4.4 *DESIGN OF A STEAM REFORMING SYSTEM TO BE CONNECTED TO THE HTTR*

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ABSTRACT

Top priority objective for developing the first heat utilization system to be connected to the HTTR is to demonstrate technical feasibility of a nuclear process heat utilization system for production of hydrogen for the first time in the world. Major issues to be resolved for coupling the heat utilization system to the HTTR are 1)to develop safety philosophy for reasonably and reliably ensuring safety of the nuclear reactor, 2)to develop control design concept for the total system of the nuclear reactor and heat utilization system because thermal dynamics of endothermic chemical reactor to be heated by nuclear heat is much different from the nuclear reactor, 3)to develop helium-heated components and 4)to develop enhanced hydrogen production technoligies for achieving competitiveness to a fossil-fired plant.

A steam reforming hydrogen production system was studied as one of the first priority candidates for an HTTR-heat utilization system due to matured technology in fossil-fired plants and since technical solutions demonstrated by the coupling of the steam reforming system to the HTTR will contribute to all other hydrogen production systems.

Basic design philosophy for the HTTR-steam reforming system is that the steam reforming plant downstream of an intermediate secondary helium loop is designed at the same safety level as fossil-fired plants and therefore the secondary helium loop was selected as a safety barrier to the HTTR nuclear reactor.

JAERI has been conducting several studies to develop a framework of the HTTR-steam reforming system. Key design achievements were as follows.

1) Hydrogen production performance was improved to achieve the competitiveness to the fossil-fired by applying new concepts of steam reformer and optimizing heat and material balance conditions of the system.

2) A natural convection type of steam generator was allocated downstream the steam reformer in the secondary helium loop to achieve sufficient system controllability with accomodating the large difference in thermal dynamics as mentioned above, and to form the safety barrier by the secondary helium loop.

3) Basic safety design criteria for fire and explosion originated at the steam reforming plant were developed.

1. Introduction

Consumption of a huge amount of fossil fuels resulted from human activities since the industrial revolution, in addition to deforestation, causes an enhanced global warming. In order to relax the global warming issue and to sustain our future development, new energy resource/carrier or energy technology to meet the following requirements may be needed to develop as early as possible;

1) freedom from resource constraint, especially stable and unlimited supply of resource,
2) environmentally friendly energy use,
3) high efficiency energy use, and
4) concentrated energy use for industries.

Such an energy technology includes to reform fossil fuels to new energy carrier.

Hydrogen is one of key energy carriers to meet the above requirements. The Ministry of International Trade and Industry has started the New Sunshine Program(R&D Program on Energy and Environmental Technologies) in April 1993, with focusing on development of hydrogen production and utilization technology[1]. A High Temperature Gas-cooled Reactor(HTGR) supplies a high temperature nuclear heat enabling us to attain a high efficiency heat utilization without any emission of CO_2 gas. Therefore, hydrogen production by the use of nuclear heat generated from an HTGR as a heat source has the high possibility to meet the above requirements.

JAERI has been studying a possibility of developing nuclear-heated hydrogen production technologies and of demonstrating technical feasibility of nuclear-heated hydrogen production at an engineering testing HTGR, called HTTR(High Temperature engineering Test Reactor) since 1990. A steam-methane reforming system is under study as a hydrogen production system to be connected to the HTTR due to its advantages as described below:

1) It is highly possible to couple it to the HTTR in the early 2000's because a fossil-fired steam reforming of natural gas or naphta is an economical and mature technology for production of hydrogen.
2) Technical solutions demonstrated by coupling the steam reforming system to the HTTR will contribute to other nuclear-heated hydrogen production systems.
3) The nuclear-heated steam reforming is a practicable means for producing hydrogen by pre-combustion removal of CO_2 from hydrocarbon resources such as natural gas and coal and has great potential as a means to facilitate the transition from fossil fuels to future hydrogen energy systems[2].

At a preliminary design conducted from fiscal 1990 through 1995, JAERI has developed a framework of the HTTR-steam reforming system. Key design achievements were as follows.

1) By applying a new concept of steam reformer heated by helium gas from nuclear reactor(precisely, from IHX) and by optimizing arrangement of helium-heated components and related heat and material balance conditions of the system, hydrogen production performance was improved to achieve the competitiveness to the fossil-fired.
2) A natural convection type of steam generator was allocated downstream the steam reformer in the secondary helium loop to achieve sufficient system controllability with accomodating a large differnece in thermal dynamics between nuclear reactor and steam reformer, and to form a safety barrier at the secondary helium loop.

3) Basic safety design criteria for fire and axplosion originated at the steam reforming plant were developed.

In the next fiscal year, JAERI is planning to start a conceptual design in consignment of the Science and Technology Agency, aiming at a start of test for developing nuclear-heated hydrogen production technologies by the steam reforming process at the HTTR in fiscal 2002.

