# PERSPECTIVES OF NUCLEAR HEAT AND HYDROGEN

WON JAE LEE*, YONG WAN KIM and JONGHWA CHANG
Korea Atomic Energy Research Institute
1045 Daedeok-daero, Yuseong-gu, Daejeon, Korea
*Corresponding author. E-mail : wjlee@kaeri.re.kr

*Invited February 11, 2009*
*Received April 6, 2009*

---

Nuclear energy plays an important role in world energy production by supplying 6% of the world's current total electricity production. However, 86% of the energy consumed worldwide to produce industrial process heat, to generate electricity and to power the transportation sector still originates in fossil fuels. To cope with dwindling fossil fuels and climate change, it is clear that a clean alternative energy that can replace fossil fuels in these sectors is urgently required. Clean hydrogen energy is one such alternative. Clean hydrogen can play an important role not only in synthetic fuel production but also through powering fuel cells in the anticipated hydrogen economy. With the introduction of the high temperature gas-cooled reactor (HTGR) that can produce nuclear heat up to 950°C without greenhouse gas emissions, nuclear power is poised to broaden its mission beyond electricity generation to the provision of nuclear process heat and the massive production of hydrogen. In this paper, the features and potential of the HTGR as the energy source of the future are addressed. Perspectives on nuclear heat and hydrogen applications using the HTGR are discussed.

---

**KEYWORDS** : HTGR, AHTGR, VHTR, Nuclear Process Heat, Nuclear Hydrogen, NHDD

## 1. INTRODUCTION

Dwindling fossil fuels and impending climate change are major energy, environmental and economic issues all over the world. Exhaustion of the fossil fuels that have been the world's major source of energy may jeopardize the international energy supply chain, threatening in turn the energy security and economic growth of nations [1]. Climate changes that are largely driven by the greenhouse-gas emissions from fossil fuels threaten human lives and the Earth's biosphere. To cope with shrinking fossil fuel supplies and growing climate change, it is clear that a more resource-free, technology-led and environmentally-friendly energy source will be required.

In 2004, the world consumed 446.7 quadrillion BTU of energy, and consumption is projected to increase to 701.6 quadrillion BTU in 2030. 2004 levels of energy reliance on fossil fuels such as oil, natural gas and coal, shown in Fig. 1, are projected to remain in the range of 86% in the future [2]. Of total fossil fuel consumption, the industrial heat sector consumed 35%, the electricity sector consumed 30% and the transportation sector consumed 23%. Considering the finite nature of fossil fuels, the requirement for a clean alternative energy that can replace fossil fuels in these three sectors is urgent. Nuclear energy that is greenhouse-gas emission-free contributes 6% of the total world energy supply and has helped significantly with the reduction of greenhouse gas emissions. However, the application of nuclear energy has been limited to electricity generation mainly by water reactors, which takes around 16% of total electricity generation. To ensure a stable electricity supply, there is growing interest around the world in introducing more water reactors for electricity generation. Even with increased nuclear generation of electricity, however, there remains the question of how to replace the fossil fuels used in the process heat and transportation sectors. Oil, natural gas and coal have been the major sources of power for these sectors, as well as the major sources of greenhouse gas emissions, and have been critical drivers of economic growth and national competitiveness. However, the current energy crisis from shrinking supplies of fossil fuels and resultant cost fluctuations has resulted in uncertain national energy security and faltering economic growth. Meanwhile, reliance on fossil fuels has resulted in excessive greenhouse gas emissions seen to drive harmful climate changes that may endanger public health. As there is no clear alternative mass energy supply that can replace fossil fuels in industrial process heat applications and transportation fuel production, it is inevitable that the role of nuclear power should be extended beyond electricity generation to these applications.

Projection of energy demand in Korea calls for production of 1.7 times more energy in 2020 than in 2000. Korea lacks natural resources and thus imported 97% of

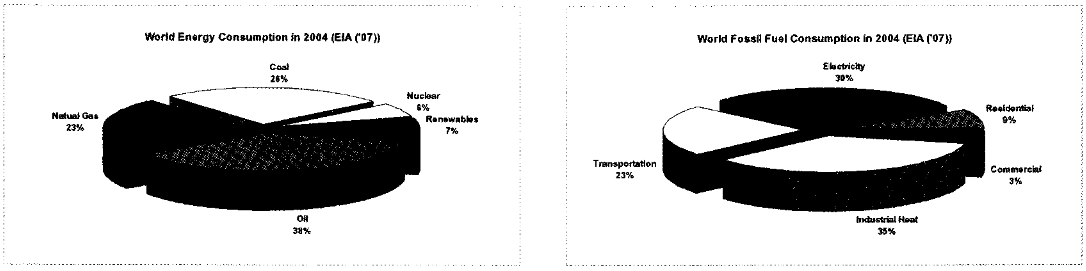


Fig. 1. World Energy Consumption (EIA (2007))

its primary energy in 2006, of which 44% was oil, mainly from the Middle East. Korea is the 6th largest emitter of carbon-dioxide ($CO_2$) in the Organization for Economic Co-operation and Development (OECD), and faces rapid climate changes at over twice the world average rate. Thus, it is imperative to develop an alternative clean energy source that can replace the fossil fuels now providing the vast majority of the Korean energy supply. Korea is a small country with a high population density, so the use of a low-density renewable energy resource such as solar or wind is geometrically limited and impractical until a revolutionary technology is developed. In this context, Korea has focused more on nuclear energy and on technology localization since the 1980s. Nuclear energy now produces more than 40% of the electricity consumed in Korea. However, its application is limited to electricity generation, as is the case elsewhere in the world. Seeking a low-carbon green growth, the Korean government has decided to increase nuclear electricity production to 59% of Korea's overall electricity production by 2030. In addition, there is a growing interest in broadening nuclear applications to allow for provision of industrial process heat and transportation fuel production.

