Journal of NUCLEAR SCIENCE and TECHNOLOGY, Vol. 45, No. 12, p. 1316–1325 (2008)

ARTICLE

Thermodynamic and Economic Analyses of HTGR Cogeneration System Performance at Various Operating Conditions for Proposing Optimized Deployment Scenarios

Qi ZHANG*, Hidekazu YOSHIKAWA, Hirotake ISHII and Hiroshi SHIMODA

Graduate School of Energy Science, Kyoto University, Gokasho, Uji, Kyoto 611-0011, Japan

(Received April 22, 2008 and accepted in revised form August 25, 2008)

Several potential deployment scenarios of high-temperature gas reactor (HTGR) cogeneration systems for the simultaneous production of hydrogen and electricity have been proposed recently. They can operate under different conditions and thereby satisfy different hydrogen and electricity demand scenarios, but their performance must be studied to demonstrate thermodynamic feasibility and economic profitability to attract sufficient investment for their deployment. Therefore, this study uses exergy analysis and exergy-based costing analysis methods to analyze HTGR cogeneration system performance thermodynamically and economically over the entire range of potential operating conditions by calculating performance indicators, exergy efficiency, and the specific cost per unit product. Furthermore, three optimized deployment scenarios with high performance for satisfying three different hydrogen demand scenarios are proposed based on the analysis results. The proposed three deployment scenarios show that the HTGR cogeneration system is thermodynamically efficient and economically competitive compared with other hydrogen and electricity generation systems. The feasibility of exergy analysis and exergy-based costing analysis methods for analyzing the HTGR cogeneration system so as to propose optimized deployment scenarios is demonstrated by the obtained findings practically.

KEYWORDS: HTGR, cogeneration system, performance analysis, exergy analysis, exergy-based cost analysis, hydrogen production

I. Introduction

High-temperature gas reactors (HTGRs) present advantages of inherent safety and a high outlet coolant temperature (about 950°C). Their inherent safety eases their acceptance by the public and their high outlet coolant temperature makes them suitable to supply heat for a cogeneration system. In particular, the outlet temperature from HTGR is higher than 850°C; thus, it is possible to generate hydrogen through a thermochemical iodine-sulfur (IS) process using the heat transferred through an intermediate heat exchanger (IHX) from high-temperature helium emitted from the reactor. The helium coming from IHX is used to drive a gas turbine directly to produce electricity. Finally, the heat of the exhaust gas leaving from the gas turbine can be exhausted freely through a precooler or used to provide heat for district heating or seawater desalination. For example, both the Gas Turbine High-Temperature Reactor 300 (GTHTR300) and Gas Turbine High-Temperature Reactor 300-Cogeneration (GTHTR300C) of the High-Temperature Test Rector (HTTR) project studied by Japan Atomic Energy Agency (JAEA) are highly advanced HTGR options that are still in the design stage.[1–11)] Their design philosophy is simplicity, economical competitiveness, and originality (SECO). They have been studied from the viewpoints of whole system design concept[1–4)] and safety.[5,6)] The economic investigation of GTHTR300 with only one product, electricity, has also been conducted by estimating all the relevant cost information associated with the equipment, nuclear fuel, management, and operation.[7,8)]

However, for an HTGR cogeneration system, such as GTHTR300C, generating hydrogen and electricity simultaneously, although several possible development scenarios with different operating conditions satisfying different demands have been proposed by JAEA[9,10)] and the Japan Atomic Industrial Forum (JAIF),[11)] the systems cannot attract sufficient business investment until their feasibility and profitability have been demonstrated quantitatively. In particular, the specific costs per unit hydrogen and electricity have never been reported for GTHTR300C because of the lack of a broadly acceptable feasible method for allocating system costs to multiple products. Therefore, this study is intended to investigate the HTGR cogeneration system performance when producing hydrogen and electricity from thermodynamic and economic aspects over the entire range of potential operating conditions. Thereby, we can propose optimized deployment scenarios with high performance to

*Corresponding author, E-mail: zhangqi@uji.energy.kyoto-u.ac.jp

provide information for attracting investment and achieving the final deployment of these systems.

Therefore, the concept of exergy is introduced in this study with the intention of conducting exergy analyses to measure the thermodynamic performance of the HTGR cogeneration system. Exergy is defined as the maximal work attainable from an energy carrier under a given environmental condition as a reference. It can be considered as the quality (working potential) of energy. Various energy carriers with similar quantities might display considerably different qualities (exergy) because exergy is a property of state that is related to both heat content and the degree of randomness (known as entropy). For example, the quality of heat depends strongly on the heat source temperature because the higher the temperature of a heat source relative to the ambient temperature, the greater the amount of heat can be converted to mechanical work: it has larger exergy. Furthermore, exergy has the characteristic that it is destroyed whenever an irreversible process occurs. In this regard, thermodynamic imperfections attributable to irreversibilities can be quantified as exergy destruction in exergy analysis because it represents losses in energy quality and usefulness, which cannot be indicated merely by energy analysis. Therefore, exergy analysis can identify thermodynamically inefficient processes in overall cogeneration systems, thereby providing a more comprehensive and precise understanding of the system's thermodynamic performance.[12)]

The concept of exergy is crucial not only for efficiency studies but also for cost accounting and economic analysis. Because cost is expected to reflect the value (working ability) of the energy carrier, the same working ability is considered to hold the same value. Therefore, exergy is useful as a basis for assigning costs to multiple products in a cogeneration system through exergy-based costing analysis (alternatively, it is called thermoeconomic analysis or exergoeconomic analysis) by combining exergy and economic analyses, which has been broadly applied to various cogeneration systems as a standard.[13–17)] The exergy-based costing analysis method is applied in this study to estimate the specific cost of the hydrogen and electricity generated by the HTGR cogeneration system.

To investigate the performance of the target HTGR system under various operating conditions, three independent parameters including the outlet temperature of IHX, the inlet temperature of the compressor, and the pressure ratio of the system are chosen to represent all other parameters to form various operating conditions. Furthermore, a software platform has been developed to facilitate the efficient use of these analysis methods. The software deals with abundant thermodynamic and cost equations. The production of the hydrogen and electricity, the exergetic efficiency of the system, and the specific costs of unit hydrogen and electricity are obtained for various operating conditions. Furthermore, three optimized deployment scenarios are proposed to meet three different demand scenarios based on the obtained performance information. The proposed optimized scenarios show that the HTGR cogeneration system is thermodynamically efficient and economically competitive compared with other hydrogen and electricity generation systems. Also, the obtained performance information of the HTGR cogeneration system under various operating conditions can provide valuable information for its future deployment.