In the following, key technologies to be developed for coupling an HTGR and hydrogen production system are discussed first, and then design philosophy and concept of the HTTR-steam reforming system for providing the capability to develop these technologies are proposed. Finally, achievements of design studies so far are presented.

2. Design philosophy and basic concept of HTTR-steam reforming system

The first HTGR in Japan, namely HTTR, is under construction at the Oarai Research Establishment of JAERI. Key technologies for assuring reasonable reliability and safety of an HTGR at malfunction or accident of the HTGR itself have been developed through a design and construction of the HTTR. For coupling a process heat utilization system for production of hydrogen to an HTGR, the following key technologies remain to be developed.

1) Enhanced hydrogen production to achieve its competitiveness to an economical fossil-fired hydrogen production plant.

2) Helium-heated components, especially helium-heated endothermic chemical reactor:

A hot helium gas which provides the nuclear generated heat to an endothermic reactor is pressurized to cool the nuclear reactor core. A heat exchanger type of chemical reactor is suitable to contain the pressurized helium.

3) Control of the total system connectiong an HTGR to a process heat utilization system with an endothermic chemical reactor which has a quite different thermal dynamics from an HTGR reactor:

In an HTGR core, a nuclear generated heat is transformed to a sensible heat of helium gas, the reactor coolant, resulting in a proportional relationship of reactor power and helium temperature. On the other hand, in an endothermic chemical reactor where an endothermic reaction occurs for production of hydrogen, a heat input enough to cause the reaction dramatically increases with increasing reaction temperature due to the Arrenhius type temperature dependence of reaction rate. A new control technology needs to be developed to balance such a quite difference in thermal dynamics between the nuclear reactor and the chemical reactor.

4) Safety measures for ensuring reasonable reliability and safety of HTGR against malfunction or failure of a hydrogen production system:

A higher probability of malfunction or failure of a hydrogen production system than a power generation system is expected to result from a severe environment of chemical reactors for production of hydrogen. A safety measures needs to prevent frequent reactor scrams triggered by such a malfunction or failure for ensuring a reasonable reliability and safety of an HTGR.

5) Safety measures against a fire/explosion caused by a combustible/explosive gas in storage at a hydrogen production system because of integration arrangement of an HTGR and hydrogen production system:

Two different potential origins of fire/explosion should be taken into account. One origin is the hydrogen production system outside the nuclear reactor building and the other is the inside of the reactor building if it is possible to form a route of explosive gas ingress from chemical reactor with the explosive gas feed to the inside of the reactor *building.*

6) Safety measures for transportation of fission products released from the reactor to the product hydrogen at a normal operation and for preventing uncontrolled release of fission products to environment at a accident of the steam reforming system.

Tritium has a possibility to be transported from the reactor to the product hydrogen through a hot tube walls of helium-heated heat exchangers such as a helium-to-helium intermediate heat exchanger(IHX) and an endothermic chemical reactor in service at a high temperature. Tritium concentration of the product hydrogen should be limited as low as reasonably achievable.

The top-priority objective for coupling a steam reforming hydrogen production system to the HTTR is to develop these technologies and then to demonstrate technical feasibility of a nuclear process heat utilization system for production of hydrogen for the first time in the world. Taking into consideration the importance of the objective, the authors have defined the following design philosophy for establishing a design concept of the HTTR-steam reforming system for providing the capability to develop those key technologies.

1) Techinical solutions demonstrated by coupling the steam reforming system to the HTTR should contribute to all other hydrogen production systems.

2) The steam reforming system is designed at the same safety level as a fossil-fired plant under a strict requirement of assuring the safety and reliability as a nuclear reactor sytem.

3) Simplicity and operator friendly methodologies are pursued.

Several design studies have been conducted to develop a design concept of the HTTR-steam reforming system for developing the key technologies of an HTGR-hydrogen production system under the design philosophy. Finally, the authors propose the following basic design concept which incorporates new ideas of passive safety features.

1) An innovative design concept of helium-heated steam reformer is developed to improve hydrogen production performance, with optimizing heat and material balance conditions of the whole steam reforming system.

2) A steam generator is installed in the helium loop(the secondary helium loop for the HTTR) for providing the stable controllability against any disturbance triggered in the steam reforming system.

3) A passive safety barrier as shown in Table 1, separating the HTTR reactor and the steam reforming system, is adopted to ensure the reactor safety passively against any transient or accident triggered at the steam reforming system.

4) Tritium transportation is limited as low as reasonably achievable primarily by purification systems of the reactor coolant helium and the secondary helium which flows in the intermediate cooling loop(named the secondary helium loop) separating the reactor cooling loop and the steam reforming loop. Both of IHX and a pair of isolation valves in the secondary helium loop provide a safety barrier for preventing uncontrolled release of fission products at the accident of secondary helium pipe rupture according to the HTTR safety design guideline.

