdot m^{-2}=1$[(b)]
周波数	ヘルツ	Hz		s^{-1}
力	ニュートン	N		$m \cdot kg \cdot s^{-2}$
圧力，応力	パスカル	Pa	N/m^2	$m^{-1} \cdot kg \cdot s^{-2}$
エネルギー，仕事，熱量	ジュール	J	N・m	$m^2 \cdot kg \cdot s^{-2}$
工率，放射束	ワット	W	J/s	$m^2 \cdot kg \cdot s^{-3}$
電荷，電気量	クーロン	C		s・A
電位差（電圧），起電力	ボルト	V	W/A	$m^2 \cdot kg \cdot s^{-3} \cdot A^{-1}$
静電容量	ファラド	F	C/V	$m^{-2} \cdot kg^{-1} \cdot s^4 \cdot A^2$
電気抵抗	オーム	Ω	V/A	$m^2 \cdot kg \cdot s^{-3} \cdot A^{-2}$
コンダクタンス	ジーメンス	S	A/V	$m^{-2} \cdot kg^{-1} \cdot s^3 \cdot A^2$
磁束	ウエーバ	Wb	V・s	$m^2 \cdot kg \cdot s^{-2} \cdot A^{-1}$
磁束密度	テスラ	T	Wb/m^2	$kg \cdot s^{-2} \cdot A^{-1}$
インダクタンス	ヘンリー	H	Wb/A	$m^2 \cdot kg \cdot s^{-2} \cdot A^{-2}$
セルシウス温度	セルシウス度[(d)]	℃		K
光束	ルーメン	lm	cd・sr[(c)]	$m^2 \cdot m^{-2} \cdot cd=cd$
照度	ルクス	lx	lm/m^2	$m^2 \cdot m^{-4} \cdot cd=m^{-2} \cdot cd$
（放射性核種の）放射能	ベクレル	Bq		s^{-1}
吸収線量，質量エネルギー分与，カーマ	グレイ	Gy	J/kg	$m^2 \cdot s^{-2}$
線量当量，周辺線量当量，方向性線量当量，個人線量当量，組織線量当	シーベルト	Sv	J/kg	$m^2 \cdot s^{-2}$

(a) ラジアン及びステラジアンの使用は、同じ次元であっても異なった性質をもった量を区別するときの組立単位の表し方として利点がある。組立単位を形作るときのいくつかの用例は表４に示されている。
(b) 実際には、使用する時には記号rad及びsrが用いられるが、習慣として組立単位としての記号“１”は明示されない。
(c) 測光学では、ステラジアンの名称と記号srを単位の表し方の中にそのまま維持している。
(d) この単位は、例としてミリセルシウス度m℃のようにSI接頭語を伴って用いても良い。

表４．単位の中に固有の名称とその独自の記号を含むSI組立単位の例

組立量	SI 組立単位		
	名称	記号	SI 基本単位による表し方
粘度	パスカル秒	Pa・s	$m^{-1} \cdot kg \cdot s^{-1}$
力のモーメント	ニュートンメートル	N・m	$m^2 \cdot kg \cdot s^{-2}$
表面張力	ニュートン毎メートル	N/m	$kg \cdot s^{-2}$
角速度	ラジアン毎秒	rad/s	$m \cdot m^{-1} \cdot s^{-1}=s^{-1}$
角加速度	ラジアン毎平方秒	rad/s^2	$m \cdot m^{-1} \cdot s^{-2}=s^{-2}$
熱流密度，放射照度	ワット毎平方メートル	W/m^2	$kg \cdot s^{-3}$
熱容量，エントロピー	ジュール毎ケルビン	J/K	$m^2 \cdot kg \cdot s^{-2} \cdot K^{-1}$
質量熱容量（比熱容量），質量エントロピー	ジュール毎キログラム毎ケルビン	J/(kg・K)	$m^2 \cdot s^{-2} \cdot K^{-1}$
質量エネルギー（比エネルギー）	ジュール毎キログラム	J/kg	$m^2 \cdot s^{-2} \cdot K^{-1}$
熱伝導率	ワット毎メートル毎ケルビン	W/(m・K)	$m \cdot kg \cdot s^{-3} \cdot K^{-1}$
体積エネルギー	ジュール毎立方メートル	J/m^3	$m^{-1} \cdot kg \cdot s^{-2}$
電界の強さ	ボルト毎メートル	V/m	$m \cdot kg \cdot s^{-3} \cdot A^{-1}$
体積電荷	クーロン毎立方メートル	C/m^3	$m^{-3} \cdot s \cdot A$
電気変位	クーロン毎平方メートル	C/m^2	$m^{-2} \cdot s \cdot A$
誘電率	ファラド毎メートル	F/m	$m^{-3} \cdot kg^{-1} \cdot s^4 \cdot A^2$
透磁率	ヘンリー毎メートル	H/m	$m \cdot kg \cdot s^{-2} \cdot A^{-2}$
モルエネルギー	ジュール毎モル	J/mol	$m^2 \cdot kg \cdot s^{-2} \cdot mol^{-1}$
モルエントロピー，モル熱容量	ジュール毎モル毎ケルビン	J/(mol・K)	$m^2 \cdot kg \cdot s^{-2} \cdot K^{-1} \cdot mol^{-1}$
照射線量（Ｘ線及びγ線）	クーロン毎キログラム	C/kg	$kg^{-1} \cdot s \cdot A$
吸収線量率	グレイ毎秒	Gy/s	$m^2 \cdot s^{-3}$
放射強度	ワット毎ステラジアン	W/sr	$m^4 \cdot m^{-2} \cdot kg \cdot s^{-3}=m^2 \cdot kg \cdot s^{-3}$
放射輝度	ワット毎平方メートル毎ステラジアン	$W/(m^2 \cdot sr)$	$m^2 \cdot m^{-2} \cdot kg \cdot s^{-3}=kg \cdot s^{-3}$