Hydrogen is considered a promising future energy solution because it is clean, abundant and storable and has a high energy density. One of the major challenges in establishing a hydrogen economy is how to produce massive quantities of hydrogen in a clean, safe and economical way. Among various hydrogen production methods, hydrogen production using the high temperature heat from nuclear energy has been the focus of recent research. Advanced countries like the United States and Japan have launched extensive nuclear hydrogen programs to meet the roadmap to the hydrogen economy. The Korean government has also established a long-term vision for transition to the hydrogen economy (MOCIE (2005)) [3]. To meet the expected demand for hydrogen, the Korea Atomic Energy Institute (KAERI) launched a nuclear hydrogen program in 2004 [4]. In 2008, the Korean Atomic Energy Commission approved the long-term development plan for the nuclear hydrogen production as a national agenda.

A High Temperature Gas-cooled Reactor (HTGR) is a helium-cooled, graphite-moderated thermal reactor with refractory tristructural-isotropic (TRISO) fuel. It is an inherently safe reactor that can produce heat of up to 950°C. HTGRs can be categorized into the conventional HTGR designed to be operated up to 785°C, the advanced HTGR (AHTGR) designed for operation up to 850°C and the very high temperature gas-cooled reactor (VHTR) designed for operation up to 950°C that is currently under development as a Generation-IV reactor. By virtue of the high temperature heat produced by the HTGR, the HTGR can be used not only to replace the fossil fuel now used to supply industrial process heat but also to produce the massive amounts of hydrogen necessary for the hydrogen economy, all while contributing high-efficiency electricity generation.

This paper first discusses the HTGR as a future energy source, and then addresses the prospect of nuclear heat and nuclear hydrogen production. Future nuclear process heat applications will include not only existing markets such as oil refineries and industrial steam supply but also emerging markets such as synthetic methanol production, clean iron ore reduction and coal-to-liquid processing. The role of nuclear hydrogen in the coming hydrogen economy and the Korean nuclear hydrogen program are introduced in this paper.

## 2. HTGR

### 2.1 Features of HTGR

The HTGR is an inherently safe thermal reactor that can operate at temperatures of up to 950°C. To attain such high temperatures, it uses thermo-chemically stable Helium gas as coolant, graphite as a neutron moderator and the refractory coated-particle fuel, TRISO. Safe shutdown of the reactor is ensured by the low power density of the core, around 3~7 W/cc, as well as by the inherent negative fuel temperature coefficient and the large graphite heat capacity. Core afterheat is removed by natural phenomena such as conduction, radiation and convection to the self-actuating reactor cavity cooling system even without any operator actions during accident conditions. Such inherent safety features provide advantages in wide range of deployment as well as public acceptance.

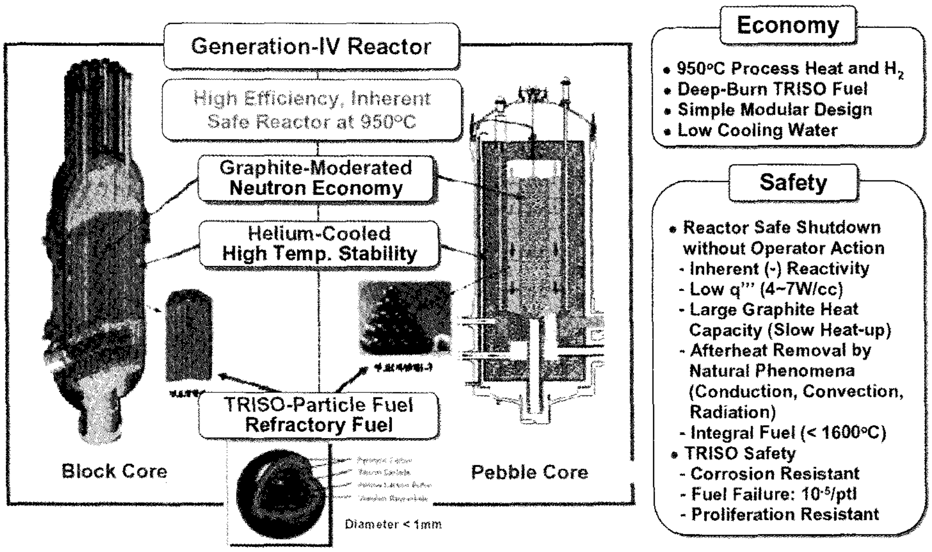


Fig. 2. Features of a HTGR

There are two types of the HTGR according to fuel type; the fuel types are the block and the pebble fuel types shown in Fig. 2. General Atomics developed a block fuel design, while FZJ developed a pebble fuel design [5,6]. The two fuel types share the same basic technology TRISO in which the 0.5mm diameter fuel kernel is multi-coated by PyC, SiC and PyC layers. In the block type, TRISO particles are lumped together into compacts that are inserted into a hexagonal graphite fuel block. Fuel blocks are loaded into the core at fixed positions and reloaded periodically. In the pebble type, TRISO particles are lumped together to make pebble fuels. Pebble fuels are distributed and continuously flow in the core and are refueled on-line during operations. TRISO particles are distinguished by high temperature integrity of up to 1600°C, fission product retention capability and corrosion resistance. These enable safe operation at an elevated temperature, deep burning of the fuel up to 60%~70% of fissions per initial metal atom (FIMA) and long-term dry storage of spent fuel. Failure probability of the TRISO particle is so low, around $10^{-5}$ per particle, that it is compared to a small containment of a water reactor.

HTGRs have been successfully operated since the 1960s. Early HTGR versions such as DRAGON, Peach Bottom, Arbeitsgemeinschaft Versuchsreaktor (AVR), Fort Saint Vrain (FSV) and Thorium High-Temperature nuclear Reactor (THTR) adopted high-enriched fuel and the steam Rankine cycle [7-9]. With the introduction of non-proliferation philosophy, the passive safety concept and advanced component technology, the reactor concept has evolved to accommodate low-enriched fuel, a low power density core, inherent passive safety and a gas-turbine Brayton cycle. Two research reactors are in operation now. The High Temperature Test Reactor (HTTR) is a $30MW_{th}$ block-type reactor at 850°C in operation at the Japanese Atomic Energy Agency (JAEA) since 1998 [10]. It achieved 950°C operation in 2004 and will be coupled to an Iodine-Sulfur hydrogen production demonstration system in 2015. High Temperature Reactor (HTR)-10 is a $10MW_{th}$ pebble-type reactor at 700°C in operation at the Institute of Nuclear and New Energy Technology (INET) since 2000 [11]. The safety of the HTGR design has been demonstrated through extensive safety demonstration tests in both research reactors.