The detail of the design concept for the items 1) to 3) is presented in the following chapter.

3. Design concept of HTTR-steam reforming system arrangement and key system components

The steam reforming system is arranged to connect to the IHX as schematically illustrated in Fig. 1. A cut-away view of the whole total system is shown in Fig. 2. The HTTR reactor supplies nuclear generated heat of 30MW to parallel-loaded two heat exchangers in *the reactor cooling loop, namely the IHX of 10MW at the rated heat exchanging rate and a pressurized water cooler of the remaining 20MW. The thermal energy of 10MW transfered at the IHX to the secondary helium loop is utilized for production of hydrogen. Heat and material balance conditions at the IHX are given in Table 2 for the maximum secondary helium temperature of 905 °C at the outlet of IHX. Due to a heat loss along a secondary helium piping from the IHX to a steam reformer, the secondary helium temperature is reduced to 880 °C at the inlet of the reformer for the IHX outlet temperature of 905 °C.*

JAERI has been conducting several design studies to develop a design concept of the HTTR-steam reforming system under the boundary conditions as defined above.

3.1 Improvement of hydrogen production performance

In the HTTR-steam reforming system, the secondary helium at the temperature of 880 °C and at the high pressure of 4MPa flows into a heat exchanger type of steam reformer, and supplies the thermal energy enough to cause a steam reforming reaction to a reforming process gas flowing inside catalyst tubes. With a conventional type of heat exchanger and for similar process gas feed conditions to a fossil-fired plant, lower hydrogen production performance of the HTTR-steam reforming system is predicted than a fossil-fired system. A comparison of operational conditions between HTTR- and fossil-fired reforming system is shown in Table 3.

Since a hydrogen production rate is expressed as the product of a reforming process gas feed rate and a reforming rate, the following improvements are found to provide higher hydrogen production performance.

1) Increasing heat input to the reforming process gas which flows in catalyst tubes
2) Increasing a reaction temperature, that is a process gas temperature at the outlet of catalyst zone in the catalyst tube
3) Optimizing reforming gas composition so as to enhance the reforming rate

Reduction in process gas pressure is one of effective improvements, but depends on the helium pressure. Survey of improved types of heat exchangers and an analytical study on enhancement of hydrogen production rate lead to the proposal shown in Fig. 3. The proposed type of helium-heated reformer as shown in Fig. 4 and its optimized operating conditions has the possibility to attain a competitive hydrogen production performance(by comparing a thermal energy utilization, 78% is competitive to 80-85% for a fossil-fired plant).

These improvements are applicable not only to HTGR-steam reforming system but also to other HTGR-hydrogen production systems because a heat exchanger type of endothermic chemical reactor is an essential technology for production of hydrogen by utilizing the nuclear heat.

3.2 Steam generator in the secondary helium loop for stable controllability and as a safety barrier

The authors have found that installation of a steam generator(SG) at the downstream of the steam reformer in the secondary loop provides the stable controllability for any disturbance at the steam reformer due to a larde capacity of heat sink. For example, for such a thermal transient that a helium temperature at the steam reformer outlet and then at the SG inlet goes up by a disturbance in the reforming process gas feed line, a helium temperature at the SG outlet can remain constant at the saturation temperature of steam. A transient analysis result is shown in Fig. 5 for a stepwise decrease in process gas flow rate by 20%. System arrangement is shown in Fig. 6. This is phenominologically explained that an increased heat input to SG due to increasing SG inlet helium temperature is possible to result in only an increased steam quality at the saturation temperature due to boiling, but not *in an increased steam temperature.*

Such an advantage of SG is utilized to prevent a reactor scram due to a malfunction or accident at the steam reforming system and therefore the secondary helium loop with SG can be functioned as a safety barrier as mentioned above. For preventing a reactor scram due to a loss of water feed to SG by a loss-of-on-site-power accident at the reforming system and by a malfunction of feed water flow rate control system for example, a natural convection type of SG with a sufficient capacity of water holdup and with a passive SG cooling system is selected as the safety barrier SG and is now under design to specify a reasonable safety requirements and reasonable configuration.

A comparison of system arrangement among candidate nuclear-heated hydrogen production processes has revealed that the technical solution to achieve stable controllability and to meet the safety requirement to the steam reforming system of designing it at the same safety level of a fossil-fired plant contributes to other hydrogen production systems.

Accordingly, the arrangement of the HTTR-steam reforming system is specified as shown in Fig. 6.

3.3 Safety barrier agaist fire/explosion

Safety barrier(functional or physical) is required to assure the safety of nuclear system and public. In the HTTR-steam reforming system has a potential possibility of two types of origins of fire/explosion, namely outside of the nuclear reactor building(R/B) and inside of the R/B. The safety design concept is schematically illustrated in Fig. 7.