This paper is organized as follows: in Sec. 2, the HTGR cogeneration system design is introduced. In Sec. 3, the exergy and exergy-based costing analysis models are introduced. In Sec. 4, the thermodynamic, exergy analysis, and exergy-based costing analysis models of the HTGR cogeneration system are described. In Sec. 5, analysis results obtained under various operating conditions are explained. Lastly, in Sec. 6, a summary of the analysis results is presented.

The meanings of variables and notations used in the equations presented in this paper are shown in the Nomenclature and Subscript sections.

II. System Design of the Target HTGR Cogeneration System

1. System Configuration

In reference to past studies,[1–11)] a typical HTGR cogeneration system is chosen in this study and presented in **Fig. 1**, with the initial design parameters kept constant. The heat capacity of the rector is 600 MWt; the inlet and outlet temperatures of the reactor are respectively 594 and 950°C. Therefore, the helium flow rate in the main loop is determined as 324 kg/s according to the specific heat of helium, as portrayed in **Table 1**. The inlet and outlet temperatures of the second loop of the IS process for producing hydrogen are respectively 900 and 500°C according to the reaction conditions. Both pressures of the main and IS process's second loops are determined as 5.1 MPa for limiting creep damage to IHX.

In this target HTGR cogeneration system, the helium and water flows in the main and second loops are numbered to identify their locations. In the main loop, for numbers 1–7, the helium from the reactor is first used to provide high-temperature heat to the IS hydrogen generation process through IHX. Subsequently, the helium from IHX enters the gas turbine directly to generate electric power by turning the generator. Finally, the helium flow from the gas turbine first passes through the recuperator. It is then cooled by cold

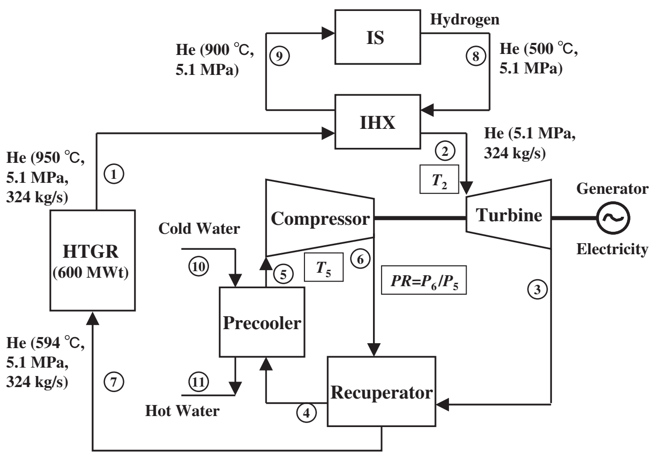


Fig. 1 Flow sheet of the HTGR cogeneration system

Table 1 Design parameters and initial conditions

Parameter	Value	Parameter	Value
HTGR thermal power	600 MWt	Cp_{He}	5.18 kJ/kg K
R_{He}	2.8 kJ/kg K	K	1.666
$\eta_{\mathrm{Compressor}}$	0.9	η_{Turbine}	0.9
ΔT	5°C	System load factor	90%
Standard Temperature ($T0$)	298.15 K	Standard Pressure ($P0$)	1.013 bar

water in a precooler for ease of compression; it returns to the reactor through the compressor and recuperator.

2. Objective of This Study

The target HTGR cogeneration system presented in Fig. 1 can produce different amounts of hydrogen and electricity at different operating conditions. For example, the outlet temperature of IHX can determine the heat capacity of IHX, then hydrogen production; the compressor's pressure ratio can determine the electricity production. The objective of this study is to investigate the HTGR cogeneration system performance under various operating conditions. Then, we propose optimized scenarios to provide information for attracting investment and achieving final deployment. Moreover, the performance analysis methods, exergy and exergy-based costing analysis methods, are introduced in the next section.

III. Exergy Analysis and Exergy-Based Cost Analysis Based on the EXCEM Model

1. EXCEM Model

Traditionally, exergy analysis is conducted using the principles of conservation of mass and energy to calculate the necessary physical parameters. Exergy-based cost analysis is carried out based on the exergy flow and various types of cost information associated with the equipment in the target system. Four key parameters, exergy, cost, energy, and mass, are used to investigate the performance of thermal systems from both thermodynamic and economic perspectives, which is called the EXCEM model,[17] as presented in **Fig. 2**. The fundamental balance equation for the EXCEM model is shown in Eq. (1), where *Input* and *Output* respectively refer to quantities entering and exiting through system boundaries. *Generation* and *Consumption* refer respectively to quantities produced and consumed within the system. *Accumulation* refers to a change (either positive or negative) in quantity within the system. General balance equations related to the exergy, cost, energy, and mass are represented by Eqs. (2)–(5).

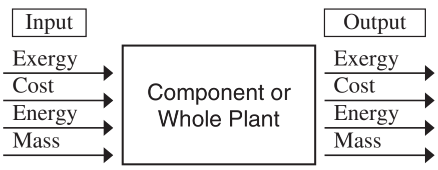


Fig. 2 EXCEM model for a component or whole plant

$$Input + Generation - Consumption - Accumulation = Output \quad (1)$$

$$Ex_{\mathrm{Input}} - Ex_{\mathrm{Consumption}} - Ex_{\mathrm{Accumulation}} = Ex_{\mathrm{Out}} \quad (2)$$

$$C_{\mathrm{Input}} + C_{\mathrm{Generation}} - C_{\mathrm{Accumulation}} = C_{\mathrm{Output}} \quad (3)$$

$$E_{\mathrm{Input}} - E_{\mathrm{Accumulation}} = E_{\mathrm{Output}} \quad (4)$$

$$M_{\mathrm{Input}} - M_{\mathrm{Accumulation}} = M_{\mathrm{Output}} \quad (5)$$

In the EXCEM model, both energy and mass are subject to conservation laws. Exergy is consumed ($Ex_{\mathrm{Consumption}}$) because of exergy destruction, and cost is generated from the capital costs and relevant operation and maintenance (OM) costs ($C_{\mathrm{Generation}}$). Generally, the accumulated items can be considered as loss attributable to the material stream vented to the environment. Therefore, exergy accumulation is always considered as an exergy loss because of the material stream vented to the surroundings. Exergy destruction is the exergy destroyed by irreversibility within the control volume attributable to one or more of the three principal irreversibilities associated with chemical reaction, heat transfer, and mechanical friction.