## 2.2 Recent Development of the HTGR

HTGRs can be divided into three categories according to operating temperatures: the conventional HTGRs designed for operation up to 785°C, the advanced HTGRs (AHTGR) designed for operation up to 850°C and the very high temperature gas-cooled reactors (VHTRs) designed for operation up to 950°C currently under development as Generation-IV reactors. Recent improvement of gas component technologies and the demand for extended application of high temperature heat have revitalized HTGR development.

Table 1 lists recent world HTGR design developments. Both block and pebble type designs with thermal power from $200MW_{th}$~$600MW_{th}$ are being developed, mostly through government support. The Modular High Temperature Gas-cooled Reactor (MHTGR), which features a steam turbine, was developed in the 1980s and received a preliminary review by the United States Nuclear Regulatory Commission (USNRC) [12]. The Gas Turbine Modular Helium Reactor (GT-MHR), which features a gas-turbine, is being jointly developed as a weapons-grade Plutonium burner by the USA and Russia [13].

**Table 1.** Recent Development of HTGR Designs

| | AHTGR : High Temp. Gas Reactor [<900°C] | | | | | VHTR [>900°C] | | |
|---|---|---|---|---|---|---|---|---|
| Name | MHTGR | GT-MHR | ANTARES | PBMR | HTR-PM | NGNP | GTHTR | NHDD |
| Developer | US | US-RUS | FR | RSA | CHN | US | JP | KR |
| Core Type | Block | Block | Block | Pebble | Pebble | Not Yet | Block | Not Yet |
| Th. Power | 350MWt | 600MWt | 600MWt | 400MWt | 250MWtx2 | <600MWt | 600MWt | 200MWt |
| $T_{out}$ | 687°C | 850°C | 850°C | 900°C | 750°C | 950°C | 950°C | 950°C |
| Fuel | UCO | $PuO_2$ | $UO_2$ | $UO_2$ | $UO_2$ | $UO_2$/UCO | $UO_2$ | $UO_2$ |
| BOP | Indirect Rankine | Direct Brayton | Indirect Brayton, Heat | Direct Brayton, Heat | Indirect Rankine | $H_2$, Elec., Heat | $H_2$, Elec., Desal. | $H_2$, Heat |
| Current Status and perspective | PSID ('86) USNRC Draft SER ('89) | BD ('03) Comp Test Operation ('18) | PCD ('07) Customer Search | Licensing Operation ('15) | Licensing Operation ('13) | PCD ('07) CD R&D, Operation ('18) | SI $H_2$ ('15), Comp R&D Commer. ('25) | R&D Operation ('22) |

France has completed the preliminary conceptual design of AREVA New Technology based on Advanced gas-cooled Reactors for Energy Supply (ANTARES) and is looking for a customer market for heat applications. The Pebble Bed Modular Reactor (PBMR) of South Africa, also featuring a gas-turbine, is under licensing review and targets operation in 2015. A recent PBMR application to process heat is being reviewed by its government. China's High Temperature Reactor Pebble-bed Module (HTR-PM) uses a steam turbine and is under licensing review, targeting operation in 2013 [14].

In terms of VHTR designs, the USA has launched an extensive Next Generation Nuclear Plant (NGNP) program for the production of hydrogen, electricity and steam. The program is supported by the US Energy Policy Act promulgated in 2005 where the project schedule, budgetary requirements and the role of regulatory authority are specified [15]. The prototype NGNP is to be built and demonstrated by 2021. The Gas Turbine High Temperature Reactor (GTHTR) in Japan is supported by the Japanese national roadmap and targets commercialization of an electricity and hydrogen system in 2025 [16]. The Nuclear Hydrogen Development and Demonstration (NHDD) project in Korea is to develop and demonstrate a dedicated hydrogen production system that aims at starting operation in 2022 and targets the demonstration of hydrogen production by 2026. The VHTR applications offer the additional capability of hydrogen production beyond the heat applications of the AHTGR.

## 2.3 High-Efficiency Electricity Generation

The high temperature heat of the HTGR enables high-efficiency electricity generation. A VHTR at 950°C with a gas-turbine Brayton cycle can generate electricity at over 50% efficiency [17]. The recent energy crisis has raised interest in introducing more nuclear electricity. Small and medium-scale electricity generation with HTGRs could offer advantages in developing countries with small grids. The air-cooling capability of the HTGR and its consequently lower cooling water requirement are advantages for deployment in arid areas. The difficulty of separating the fissile material from the TRISO particle strengthens the proliferation resistance of HTGRs. Residual heat of the HTGR power cycle can be used to desalinate sea water. Fig. 3 shows a conceptual configuration of the co-generation system for both electricity and desalination. Both the gas-turbine in the primary loop and the steam-turbine in the secondary steam loop generate electricity and the exhaust steam from the high-pressure turbine provides heat to the desalination system. Preliminary evaluation of the system at 750°C results in a maximum electricity production efficiency of up to 50% and a maximum desalinated water production rate of up to 216ktons/day, depending on the allocation of the thermal power.

## 2.4 Effective Use of Fuel Resources and High-Level Waste Reduction

The extra high burn-up capability, the so called deep-burn up of as much as 60%~70% FIMA, of the TRISO particle can be used to burn Plutonium from weapons and Transuranics (TRU) recycled from the spent fuel of water reactors. An HTGR burner with a full TRU core was assessed and found to burn the TRU up to 65%. This implies that the spent TRU fuel can be directly disposed because of its low high-level waste inventory and decay heat. The requirement for subsequent fast burner reactors