Against the fire/explosion outside the R/B, it is reasonable to assure safety integrity of safety-related items as the nuclear system against a potential fire/explosion because a low possibility of fire/explosion should be assumed. However, against fire/explosion inside the R/B, it is the principle to take a safety measures to prevent occurrence of fire/explosion. In detail, the secondary helium piping system is designed to prevent the formation of route of explosive gas ingress from the steam reformer into the R/B. For the HTTR-steam reforming system, a possibility of pipe rupture of the secondary helium loop does not seem to completely exclude and therefore, the basic design concept is to limit ingress amount of explosive gas within an allowable limit to prevent any hazard to safety-related items such as the reactor containment vessel. A combination of the C/V isolation valves and emergengy shut-off valve in the process gas feed line is effective to restrict the amount of ingress gas.

4. Concluding remarks

Based on the defined design philosophy, the authors have conducted design studies to develop a design concept of the HTTR-steam reforming system. The framework of the system arrangement and the helium-heated steam reformer concept have been specified for achieving a competitive hydrogen production performance to a fossil-fired plant and for ensuring a stable controllability and safety barrier.

A heat transfer enhancement, an increased heat input to the process gas and others contribute to a competitive hydrogen production performance, in detail, the thermal energy utilization of around 80%.

A steam generator is designed to install at the downstream of the steam reformer in the secondary helium loop, providing the stable controllability and the safety barrier against malfunctions or accidents in the process gas and feed water lines.

A safety design concept is developed for explosion/fire due to explosive gas, taking *into account difference of safety requirements depending upon the origins of fire/explosion.*

These technical solutions will contribute to other hydrogen production systems.

In consignment of the Science and Technology Agency, JAERI is plannning to establish the design concept of the HTTR-steam reforming system and the related R&Ds, aiming at a start of test operation of the steam reforming system in fiscal 2002.

References

[1] C.Watanabe, "MITI's new comprehensive approach to energy and environmental technologies: the New Sunshine Program", presented at the 7th Japanese-French Expert Meeting on Energy and Environmental Technologies, May 31-June 1, 1993, Tokyo, Japan.

[2] Y.Mori et al., "Pre-combuction removal of carbon dioxide from natural gas power plants and the transition to hydrogen energy systems", J. of Energy Resources Technology, vol.114(Sept. 1992), p.221-226.

Table 1 Passive safety barrier for ensuring the reactor safety against transient/accident triggered at the steam reforming system

Transient / accident		Safety barrier
Thermal-hydraulic transients triggered at the steam reforming system		Physical barrier of the secondary helium loop installing a natural convection type of steam generator for preventing a reactor scram
Fire and explosion accident	Originated outside the HTTR reactor building	Functional barrier of safe distance for preventing damage at the reactor building and components important to safety
	Within the reactor building	Physical barrier of the secondary helium loop and emergency shut-off valves (or isolation valve) for preventing occurrence of explosion or for preventing damage at componets important to safety

Table 2 Heat and material balance conditions at the IHX and key design parameters of the IHX

Rated heat exchanging rate	9.94MW
Primary helium	
Temperature at the inlet/outlet	950°C/389°C
Pressure at the inlet	4.02MPa
Mass flow rate	12.2t/h
Secondary helium (for the maximum design allowable temperature at the outlet of 905°C)	
Temperature at the inlet/outlet	158°C/905°C
Pressure at the inlet	4.14MPa
Mass flow rate	9.07t/h
Type	Counter-current and helically wound tube type of shell-and-tube heat exchanger
Design condition of heat transfer tubes	
Design temperature	955°C
Design pressure	0.29MPa
Design pressure drop through IHX (for maximum flow rate at the normal operation)	
Primary helium	9.2kPa
Secondary helium	50.2kPa

Table 3 Comparison of operational conditions and performance of steam reformers

Reformer type	Fossil-fired	Helium-heated without improvements	Improved helium-heated
Process gas pressure	1〜3MPa depending upon final products	>Helium pressure P_{He} of 4.0MPa	Balanced presure (≅ P_{He}) → 4.5MPa at the inlet of steam reformer
Maximum process gas temperature	850〜900℃	≦750℃	800℃
Maximum heat flux to catalyst zone	50〜80 kW/m²	10〜20 kW/m²	40kW/m²
Thermal energy utilization of steam reformer	80〜85%	(〜50%)*	78%
CO_2 emission from heat source for heat source power	3t-CO_2/h/10MW	0	