2. Exergy Analysis

Exergy analysis is designed to measure the thermodynamic performance of the system quantitatively using exergy efficiency. The exergy efficiency is obtained by calculating the ratio of the exergy value of the product, Ex_{P}, to the exergy value of the fuel, Ex_{F}, as given by Eq. (6) for one component or for the whole system. Furthermore, Ex_{D} and Ex_{L} respectively represent the corresponding exergy destruction and exergy loss. For example, for a compressor, the exergy fuel Ex_{F} is the driver power electricity; the exergy product Ex_{P} is the increased exergy of the compressed working fluid. For a turbine, Ex_{F} is the decreased exergy of the working fluid; Ex_{P} is the produced electricity. For a heat exchanger that is designed to heat the working fluid to a low temperature, Ex_{F} is the decreased exergy of the high-temperature working fluid; Ex_{P} is the increased exergy of the low-temperature working fluid.

$$\varepsilon = \frac{Ex_{\mathrm{P}}}{Ex_{\mathrm{F}}} = 1 - \frac{(Ex_{\mathrm{D}} + Ex_{\mathrm{L}})}{Ex_{\mathrm{F}}} \quad (6)$$

3. Exergy-Based Cost Analysis Method

Exergy-based cost analysis combines exergy and economic analyses based on the concept that exergy is the rational basis for assigning costs to calculate the cost of each product generated by a cogeneration system. The reasoning behind the exergy-based costing method is that cost is expected to represent a value. For this reason, the equal working abilities (exergies) of energy carriers can be considered as having equal values. In addition, referring to the Nomenclature section, for one component in the target system, as shown in Eqs. (7) and (8), Z represents the sum of capital costs and the OM cost per unit second of the component, C_F represents the cost of exergy fuel, Ex_F, which is described in the preceding paragraph of exergy analysis, and C_P represents the cost of exergy product Ex_P, which was also described in the preceding paragraph. The cost of the exergy product is obtained by adding the cost of exergy fuel to the cost information of the corresponding equipment: both exist for obtaining the exergy product. In addition, c_F and c_P represent unit costs of the exergy fuel and the exergy product; using them, the cost allocation for multiple products can be realized flexibly.

$$c_F = \frac{C_F}{Ex_F} \tag{7}$$

$$c_P = \frac{C_P}{Ex_P} = \frac{C_F + Z}{Ex_P} \tag{8}$$

4. Conduct of Exergy Analysis and Exergy-Based Cost Analysis for Systems

Based on the EXCEM model, exergy and exergy-based costing analyses can be conducted for detailed thermal systems, as depicted in **Fig. 3**. Based on the flow values in mass flow, unknown thermodynamic parameters, such as temperatures and pressures in various locations, are calculable based on the energy conservation law. Furthermore, based on the values of mass flows and thermodynamic parameters, the values in exergy flows are obtainable using the second law of thermodynamics. Finally, the exergy analysis can be conducted based on exergy flows, and the exergy-based costing analysis can be conducted based on the combination of exergy flows and the cost information of the equipment in the target system. In the next section, system models, analytical models, for the target HTGR cogeneration system are presented.

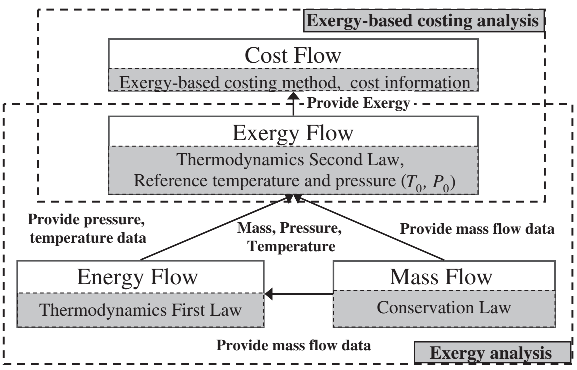


Fig. 3 Exergy and exergy-based costing analyses based on EXCEM model

IV. System Analysis Models for the Target HTGR Cogeneration System

In Sec. 2, the system configuration of the target HTGR cogeneration system is presented; performance analysis models are introduced in Sec. 3. Next, the performance analysis model for the target HTGR cogeneration system is introduced step-by-step.

1. Thermodynamic Model

Basic thermodynamic analysis based on mass and energy conservation laws is the basis of exergy and exergy-based costing analyses: the main process physical parameters are related based on the first law of thermodynamics. For this study, heat exchangers (*e.g.*, recuperator, precooler, and reactor) are simplified as totally adiabatic, meaning that we assume that no heat loss occurs during heat exchange processes. Polytrophic efficiencies of the compressor and turbine, heat exchanger efficiency, and minimum temperature differences, in addition to the relative pressure losses, are assumed as known and constant. Consequently, all temperatures, mass flows, heat flows, and system efficiencies are obtainable. The unknown physical parameters of the processes are obtainable using a stable thermodynamic model relating the process parameters if all leakages are also neglected. The reactor is modeled simply as a heat source, as in Eq. (9).

$$Q_{\text{Reactor}} = M_{\text{He,Main}} Cp_{\text{He}} (T_1 - T_7) \tag{9}$$

IHX is used to provide super-high-temperature heat to produce hydrogen through the thermochemical "IS" process; the heat exchange can be expressed as Eq. (10). Furthermore, the hydrogen production per second (m^3/s) is calculated using an empirical equation with the assumption of 50% efficiency, as shown in Eq. (11).[18] At the same time, the temperature difference condition is expected to be satisfied, as shown in Eq. (12): in fact, ΔT is constant at 5°C for analyses presented in this paper, as presented in Table 1.

$$M_{\text{He,IS}} Cp_{\text{He}} (T_9 - T_8) = M_{\text{He,Main}} Cp_{\text{He}} (T_1 - T_2) \tag{10}$$

$$\begin{aligned} Production_{\text{Hydrogen}} &= M_{\text{He,IS}} Cp_{\text{He}} (T_9 - T_8) \\ &\quad \times 0.5/286 \times 22.4/1000 \end{aligned} \tag{11}$$

$$T_1 - T_9 \geq \Delta T, T_2 - T_8 \geq \Delta T \tag{12}$$

Figure 4 shows that the compressor and gas turbine are described as polytrophic processes, in which the polytrophic efficiencies are assumed to be constant. Then, the temperatures, pressure ratio, and power are related by Eqs. (13)–(16).

$$\frac{T_{6s}}{T_5} = PR^{\frac{k-1}{k}} \text{ where } \frac{T_{6s} - T_5}{T_6 - T_5} = \eta_{\text{Compressor}} \tag{13}$$

$$\frac{T_{3s}}{T_2} = \left(\frac{1}{PR}\right)^{\frac{k-1}{k}}, \text{ where } \frac{T_2 - T_3}{T_2 - T_{3s}} = \eta_{\text{Turbine}} \tag{14}$$

$$\begin{aligned} W_{\text{Compressor}} &= M_{\text{He,Main}} Cp_{\text{He}} (T_6 - T_5); W_{\text{Turbine}} \\ &= M_{\text{He,Main}} Cp_{\text{He}} (T_2 - T_3) \end{aligned} \tag{15}$$

$$Production_{\text{Electricity}} = W_{\text{Turbine}} - W_{\text{Compressor}} \tag{16}$$