表６．国際単位系と併用されるが国際単位系に属さない単位

名称	記号	SI 単位による値
分	min	1 min=60s
時	h	1h =60 min=3600 s
日	d	1 d=24 h=86400 s
度	°	$1° =(\pi/180)$ rad
分	’	$1’ =(1/60)° =(\pi/10800)$ rad
秒	”	$1” =(1/60)’ =(\pi/648000)$ rad
リットル	l、L	$1l=1\ dm^3=10^{-3}m^3$
トン	t	$1t=10^3$ kg
ネーパ	Np	1Np=1
ベル	B	1B=(1/2)ln10(Np)

表７．国際単位系と併用されこれに属さない単位で
SI単位で表される数値が実験的に得られるもの

名称	記号	SI 単位であらわされる数値
電子ボルト	eV	$1eV=1.60217733(49)\times10^{-19}J$
統一原子質量単位	u	$1u=1.6605402(10)\times10^{-27}kg$
天文単位	ua	$1ua=1.49597870691(30)\times10^{11}m$

表８．国際単位系に属さないが国際単位系と
併用されるその他の単位

名称	記号	SI 単位であらわされる数値
海里		１海里=1852m
ノット		１ノット=１海里毎時=(1852/3600)m/s
アール	a	$1\ a=1\ dam^2=10^2m^2$
ヘクタール	ha	$1\ ha=1\ hm^2=10^4m^2$
バール	bar	$1\ bar=0.1MPa=100kPa=1000hPa=10^5Pa$
オングストローム	Å	$1\ Å=0.1nm=10^{-10}m$
バーン	b	$1\ b=100fm^2=10^{-28}m^2$

表９．固有の名称を含むCGS組立単位

名称	記号	SI 単位であらわされる数値
エルグ	erg	$1\ erg=10^{-7}\ J$
ダイン	dyn	$1\ dyn=10^{-5}N$
ポアズ	P	$1\ P=1\ dyn \cdot s/cm^2=0.1Pa \cdot s$
ストークス	St	$1\ St =1cm^2/s=10^{-4}m^2/s$
ガウス	G	$1\ G \triangleq 10^{-4}T$
エルステッド	Oe	$1\ Oe \triangleq (1000/4\pi)A/m$
マクスウェル	Mx	$1\ Mx \triangleq 10^{-8}Wb$
スチルブ	sb	$1\ sb =1cd/cm^2=10^4cd/m^2$
ホト	ph	$1\ ph=10^4lx$
ガル	Gal	$1\ Gal =1cm/s^2=10^{-2}m/s^2$

表10．国際単位に属さないその他の単位の例

名称	記号	SI 単位であらわされる数値
キュリー	Ci	$1\ Ci=3.7\times10^{10}Bq$
レントゲン	R	$1\ R = 2.58\times10^{-4}C/kg$
ラド	rad	$1\ rad=1cGy=10^{-2}Gy$
レム	rem	$1\ rem=1\ cSv=10^{-2}Sv$
X線単位		$1X\ unit=1.002\times10^{-4}nm$
ガンマ	γ	$1\gamma=1\ nT=10^{-9}T$
ジャンスキー	Jy	$1\ Jy=10^{-26}W \cdot m^{-2} \cdot Hz^{-1}$
フェルミ		$1\ fermi=1\ fm=10^{-15}m$
メートル系カラット		$1\ metric\ carat = 200\ mg = 2\times10^{-4}kg$
トル	Torr	1 Torr = (101 325/760) Pa
標準大気圧	atm	1 atm = 101 325 Pa
カロリー	cal	
ミクロン	μ	$1\ \mu=1\mu m=10^{-6}m$

（第７版，1998年改訂）