(*) Based on JAERI's design data

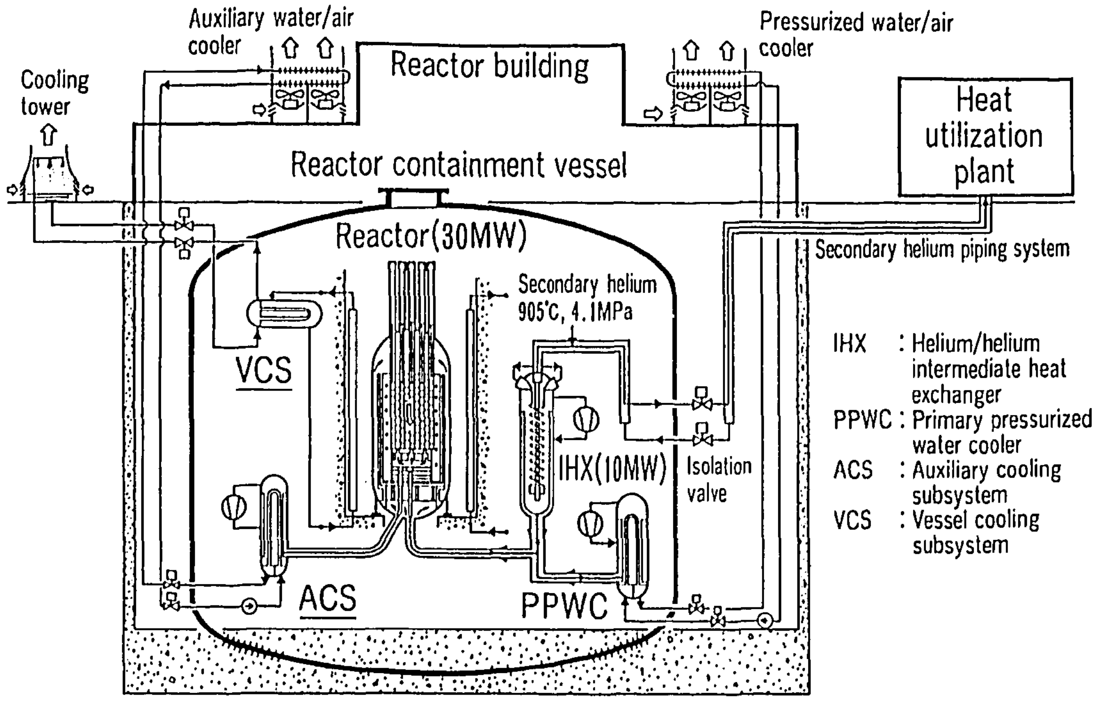

Fig.1 Simplified diagram of the HTTR plant with a heat utilization system.

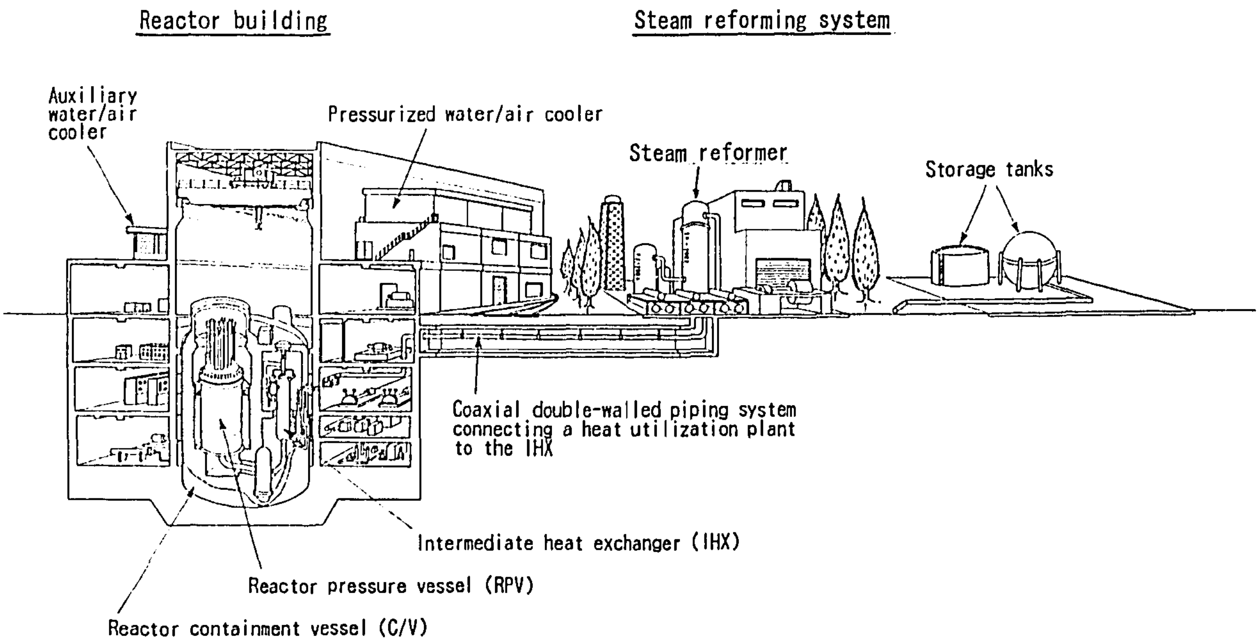

Fig.2 Cutaway drawing of the HTTR-steam reforming system.