As with IHX, the recuperator is also used to transfer heat between helium streams at different temperatures. The energy balance and the temperature difference condition for the

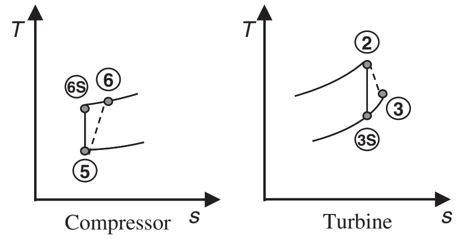


Fig. 4 Temperature (T) entropy (s) graphs of thermodynamic performance characteristics of the compressor and turbine caused by friction

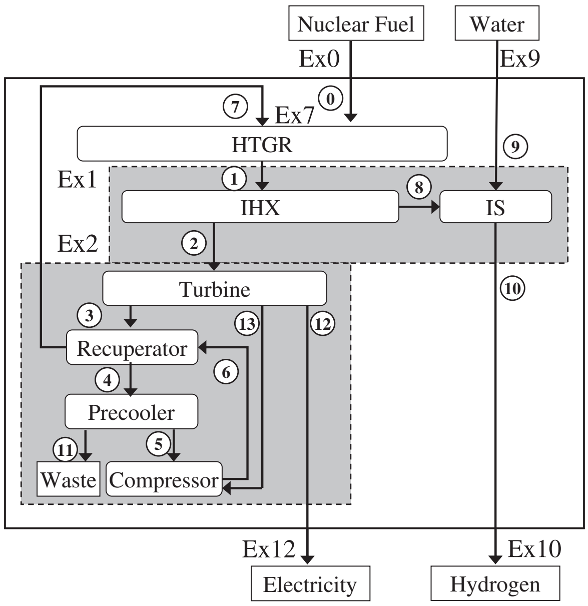


Fig. 5 Frame graph of exergy and exergy-based costing analyses for the HTGR cogeneration system

recuperator are shown in Eqs. (17) and (18). Furthermore, ΔT is constant at 5°C.

$$M_{\mathrm{He,Main}}Cp_{\mathrm{He}}(T_7 - T_6) = M_{\mathrm{He,Main}}Cp_{\mathrm{He}}(T_3 - T_4) \quad (17)$$

$$T_3 - T_7 \geq \Delta T, T_4 - T_6 \geq \Delta T \quad (18)$$

Finally, between the outlet of the recuperator and the inlet of the compressor, a precooler is used for decreasing the helium temperature to make it easily compressible; the waste heat is finally emitted to the environment.

2. Exergy Analysis Model for the HTGR Cogeneration System

According to the introduction of the application of the EXCEM model for a thermal system in section 3, when all the necessary values of mass flow and physical parameters are obtained, the exergy analysis can be done. Therefore, based on the obtained physical parameters in the basic thermodynamic model described above, the exergy analysis model of the HTGR cogeneration system can be constructed, as presented in **Fig. 5**.

In fact, excluding the nuclear, magnetic, electrical and interfacial effects, the total exergy of a material stream is divisible into four components: kinetic exergy, potential exergy, physical exergy, and chemical exergy. The kinetic exergy and potential exergy are respectively equal to the kinetic and potential energies, which are always negligible for the working substance in an actual thermodynamic system because of uniform motion and negligible height difference. The physical exergy associated with a material stream having a specific enthalpy and a specific entropy caused by the differences in temperature and pressure between the stream and the environment. The chemical exergy of an energy carrier is the amount of energy released if the components in the energy carrier through chemical reactions are transferred to the environment components and diffused into this environment. In this HTGR cogeneration system, the system is in a steady state and a steady flow with negligible potential and kinetic energy effects. Furthermore, the working substance, helium, is not involved in any chemical reaction; thus, only the physical exergy of the helium is considered, and the specific exergy is represented as Eq. (19) because the specific heat Cp_{He} of helium is temperature-independent, as shown in Table 1. However, regarding the fuel of the IS process, water, and the product of the IS process, hydrogen as energy medium, the physical exergy has no important meaning. Therefore, only their chemical exergy is considered here. Furthermore, the chemical exergies of hydrogen and water are determined from the mass (in kilograms) by multiplying the standard chemical exergy to be 118 and 0.0025 MJ/kg, respectively,[19] as shown in Eq. (20).

Regarding the HTGR cogeneration system, the exergy fuels of the whole system are the nuclear fuel exergy supply and the exergy of the water supplied for hydrogen production in the IS process. The HTGR cogeneration system has two products, hydrogen and electricity. They are respectively the exergy products of the IS and gas turbine, but the exergy supply of the compressor must be subtracted from the exergy product of turbine. Referring to the exergy analysis model presented in Fig. 5, the exergy analysis can be performed for the HTGR cogeneration system using the exergy calculation equations shown in Eqs. (19) and (20). The exergy supply from the nuclear fuel in the reactor is considered equal to the heat capacity of 600 MWt because of the very high temperature of the fission nuclear reaction. Therefore, the total exergy efficiency of the system is calculated, as shown in Eq. (20).

$$ex_{\mathrm{He}} = Cp_{\mathrm{He}}\left(T - T_0 - T_0 \ln \frac{T}{T_0}\right) + R_{\mathrm{He}}T_0 \ln \frac{P}{P_0} \quad (19)$$

$$\begin{aligned}
\varepsilon_{\mathrm{whole}} &= \frac{Ex10 + Ex12}{Ex0 + Ex9} \times 100\% \\
Ex0 &= 600\,(\mathrm{MJ/S}) \\
Ex9 &= M_{\mathrm{Water}} \times 0.0025\,(\mathrm{MJ/kg}) \\
Ex10 &= M_{\mathrm{He,Main}}Cp_{\mathrm{He}}(950 - T_2)/286/1000 \\
&\quad \times 118\,(\mathrm{MJ/S}) \\
Ex12 &= M_{\mathrm{He,Main}}Cp_{\mathrm{He}}T_2\left(1 - \frac{1}{PR^{\frac{k-1}{k}}}\right)\eta_{\mathrm{Turbine}} \\
&\quad - \frac{M_{\mathrm{He,Main}}Cp_{\mathrm{He}}T_5(PR^{\frac{k-1}{k}} - 1)}{\eta_{\mathrm{Compressor}}}
\end{aligned} \quad (20)$$

3. Economic Analysis Model for the HTGR Cogeneration System

To carry out exergy-based costing analysis, the basic economic analysis for the target system must be finished first. For economic analysis, the capital, operation and maintenance (OM), and fuel costs are estimated using rational assumptions for inflation, cost escalation, cost stabilization, depreciation, taxes, and so on. Economic analysis is one part of exergy-based costing analysis; the obtained values in the economic analysis are used to construct the cost balance in exergy-based costing analysis.