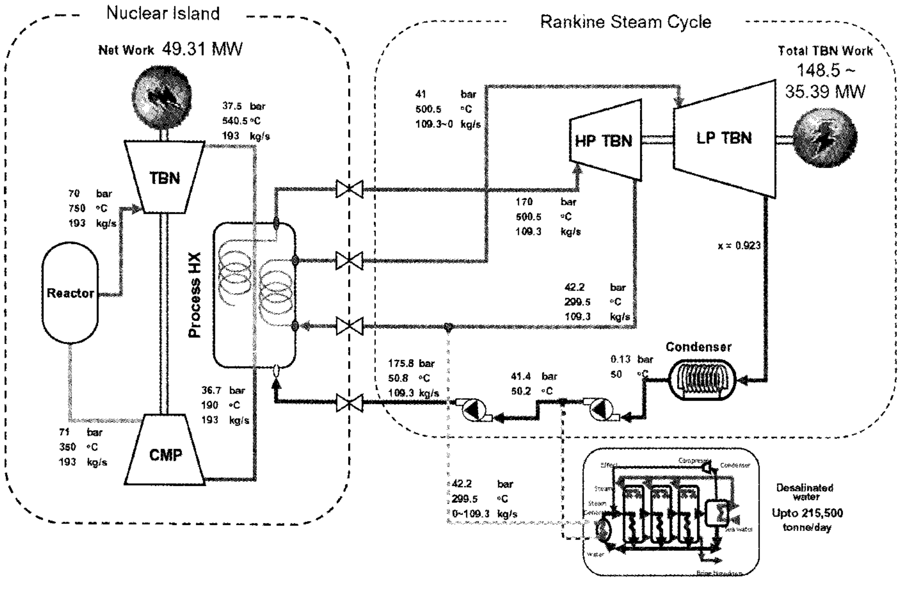


Fig. 3. Conceptual Configuration of Co-generation System

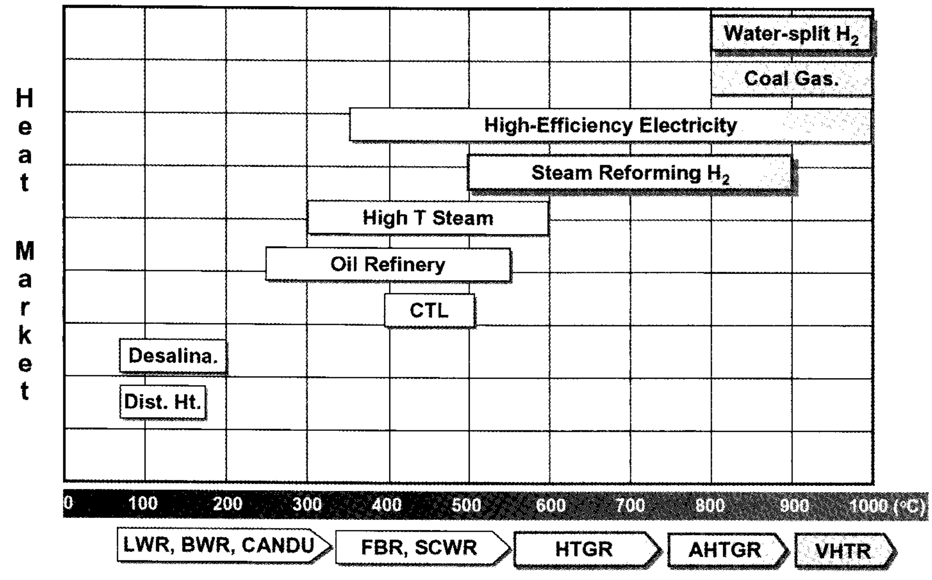


Fig. 4. Potential Process Heat Markets using Nuclear Energy

and reprocessing can be reduced to one over three. The United States Department of Energy (USDOE) launched a Deep Burn-Modular Helium Reactor (DB-MHR) project for burning the TRU from the water reactors and a GT-MHR project for a weapons-grade Plutonium burner [18]. Deep-burn capability also provides a potential for the use of Thorium fuel in HTGRs. Thorium is abundant and is considered as an alternative fuel replacing finite Uranium. A Thorium core requires longer burn-up for conversion of the Thorium into a self-sustainable amount of U-233 fissile.

## 2.5 Process Heat and Hydrogen

By virtue of its high temperature, an HTGR can deliver efficient heat not only to replace the fossil fuel burned to supply industrial process heating, but also to produce massive quantities of hydrogen for the hydrogen economy [19, 22]. Fig. 4 shows the potential markets for nuclear heat applications. They include district heating and desalination at low temperature ranges, oil refineries, coal-to-liquid production, high temperature steam for industrial complexes, steam-methane reforming hydrogen production and high-efficiency electricity generation at

**Table 2**. Decrements of Carbon Dioxide Emissions from Industrial Processes

| Process | | Carbon Oxide Emissions |
|---|---|---|
| Heavy Oil Recovery | Conventional | 2 ton OIP→1 ton Product + 2.5 ton $CO_2$ |
| | Nuclear | 2 ton OIP + 12 MWh→2 ton Product + no $CO_2$ |
| Methanol Production | Conventional | 300 $m^3$ Gas→1 ton Product + 1.5 ton $CO_2$ |
| | Nuclear | 300 $m^3$ Gas + 3 MWh→2 ton Product + no $CO_2$ |
| Oil Shale | Conventional | 2 ton Shale→1 ton Product + 2.5 ton $CO_2$ |
| | Nuclear | 2 ton Shale + 12 MWh→2 ton Product + no $CO_2$ |
| Biomass Conversion | Conventional | 2 ton Biomass→1 ton Product ($CH_3OH$) |
| | Nuclear | 2 ton Biomass + 10 MWh→2t Product |

medium temperature ranges, as well as coal gasification and water-split hydrogen production at high temperatures. Major applications of the HTGR are in the medium and high temperature ranges, as covered in sections III and IV.

Strategically, a two-step approach is being reviewed in Korea. The 1st step aims at a mid-term deployment of the AHTGR by the late 2010s to replace the process heat now supplied by fossil fuel. The AHTGR at 850°C is based on a semi-mature technology with low technical and licensing risks so that the target can be met. Two application areas are being considered. Both produce hydrogen by steam-methane reforming and then the product hydrogen is used 1) to produce synthetic methanol by recycling captured $CO_2$ and 2) to reduce iron ore. The 2nd step aims at a long-term deployment of the VHTR for the production of hydrogen. Considering that there are still challenges to be resolved with the VHTR and water-split hydrogen production technologies, the target is to demonstrate the system by the middle of the 2020s. This two-step approach is deemed practical and achievable by introducing the semi-mature technologies of the AHTGR first and then extending them to the future technologies of the VHTR.