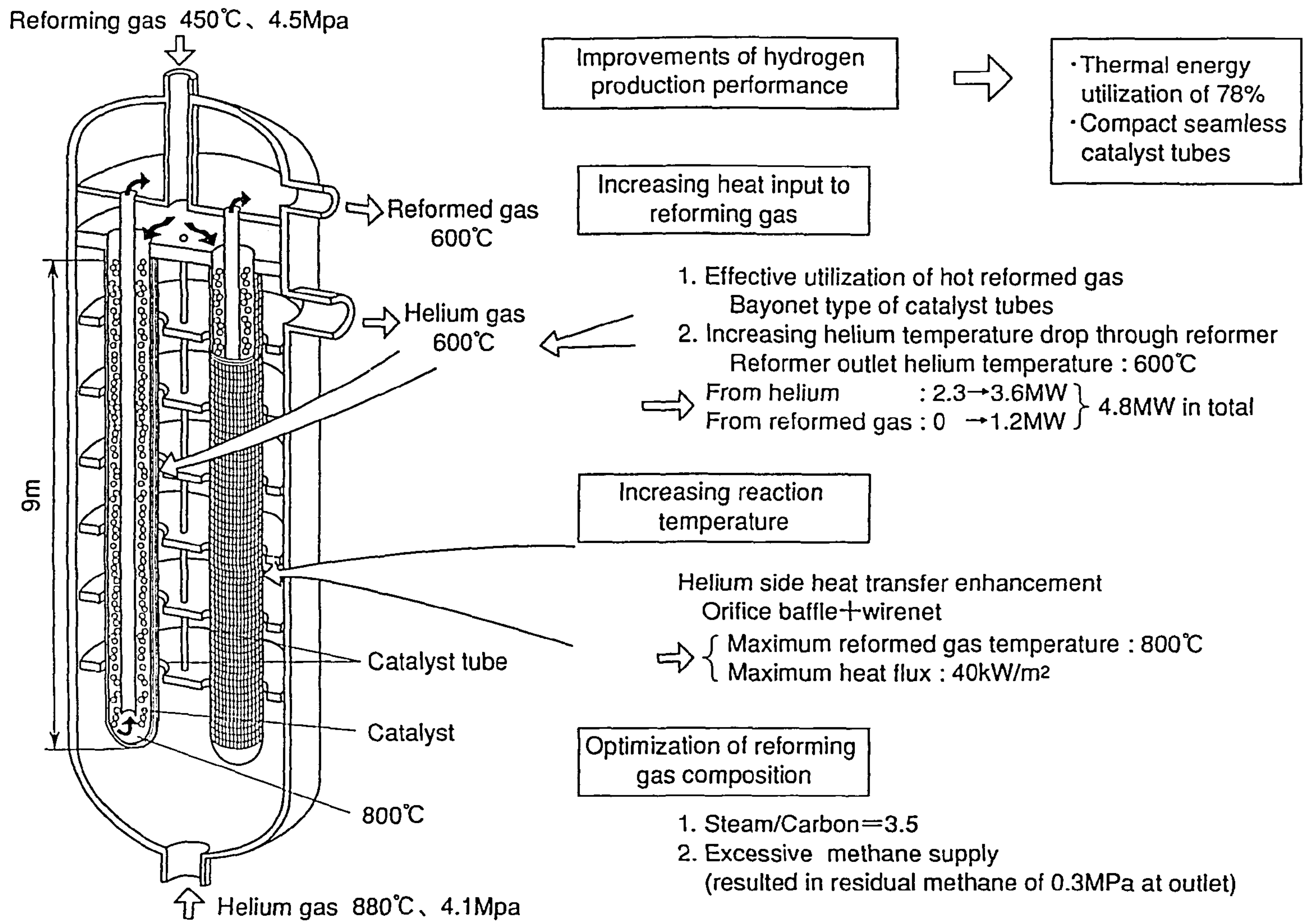

Fig.3 Improvements of helium-heated steam reformer performance.