The computation method for the total cost of one component per second, Z, is shown in Eq. (21). Here, the total capital cost (TCC) of the equipment is amortized using the annual capital recovery factor (CRF) given by Eq. (22), where n is the lifetime and d is the discount rate. Finally, the sum of the annual capital and OM costs is transformed to a second unit, and LF is the load factor of the system; one year has 365 d, one day has 24 h, and one hour has 3600 s.

Before this study, cost information related to the equipment used in GTHTR300 was investigated;[8] aside from this report, there are no other capital cost data of equipment used in the HTGR cogeneration system. Furthermore, in general, capital costs for power plant equipment with a different capacity are calculable by assuming that they are directly related to the production capacity with the power of 0.65, as in Eq. (23); such scale laws are frequently used for the evaluation of industrial plants.[20] Therefore, capital costs of the equipment in the HTGR cogeneration system are determined using this scale law by referring to production capacities and capital costs of the equipment in the past investigations,[18] as shown in **Table 2**. The nuclear reactor cost is most complicated when the capital, annual OM, and annual fuel costs are considered. The annual OM and fuel costs of the nuclear reactor are assumed respectively as 16 and 32 M$ according to a study conducted by JAEA[8] with the exchange ratio of 120 between the Japanese yen and US dollar; apparently, no other cost information of the HTGR is available in the relevant literature. Furthermore, the annual OM costs of other equipment are considered as 5% of the annual capital cost; the cost of water for the hydrogen production by the IS process is 1.5 $/ton. Load factors of the equipment used for the whole system are assumed to be 90%.

Table 2 Basic economic data of the equipment at $T_2 = 850°\text{C}$, $T_5 = 80°\text{C}$, and $PR = 2$

Component	Capital cost (M$)	Lifetime (year)	Discount rate (%)
HTGR	500	40	4
IHX	20	20	4
IS	50	40	4
Turbine (& Generator)	30	20	4
Recuperator	20	20	4
Precooler	20	20	4
Compressor	12	20	4

$$Z = \frac{TCC \times CRF + OM}{LF \times 365 \times 24 \times 3600} \tag{21}$$

$$CRF = \frac{d(1+d)^n}{(1+d)^n - 1} \tag{22}$$

$$TCC = TCC_{\text{Reference}}\left(\frac{Capacity}{Capacity_{\text{Reference}}}\right)^x \tag{23}$$

4. Exergy-Based Cost Analysis Model for the HTGR Cogeneration System

When all types of necessary cost information associated with the equipment and fuel are obtained, the production cost per unit of product is obtainable using the exergy-based costing method. Different from the basic thermodynamic and exergy analyses, which are conducted based on scientific laws, the cost allocation method is a subjective issue that might differ among individual people. For this study, the exergy-based costing analysis is conducted as presented in Fig. 5. The reasoning behind this approach is that IHX and IS equipment are considered existing for hydrogen production, whereas the compressor, turbine, precooler, and recuperator equipment are considered existing for electricity production. Consequently, costs associated with the reactor are divided according to the exergy consumptions, respectively, for hydrogen and electricity productions. The respective calculation methods are presented in Eqs. (24) and (25): $Ex_{\text{Reactor,P}}$ is the exergy product provided by the reactor; $Ex_{\text{IHX,F}}$ is the exergy fuel for IHX; and Z is the cost associated with each device.

$$Cost_{\text{Hydrogen}} = \frac{\left(Z_{\text{IHX}} + Z_{\text{IS}} + \dfrac{Z_{\text{Reactor}}(Ex_{\text{IHX,F}})}{Ex_{\text{Reactor,P}}}\right)}{Production_{\text{Hydrogen}}} \tag{24}$$

$$Cost_{\text{Electricity}} = \frac{\left(Z_{\text{Recuperator}} + Z_{\text{Precooler}} + Z_{\text{Compressor}} + Z_{\text{Turbine}} + Z_{\text{Reactor}}\left(1 - \dfrac{Ex_{\text{IHX,F}}}{Ex_{\text{Reactor,P}}}\right)\right)}{Production_{\text{Electricity}}} \tag{25}$$

V. Performance Analysis Results

Both exergy and exergy-based costing analyses described in the preceding section are used to test the performance of the target HTGR cogeneration system from thermodynamic and economic perspectives. The analysis results are reported and discussed in this section.

1. EXCEM Studio

Calculating various operating conditions is difficult because of the many equations, relations, and constraints used for the analysis models. Therefore, a software platform named "EXCEM Studio" was produced. It supports exergy and exergy-based costing analyses for HTGR cogeneration systems. EXCEM Studio realizes thermodynamic, exergy, and exergy-based costing analyses as operational modules; mass flow data, known physical parameters, and cost information are used as initial data.

2. Independent Parameters and Their Valid Ranges

To investigate the performance of the HTGR cogeneration systems at different operating conditions, independent parameters that can represent all other physical parameters to form operating conditions must be chosen first. In the HTGR cogeneration system displayed in Fig. 1, the thermodynamic parameters were determined according to chemical reaction conditions in the IS process for producing hydrogen. Therefore, independent parameters are chosen from the main loop of the system. Because the heat capacity, inlet temperature T_7, and outlet temperature T_1 of the reactor are constant, first, the temperature at point 2, T_2, is chosen as an independent parameter for determining the heat capacity of IHX, and therefore, the production of hydrogen. Furthermore, the pressure ratio of the system is independent of the thermal exergy produced from the temperature difference. The pressure ratio of the system, PR, (between locations 6 and 5 presented in Fig. 1) is also chosen as an independent parameter. Using T_2 and PR, the temperature T_3 is obtainable according to the thermodynamic relation shown in Eq. (14). Because T_3 and T_7 are known parameters, as for the heat balance in the recuperator, either T_6 or T_4 must be known to calculate the other. Furthermore, T_5 and T_6 can be related using PR according to the basic thermodynamic model, as shown in Eq. (13), in the previous section. Therefore, T_5 is chosen as the third independent parameter; T_6 is obtained using the thermodynamic relation in Eq. (13); then, T_4 is obtained using the heat balance in the recuperator based on T_3, T_6, and T_7. Therefore, three independent parameters including T_2, T_5, and PR are chosen to relate all other parameters using the thermodynamic relations in the thermodynamic model described in the previous section.