### 2.6 Economic Aspects of HTGR Deployment

The economic advantage of deploying the HTGR is in its simple and modular design features and its high temperature efficiency. The simple design shortens the construction period and reduces the operation and maintenance costs. The modularity of its design enables the installation of multiple units at a site. Both features reduce the investment risk, since investors can recoup their investments by operating the initial units during the construction of the subsequent units. The small and medium sizes of the HTGR fit the industry demand and the electricity grids in developing countries. Multiple installations of the small and medium units add value in industrial applications, since uninterrupted energy supply is possible by controlling the overhaul of individual units. The inherent safety features of the HTGR and the extremely low probability of fuel failure allow a proximate location between HTGRs and industrial plants.

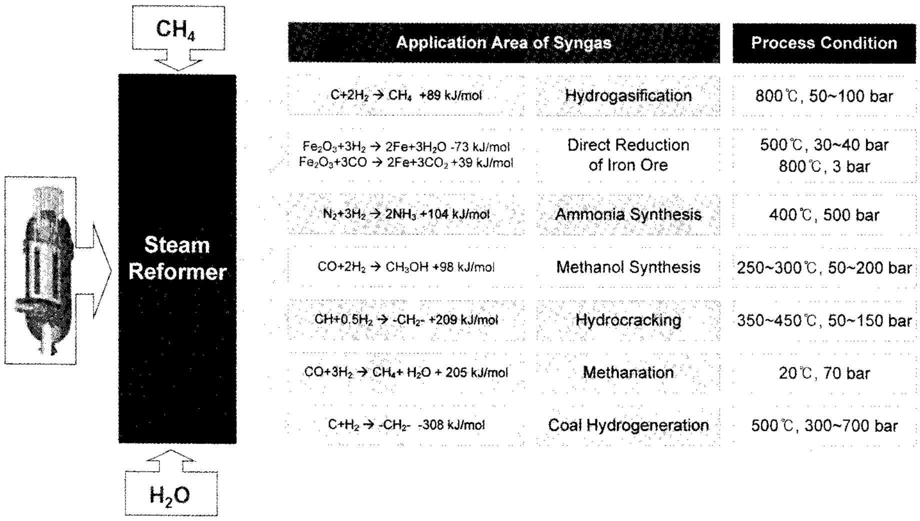
## 3. NUCLEAR HEAT

High temperature heat of an HTGR can be used to replace both the existing and emerging process heat markets as discussed in the previous section. In this section, nuclear heat applications to the steam reforming, the methanol production, the iron ore reduction, the oil refinery, the steam production and the coal liquidification are discussed. Nuclear heat applications can reduce a massive amount of $CO_2$ emissions that would be otherwise generated by fossil fuels [23-25]. The reduction of $CO_2$ emissions possible through replacing fossil fuels with nuclear heating in common industrial processes is shown in Table 2.

### 3.1 Nuclear Steam Reforming

The steam reforming process is one of the near-term applications of the HTGR. Steam reforming is an endothermic conversion reaction to get pure hydrogen from the hydrogen in water and methane, while carbon monoxide (CO) is obtained from the carbon in methane and the oxygen in water. Synthetic hydrogen is a commercial source of hydrogen for hydro-gasification, direct reduction of iron ore, ammonia synthesis, methanol synthesis, hydro-cracking, methanation, coal hydrogenation and other purposes, as shown in Fig. 5. In addition, hydrogen is widely used in the desulfuration process in oil refineries and in advanced hydrocarbon production processes for substances such as polycarbonate. At present, numerous fossil fuels are consumed as thermal energy to produce hydrogen through the steam reforming process.

For nuclear steam reforming, coupling technology between the nuclear system and the steam reforming process is a key technical challenge, since the steam



| Application Area of Syngas | | Process Condition |
|---|---|---|
| $C+2H_2 \rightarrow CH_4$ +89 kJ/mol | Hydrogasification | 800℃, 50~100 bar |
| $Fe_2O_3+3H_2 \rightarrow 2Fe+3H_2O$ -73 kJ/mol<br>$Fe_2O_3+3CO \rightarrow 2Fe+3CO_2$ +39 kJ/mol | Direct Reduction of Iron Ore | 500℃, 30~40 bar<br>800℃, 3 bar |
| $N_2+3H_2 \rightarrow 2NH_3$ +104 kJ/mol | Ammonia Synthesis | 400℃, 500 bar |
| $CO+2H_2 \rightarrow CH_3OH$ +98 kJ/mol | Methanol Synthesis | 250~300℃, 50~200 bar |
| $CH+0.5H_2 \rightarrow -CH_2-$ +209 kJ/mol | Hydrocracking | 350~450℃, 50~150 bar |
| $CO+3H_2 \rightarrow CH_4+H_2O$ + 205 kJ/mol | Methanation | 20℃, 70 bar |
| $C+H_2 \rightarrow -CH_2-$ -308 kJ/mol | Coal Hydrogeneration | 500℃, 300~700 bar |

Fig. 5. Nuclear Steam Reforming and Its Application

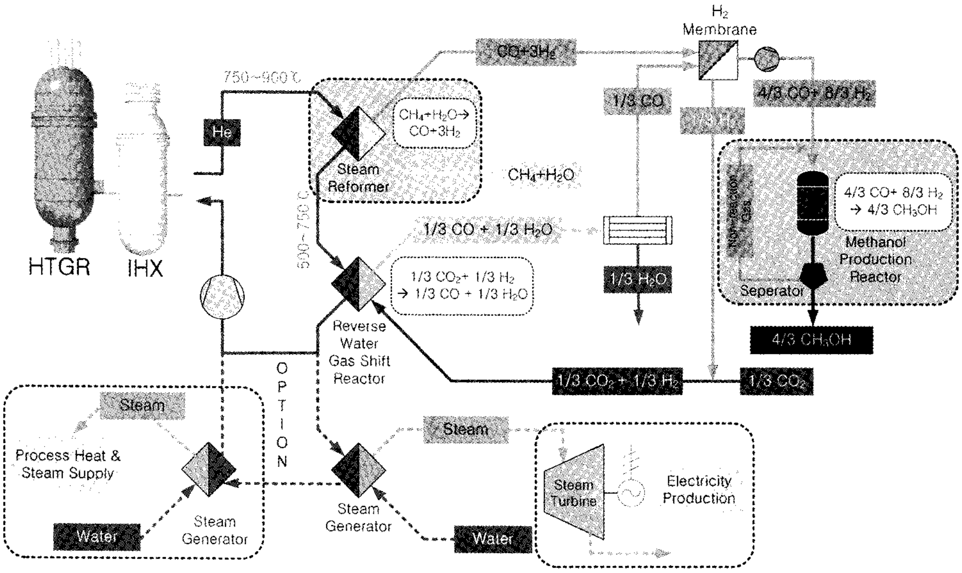


Fig. 6. Conceptual Configuration of Nuclear Methanol System

reforming process itself is well proven. There was an extensive efforts by JAEA to produce hydrogen by the steam methane neforming process using nuclear heat and JAEA completed a small-scale demonstration using an HTTR[26]. The economy of nuclear steam reforming is strongly influenced by the cost of natural gas.