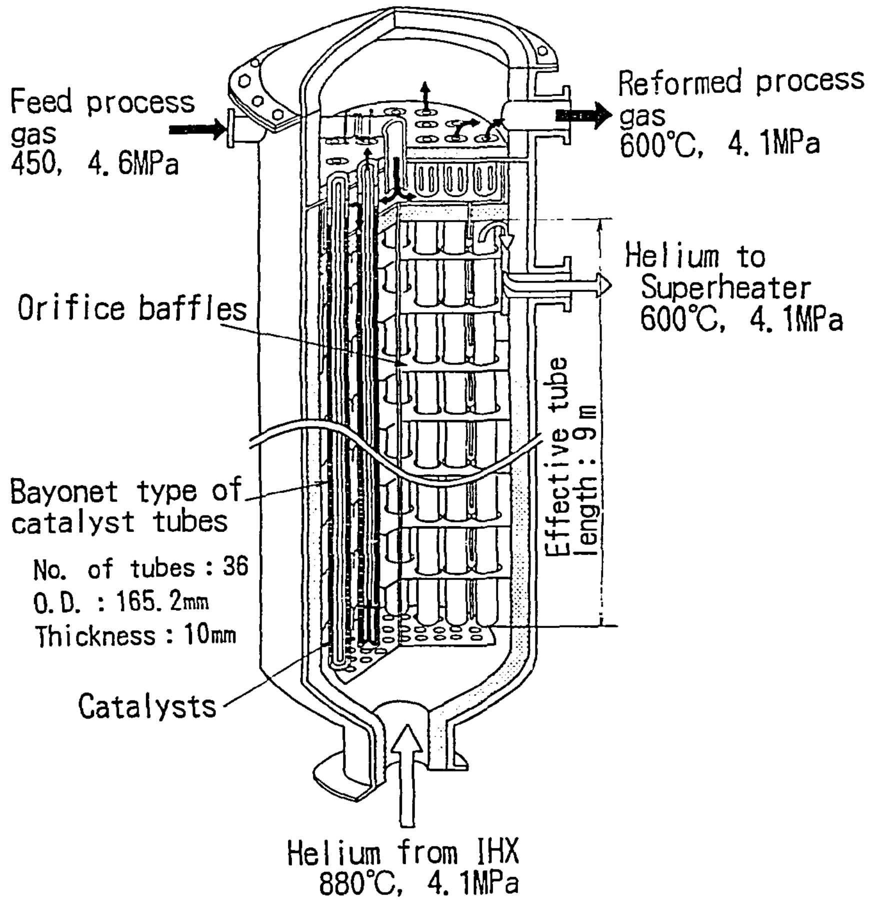

Fig. 4 Schematic illustration of HTTR-steam reformer

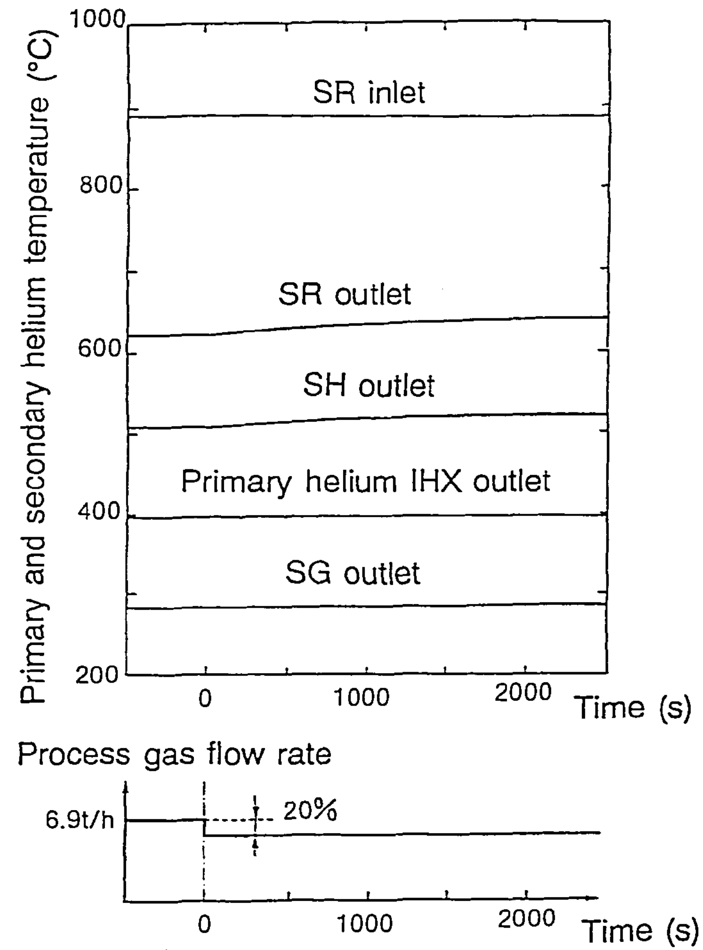

Fig.5 Helium gas temperatures at the HTTR-steam reforming hydrogen production system by transient thermal hydraulic analysis.