Furthermore, the valid range of these three independent parameters must be determined according to some restrictions because of the laws of thermodynamics and tradeoffs of thermal efficiency and system design complexity. For the inlet temperature of the turbine, T_2, if it runs over 850°C, turbine blade cooling becomes necessary, but it must be higher than the inlet temperature of the reactor, T_7, and is expected to leave a sufficient temperature difference range between T_2 and T_7 for generating electricity. Therefore, the valid range of T_2 is determined as 740–850°C in this study in reference to reports of earlier studies in the literature.[9,10] The valid range of PR is determined as 1.5–2 because of the restriction shown in Eq. (26); for the valid range of T_5, it is expected to be higher than the cold water inlet temperature, but higher temperatures require more energy consumption by compressors. For this reason, the valid range of T_5 is determined as 30–160°C, in reference to prior studies.[9,10)]

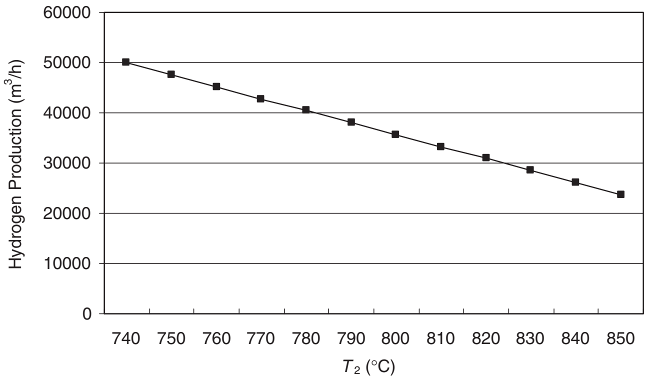


Fig. 6 Hydrogen productions under various operating conditions

$$T_3 = (T_2 - \eta_{Turbine} \times (T_2 - T_2 PR^{\frac{1-k}{k}})) > T_7 \tag{26}$$

3. Analysis Results

Results of these analyses are reported and discussed in this section. First, as depicted in **Fig. 6**, the production of hydrogen calculated using Eqs. (10) and (11) is determined solely by T_2; it is inversely related to T_2. Whereas the production of electricity is determined by T_2, T_5, and PR in their valid ranges, the production of electricity calculated using Eqs. (13)–(16) is proportional to T_2 and PR, while it is inversely proportional to T_5, as shown in **Fig. 7**. The exergy efficiency of the whole system calculated in Eq. (20) is presented in **Fig. 8**. In situations with a low pressure ratio, the low temperature T_2 can make the system operate efficiently through efficient hydrogen production. In situations with a high pressure ratio, the high temperature T_2 can make the system operate efficiently through efficient electricity production. The unit generation costs of hydrogen and electricity calculated using the exergy-based costing analysis method in Eqs. (24) and (25) are presented in **Figs. 9** and **10**, respectively. The generation cost of hydrogen is related to T_2 solely: in the valid range of T_2, operating conditions with lower T_2 generate hydrogen with lower cost because of scale benefits, whereas in the valid ranges of PR, T_2, and T_5, operating conditions with higher PR, higher T_2 and lower T_5 generate electricity more economically because of scale benefits.

To choose optimized HTGR cogeneration systems, the performance must be considered comprehensively from multiple viewpoints. In particular, the market demand of hydrogen should be satisfied preferentially according to the deployment plans.[9–11] Therefore, the global optimum scenario particularly addressing only one performance indicator has almost no practical meaning. The annual consumption of hydrogen would be 735 m^3 per FCV if the fuel consumption of fuel cell vehicles (FCVs) were 13.6 km/m^3 and the annual mileage of one FCV would be 10,000 km.[9] Therefore, with the market penetration ratio of FCVs increasing, three cases are assumed here sequentially for satisfying the respective increasing hydrogen demands of 3150, 5000, and 6600 FCVs annually. Therefore, three optimized deployment scenarios