## 3.2 Nuclear Methanol

At present, methanol is used as a feedstock for fuel addition and chemical materials such as formaldehyde and acetic acid, etc. The worldwide and domestic markets for methanol were 40Mtons/yr and 1.5Mtons/yr in 2007, respectively. These demands are expected to increase up to 80Mtons/yr and 2.2Mtons/yr in 2020. Most methanol is now produced from coal and natural gas. Emerging markets of methanol are expected for transportation fuel and olefin production in near term. As an alternative for oil in the transportation market, De-methyl Ether (DME) fuel that can share the infrastructure of liquefied petroleum gas (LPG) is being extensively studied in Korea. If DME fuel and olefin markets were to be commercialized, it is predicted there would be an additional domestic market for methanol of 4Mtons/yr in 2010 and 8.3Mtons/yr in 2020.

To recycle captured $CO_2$, the Korea Institute of Science

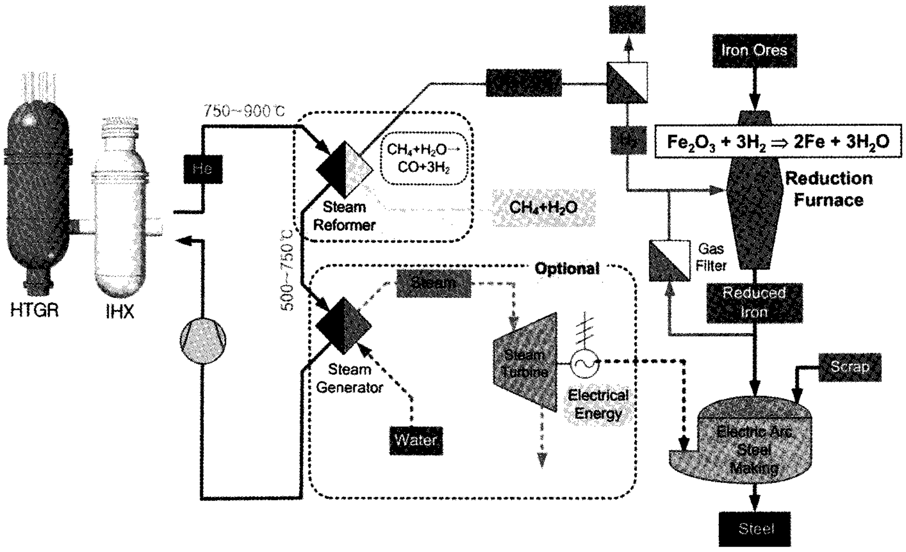


Fig. 7. Conceptual Configuration of Nuclear Steel System

and Technology (KIST) developed and demonstrated a direct methanol production process using hydrogen and captured $CO_2$, the so-called CAMERE-I process. The process consists of a reverse water shift reaction and methanol production.

- Reverse water shift reaction:

$CO_2 + 3H_2 \rightarrow CO+2H_2+H_2O$

- Methanol production:

$2H_2+CO \rightarrow CH_3OH$

- Balance:

$CO_2 + 3H_2 \rightarrow CH_3OH + H_2O$

By introducing the steam reforming process to produce hydrogen in the subsequently developed CAMERE-II procedure, the methanol production process has been modified as follows:

- Steam reforming:

$CH_4 + H_2O \rightarrow CO + 3H_2$

- Reverse water shift reaction and methanol production:

$0.33CO_2 + CO + 3H_2 \rightarrow 1.33CH_3OH + 0.33H_2O$

- Balance:

$0.33CO_2 + CO + 3H_2 \rightarrow 1.33CH_3OH + 0.33H_2O$

The concept of nuclear methanol production is to use the AHTGR heat at 850 °C in the CAMERE-II process. AHTGR heat ranging from 750 °C to 850 °C is supplied to the steam reforming process and heat ranging from 500 °C to 750 °C is used in the reverse water shift reaction. A conceptual configuration of the nuclear methanol system is given in Fig. 6. Interfaces between the nuclear system and the methanol production system are the steam reformer and the reverse water shift reactor; it is these interfaces that present the technical challenges. As an option, residual heat can be used to produce steam and/or electricity. Preliminary analysis has shown that a 450MW$_{th}$ AHTGR can produce 1Mtons/yr of methanol by recycling 0.35Mtons/yr of $CO_2$. By replacing fossil fuel in the steam reforming process, an AHTGR can reduce $CO_2$ emissions by 0.96Mtons/yr. It is estimated that the cost of nuclear methanol production is $360/ton.

### 3.3 Nuclear Steel

Steel companies are among the largest fossil fuel energy users and, thus, are also among the largest sources of $CO_2$ emissions. Two tons of carbon dioxide are emitted to produce one ton of steel in the present steel production process. Given this state of affairs, steel making companies are looking for a clean alternative steel making process. There are two options for using HTGR heat in an alternative steel production process. The high temperature heat of an HTGR can be directly supplied to various sub-processes in the overall process of steel making [27]. Replacement of conventional fossil fuels with nuclear heat in various steel production sub-processes reduces the emission of $CO_2$. Another option is the direct reduction of iron ores using hydrogen. Hydrogen can be produced by steam reforming using an AHTGR or by a water-splitting process using a VHTR. Various processes for the direct reduction of iron ores through the use of hydrogen or hydrogen-rich reducing gases such as natural gas have been proposed, but the basic concepts of these various processes are similar to one another. Theoretically, such processes do not emit $CO_2$ and produce only water and reduced iron.