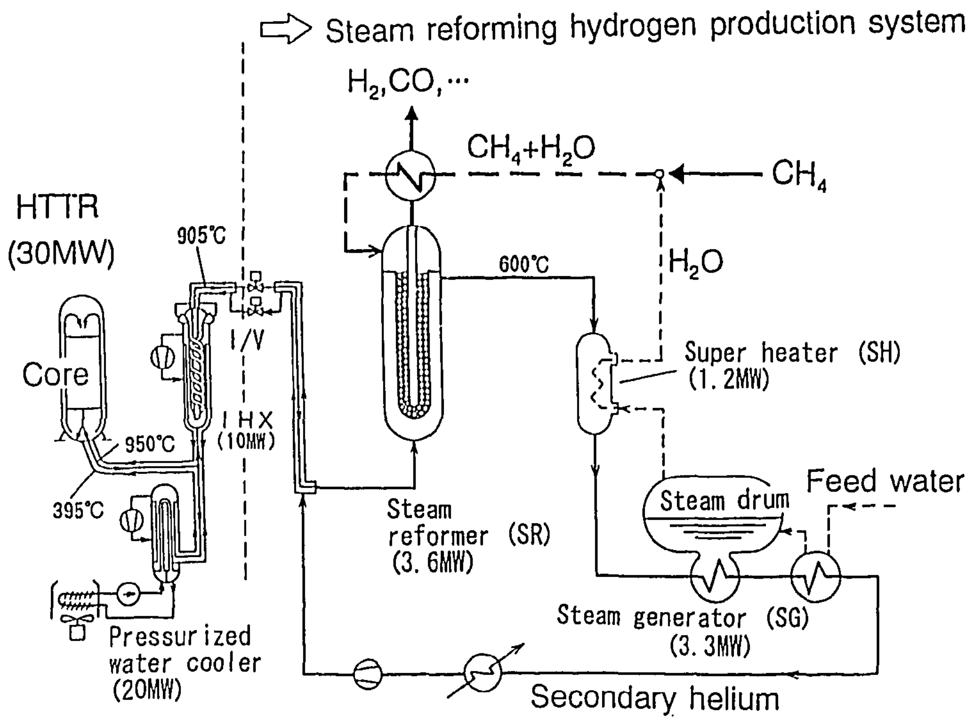

Fig.6 Flow scheme of the HTTR-steam reforming hydrogen production system.

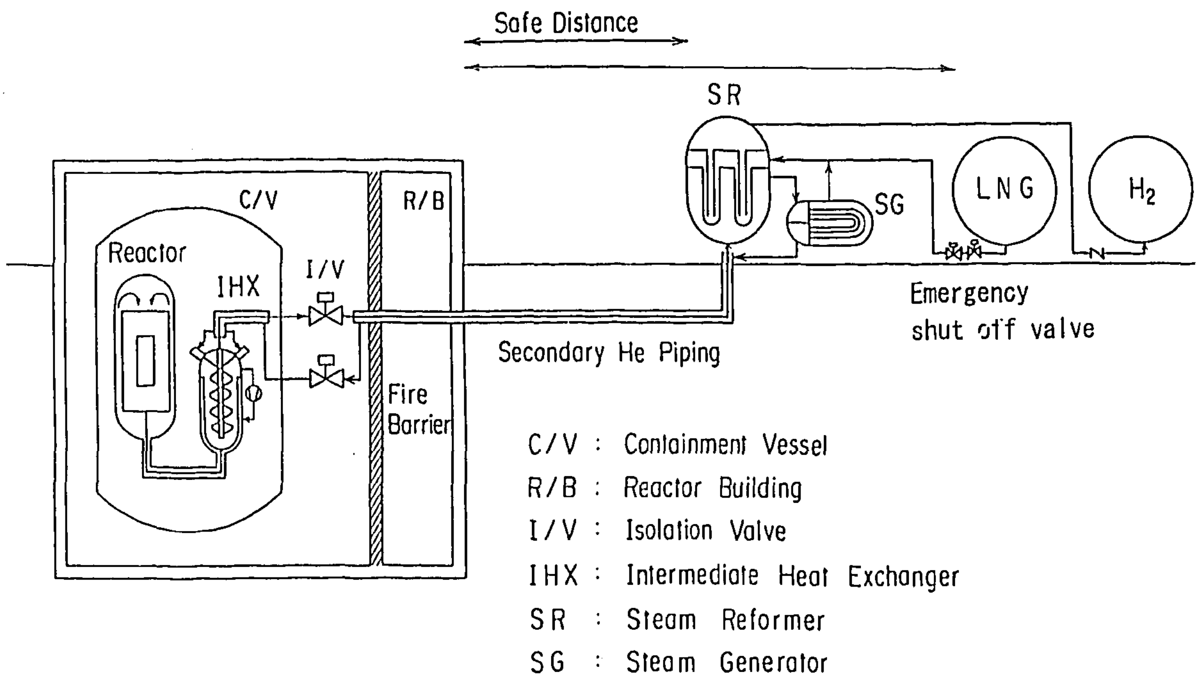

Fig.7 Safety design concept against fire and explosion.