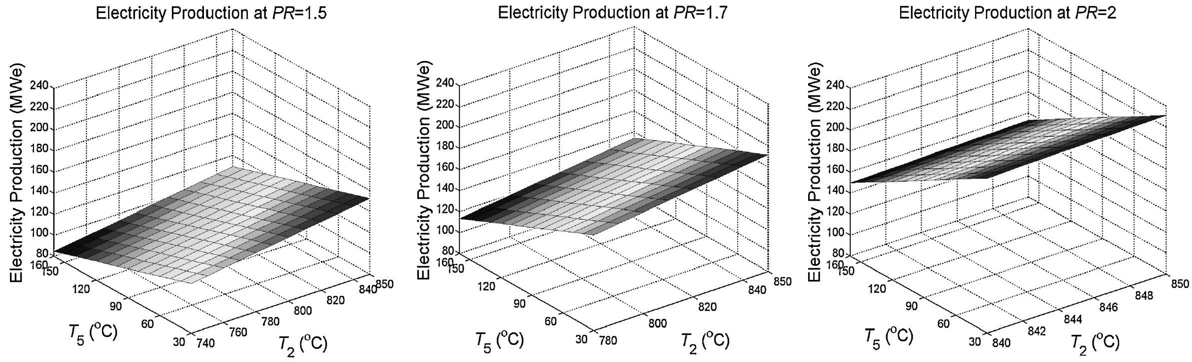


Fig. 7 Electricity productions under various operating conditions

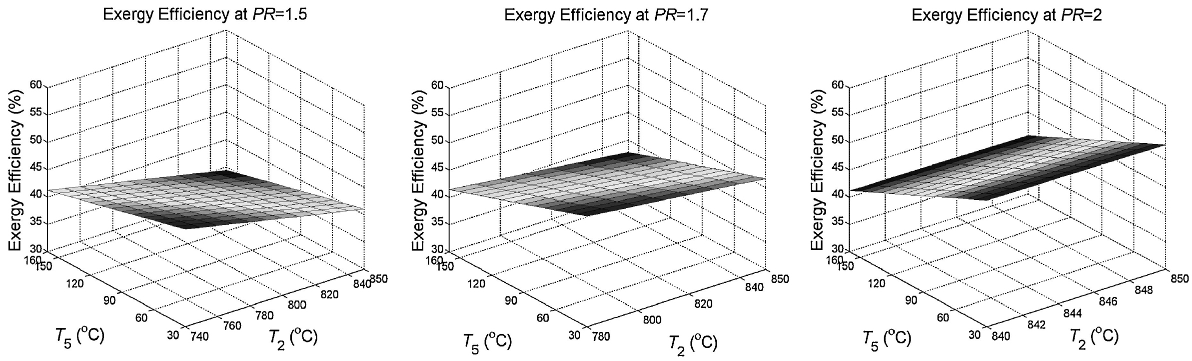


Fig. 8 System exergy efficiencies under various operating conditions

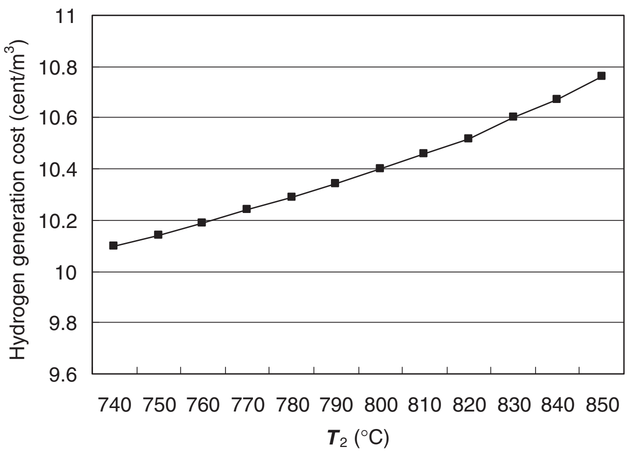


Fig. 9 Generation cost per unit hydrogen under various operating conditions

are proposed, as shown in **Table 3**, to satisfy the three hydrogen demand cases with the maximum exergy efficiency based on the obtained production, exergy efficiency, and generation costs of hydrogen and electricity under various operating conditions. For Case 1, abundant electricity power is producible efficiently at low cost, and the produced hydrogen only can sustain 3150 FCVs annually; in Case 3, abundant hydrogen is producible efficiently with low cost for sustaining 6600 FCVs annually. Case 2 is between Cases 1 and 3; the produced hydrogen can sustain 5000 FCVs annually. **Figure 11** shows that the three proposed deployment scenarios of HTGR cogeneration systems are thermodynamically efficient and economically competitive compared with other hydrogen and electricity production methods. Detailed preconditions and assumptions are shown in **Table 4**;[8,21] the US dollar and Japanese yen exchange rate is considered as 120 for this study.

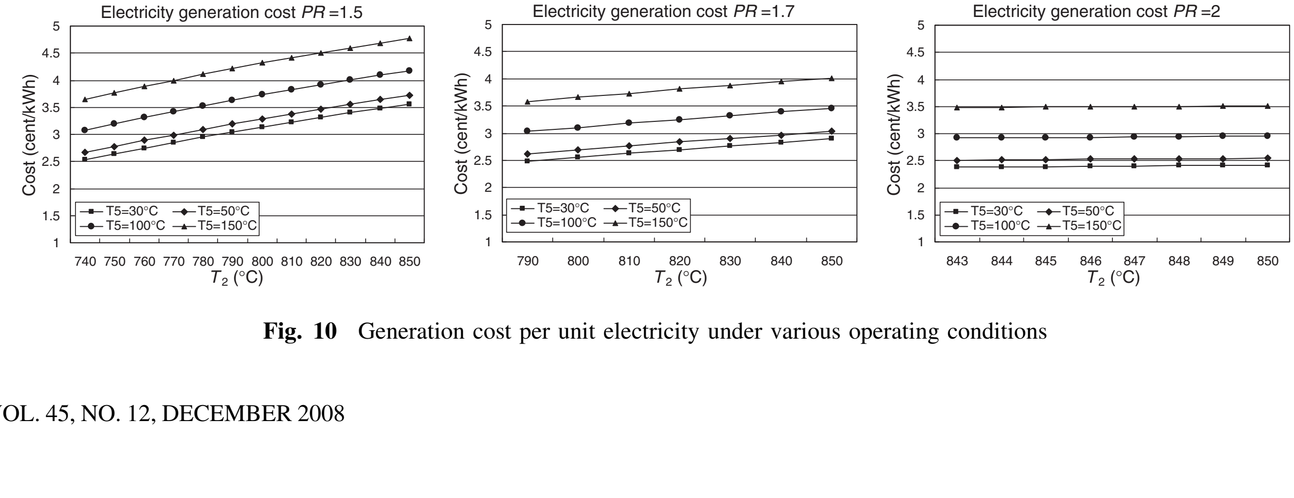
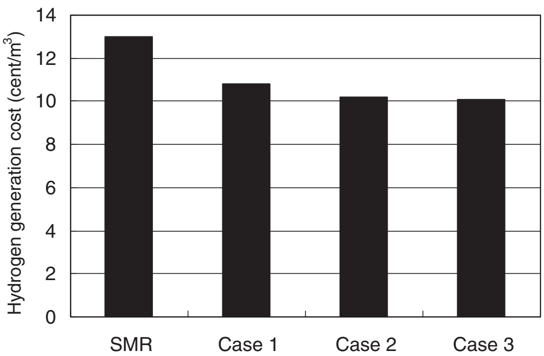


Fig. 10 Generation cost per unit electricity under various operating conditions

Table 3 Three optimized deployment scenarios proposed to satisfy different demands

Case	T_2 (°C)	T_5 (°C)	PR	Production		Cost		Exergy efficiency (%)
				Electricity (MWe)	H_2 (m^3/h)	Electricity (cent/kWh)	H_2 (cent/m^3)	
Case 1	850	30	2.0	231.2	23760.5	2.42	10.8	50.13
Case 2	790	30	1.7	174.2	38016.8	2.48	10.2	47.58
Case 3	740	30	1.5	130.2	49897.1	2.53	10.1	46.03



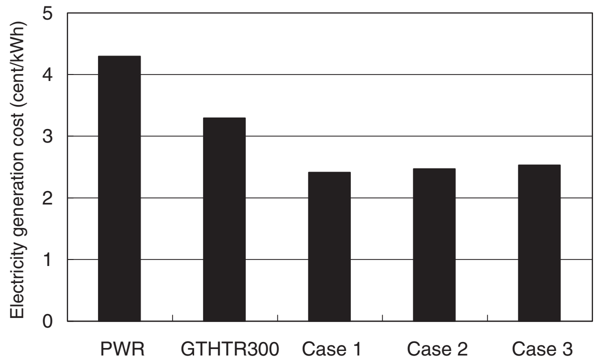


Fig. 11 Cost comparisons of the proposed HTGR cogeneration systems with other hydrogen and electricity production methods

Table 4 Preconditions and assumptions of SMR for hydrogen production and PWR, GTHTR300 for electricity production

SMR cost information[21]	
Capital cost	0.27 billion \$
Natural gas cost	0.018 \$/1000 kcal
Operating rate	90%
Maintenance Cost	21% of capital cost
CO_2 fixation cost	0.2 \$/kg-CO_2
Hydrogen cost by SMR	0.13 \$/m^3
Electricity cost generated by PWR[8] (1300 MW, 80% load factor)	4.3 cent/kWh
Electricity cost generated by GTHTR300[8] (600 MW, 90% load factor)	3.3 cent/kWh

VI. Conclusion

For this study, an HTGR cogeneration system producing electricity and hydrogen simultaneously was chosen as a target system. Exergy and exergy-based costing analysis methods were used to study the performance of the HTGR cogeneration system under various possible operating conditions from thermodynamic and economic perspectives. Based on the analysis results, three optimized deployment scenarios with high performance were proposed to satisfy different hydrogen demands as examples. The proposed HTGR cogeneration system deployment scenarios were proved to be thermodynamically efficient and economically competitive compared with other hydrogen and electricity producing systems. Results of this study demonstrate the feasibility of exergy and exergy-based costing analysis methods for analyzing the HTGR cogeneration system so as to propose optimized deployment scenarios practically.