- Direct iron ore reduction by hydrogen:

$Fe_2O_3 + 3H_2 \text{->} 2Fe+3H_2O$

Steel making by the direct hydrogen reduction process is included in the Japanese ‘Cool Earth 2050’ plan, and Korean steel making companies are becoming interested in the process. A comparison of steel production investment costs showed that a direct reduction process using hydrogen is around 65% of a conventional blast furnace process [28]. Nuclear steel system under consideration is to use AHTGR heat at 850°C in hydrogen production by steam reforming and in electricity generation through a steam power cycle. Both heat and electricity from the AHTGR are to be used in the direct iron ore reduction process. The conceptual configuration of such a nuclear steel system is given in Fig. 7. In order to produce 5Mtons/yr of steel by the direct hydrogen reduction process, 260,000tons/yr of hydrogen is needed [28], which is equivalent to the amount of hydrogen that can be produced by an AHTGR of 450$MW_{th}$.

### 3.4 Nuclear Oil Refinery

The oil refining industries are the ones of the largest process heat markets in Korea. An HTGR can provide the process heat needed in the distillation unit, as shown in Fig. 8. The oil refining industries also use a large amount of hydrogen that is produced on site by steam reforming using fossil fuels. An AHTGR has the potential for producing hydrogen and at the same time for providing process heat to the distillation unit.

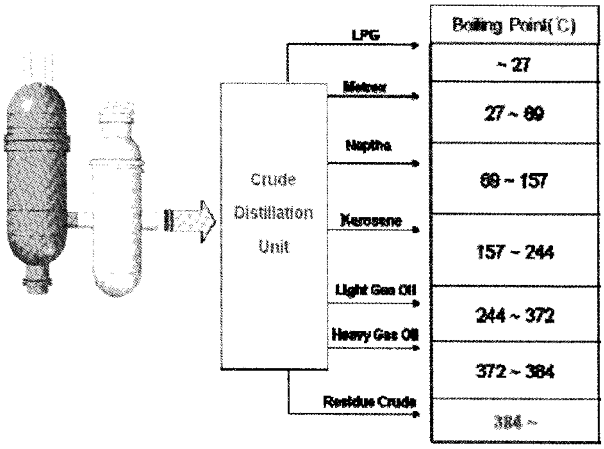


Fig. 8. Process Heat Supply for Crude Oil Distillation Unit

### 3.5 Nuclear Steam

Market search has been performed in the Yeosu chemical complex, where many industrial refineries, chemical plants and power plants are located. Approximately 150,000 tons/day of steam including high pressure steam exceeding 380°C is produced and consumed in this area. Half of this steam is produced from fossil fuels such as coal and natural gases. It is estimated that seven HTGRs could produce the steam required in the Yeosu complex. In addition, 170,000 $Nm^3/hr$ of hydrogen is produced from natural gas steam reforming and distributed inside the complex for chemical processes. An AHTGR of 250$MW_{th}$ could produce the necessary hydrogen by the nuclear steam reforming. There are piping networks for a central steam and hydrogen supply system already in place in the Yeosu chemical complex that could be used for distribution of nuclear steam and hydrogen.

### 3.6 Nuclear Coal-to-Liquid (CTL)

In order to reduce dependence on oil, the conversion of coal to hydrocarbon liquid fuel is being studied widely. The technology was originally developed in Germany during World War II. Since the 1950s, the South African Coal Oil Corporation (SASOL) has been operating commercial coal to liquid plants, producing approximately 30% of South Africa's automotive fuels [29]. The USA and China are currently trying to produce synthetic fuels from their abundant coal resources. Because of an increase

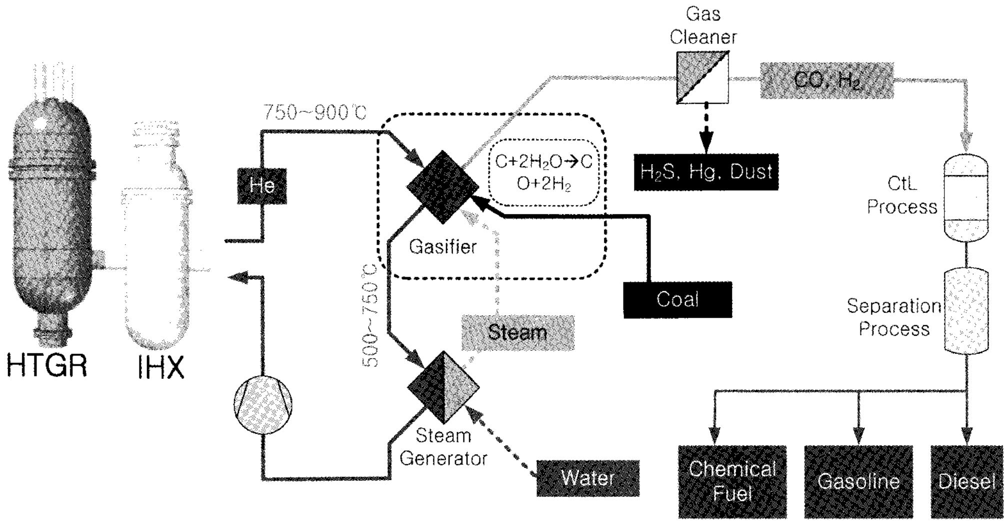


Fig. 9. Conceptual Configuration of Nuclear Coal-to-Liquid Process

in oil prices, the coal-to-liquid (CTL) process has also become a focus of research in Korea. However, the problem of the CTL process is that almost half of the coal is converted to $CO_2$. This problem can be solved by applying nuclear heat, which would allow most of the coal to be converted to synthetic fuel without $CO_2$ emissions. The fuel cost of nuclear CTL technology is estimated around half of current CTL technology. Nuclear CTL can be economical if the price of coal continues to increase and a carbon tax is applied. In this context, the South African government is considering the nuclear CTL application to its conventional CTL process. Fig. 9 shows the conceptual configuration of a nuclear CTL system. Heat generated from an HTGR is used for a coal gasifier and the residual low temperature heat produces steam for the gasifier.