Nomenclature

- Ex: Exergy flow (kJ/s)
- M: Mass flow (kg/s)
- C: Cost flow (\$/s)
- c: Cost per exergy flow (\$/kJ/s)
- E: Energy flow (kJ/s)
- Z: Capital & OM costs per unit second (\$/s)
- OM: Operations and maintenance (\$/s)
- ε: Exergetic Efficiency (%)
- Cp: Specific heat (kJ/kg K)
- Q: Heat flow (kW)
- W: Power (kW)
- TCC: Total capital cost
- LF: Load factor (%)
- $Capacity$: Capacity of equipment
- H: Polytrophic efficiency (%)
- PR: Compress ratio
- K: Ratio of the specific heats of constant pressure and constant volume
- ex: Specific exergy flow (kJ/kg)
- R: Gas constant (kJ/kg K)
- P: Pressure (bar)
- CRF: Capital recovery factor
- ΔT: Temperature difference in heat exchangers (K)
- H: Specific enthalpy (kJ/kg)
- s: Specific entropy (kJ/kg)

IS: Iodine-sulfur hydrogen production
Z: Sum of *TCC* and *OM*
n: Life time (years)
d: Discount rate (%)

Subscripts

F: Fuel
D: Destruction
He: Helium
Main: Main loop
Reactor: Reactor
IHX: Intermediate heat exchanger
Whole: Whole system
Electricity: Electricity
P: Product
L: Loss
IS: IS loop
Compressor: Compressor
Turbine: Turbine
Recuperator: Recuperator
Water: Water
Hydrogen: Hydrogen

References

1) X. Yan, K. Kunitomi, T. Nakata, S. Shiozawa, "GTHTR300 design and development," *Nucl. Eng. Des.*, **222**[2–3], 247–262 (2003).
2) K. Kunitomi, S. Katanishi, S. Takada, T. Takizuka, X. Yan, "Japan's future HTR—the GTHTR300," *Nucl. Eng. Des.*, **233**, 309–327 (2004).
3) S. Shiozawa, S. Fujikawa, T. Iyoku, K. Kunitomi, Y. Tachibana, "Overview of HTTR design features," *Nucl. Eng. Des.*, **233**, 11–21 (2004).
4) K. Kunitomi, X. Yan, S. Shiozawa, N. Fujimoto, "GTHTR300C for hydrogen cogeneration," *Proc. 2nd Int. Topical Meeting on High Temperature Reactor Technology (HTR-2004)*, Beijing, China, Sept. 22–24, 2004 (2004).
5) T. Nishihara, K. Ohashi, T. Murakami, K. Kunitomi, "Safety design philosophy of hydrogen cogeneration high temperature gas cooled reactor (GTHTR300C)," *J. Nucl. Sci. Technol.*, **5**[4], 325–333 (2006), [in Japanese].
6) K. Ohashi, T. Nishihara, K. Kunitomi, "Fundamental philosophy on the safety design of HTTR-IS hydrogen production system," *J. Nucl. Sci. Technol.*, **6**[1], 46–57 (2007), [in Japanese].
7) X. Yan, T. Takizuka, S. Takada, K. Kunitomi, I. Minatsuki, Y. Mizokami, "Cost and performance design approach for GTHTR300 power conversion system," *Nucl. Eng. Des.*, **226**[3], 351–373 (2003).
8) M. Takei, S. Kosugiyama, T. Mouri, S. Katashi, K. Kunitomi, "Economical evaluation on gas turbine high temperature reactor 300 (GTHTR300)," *J. Nucl. Sci. Technol.*, **5**[4], 109–117 (2006), [in Japanese].
9) T. Takeda, T. Nishihara, K. Kunitomi, "Deployment scenario of GTHTR300 cogeneration system," *Proc. Global 2005*, Tsukuba, Japan, Oct. 9–13, 2005, Paper No. 325 (2005).
10) K. Kunitomi, X. Yan, T. Nishihara, N. Sakaba, T. Mouri, "JAEA's VHTR for hydrogen and electricity cogeneration GTHTR300C," *Korean Nucl. Eng. Des.*, **39**[1], 9–20 (2007).
11) *Introduction Scenarios and Research Development Roadmap for the High Temperature Gas Reactor (HTGR)—WG2 Report for the Workshop of Future Development of HTGR*, Japan Atomic Industrial Forum (JAIF) (2007), [in Japanese].
12) G. Wall, "Exergy—a useful concept," Ph.D. thesis, Chalmers University of Technology, Sweden (1986).
13) A. M. Nashar, "Cost allocation of electricity and water in a cogeneration plant," *Desalination*, **85**[2], 197–212 (1992).
14) G. Tsatsaronis, "Thermoeconomic analysis and optimization of energy systems," *Prog. Energy Combust. Sci.*, **19**[3], 227–257 (1993).
15) G. Tsatsaronis, J. Pisa, "Exergoeconomic evaluation and optimization of energy systems-application to the CGAM problem," *Energy*, **19**[3], 287–321 (1993).
16) A. Valero, M. A. Lozano, L. Serra, G. Tsatsaronis, J. Pisa, C. A. Frangopoulos, M. R. von Spakovsky, "CGAM problem: definition and conventional solution," *Energy*, **19**[3], 279–286 (1994).
17) M. A. Rosen, I. Dincer, "Exergy-cost-energy-mass analysis of thermal systems and processes," *Energy Convers. Manage.*, **44**[10], 1633–1651 (2003).
18) H. Karasawa, "Cost evaluation for centralized hydrogen production," *Prog. Nucl. Energy*, **47**, 512–518 (2005).
19) S. Bilgen, K. Kaygusuz, "The calculation of the chemical exergies of coal-based fuels by using the higher heating values," *Appl. Energy*, doi:10.1016/j.apenergy.2008.02.001 (2008).
20) D. S. Remer, F. B. Mattos, "Cost and scale-up factors, international inflation indexes and location factors," *Int. J. Prod. Econ.*, **84**[10], 1–16 (2003).
21) M. Yamawaki, T. Nishihara, Y. Inagaki, K. Minato, H. Oigawa, K. Onuki, R. Hino, M. Ogawa, "Application of nuclear energy for environmentally friendly hydrogen generation," *Int. J. Hydrogen Energy*, **32**[14], 2719–2725 (2007).