## 4. NUCLEAR HYDROGEN

### 4.1 Hydrogen Economy Roadmap

Hydrogen is considered one of the promising future energy solutions due to its high energy density and its clean, abundant and storable nature. Though controversy remains over the prospect of a future hydrogen economy, there is an increasing consensus that the hydrogen economy is a practical and inevitable future rather than merely an option to protect against climate change and the exhaustion of fossil fuel supplies. Hydrogen has already been used as chemical feedstock in oil refining, fertilizers and chemicals, etc. In the future hydrogen economy, hydrogen will additionally be used as the fuel for fuel cells in transportation, distributed electricity generation and portable electronic devices, as well as for the feedstock in emerging markets such as synthetic fuel, clean iron ore reduction and coal-to-liquid conversion, etc. World hydrogen demand that was 50Mtons/yr in 2008 is projected to increase to 78Mtons/yr in 2030 and to 166Mtons/yr in 2040. Hydrogen supply in Korea was 1Mtons/yr in 2008 and is expected to increase to 3.6Mtons/yr in 2030 and to 11.8Mtons/yr in 2040. The market demand will increase rapidly when entering the hydrogen economy in the 2030s.

In light of this anticipated increase in reliance on and demand for hydrogen, advanced countries have put forward their roadmaps to the hydrogen economy and have launched extensive programs in support of those roadmaps. In Korea, rapid climate changes and heavy reliance on imported fossil fuels have motivated the government to set up a roadmap to the hydrogen economy (MOCIE (2005)). As shown in Fig. 10, the roadmap consists of four phases: 1) the technology development phase in the 2010s, 2) the introduction phase in the 2020s, 3) the commercialization phase in the 2030s and 4) the hydrogen economy in the 2040s. For each phase, specific targets are given for hydrogen utilization (fuel cells for cars, central and distributed electricity generation), hydrogen production (fossil energy such as natural gas and coal, nuclear energy and renewable energy), hydrogen storage (high pressure gas, liquid and carbon nanotube) and hydrogen supply (onsite and offsite stations). The reference projection of the hydrogen share in the total energy demand is 7% in the 2030s and 15% in the 2040s. The nuclear hydrogen option adds 5% more to the hydrogen share in the 2040s.

### 4.2 Nuclear Hydrogen Perspectives

The roadmap to the hydrogen economy requires the balanced development of hydrogen production, storage/delivery and utilization technologies. One of the major challenges is determining how to produce massive quantities

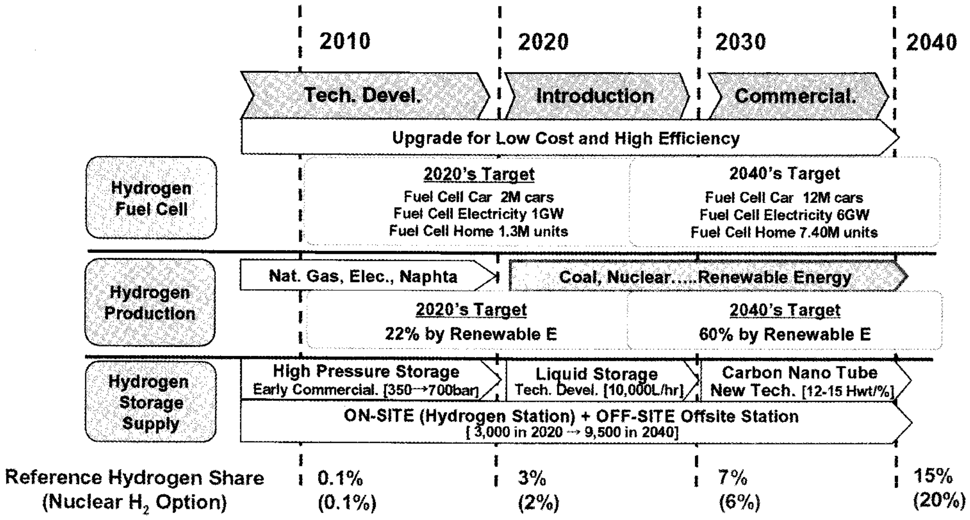


Fig. 10. Roadmap to Hydrogen Economy in Korea (MOCIE (2005))

of hydrogen in a clean, safe and economic way. Among various hydrogen production methods, the massive, safe and economic production of hydrogen by water splitting using a VHTR can provide a successful path to the hydrogen economy. Particularly in Korea, where usable land is limited, the nuclear production of hydrogen is deemed a practical solution due to its high energy density. Another merit of nuclear hydrogen is that the nuclear is a sustainable and technology-led energy not affected by the uncertainties plaguing fossil fuel supplies. Advanced countries like the United States and Japan have launched extensive nuclear hydrogen projects to meet their roadmaps to the hydrogen economy. Korea also launched a nuclear hydrogen project in 2004.

Current hydrogen demand is mainly from oil refinery and chemical industries. Hydrogen is mostly produced by steam reforming using the fossil fuel heat. Against the fossil fuel run-out and climate changes, there is a growing interest in introducing the nuclear hydrogen to the existing hydrogen markets. In Korea, more than 0.6Mtons/yr of hydrogen is produced and consumed at oil refinery industries. Considering that a commercial scale 600MWth VHTR can produce 0.06Mtons/yr of hydrogen. More than 10 nuclear hydrogen units are required to replace current steam reforming hydrogen production in the oil refinery. In the hydrogen economy in the 2040s, it is projected that the 25% of total hydrogen demand is supplied by the nuclear hydrogen, which is around 3Mtons/yr. For this, it is expected that 50 nuclear hydrogen units will be required.

### 4.3 Nuclear Hydrogen Program in Korea

In 2008, Korean Atomic Energy Commission officially approved the nuclear hydrogen program and now the nuclear hydrogen program became the national agenda. Nuclear hydrogen program in Korea consists of two major projects; the nuclear hydrogen key technologies development project and the nuclear hydrogen development and demonstration (NHDD) project. Fig. 11 illustrates the implementation plan of the nuclear hydrogen program. The key technologies development project was launched at KAERI in 2006 and it focuses on the development and validation of key and challenging technologies required for the realization of the nuclear hydrogen system [30]. The project will run up to 2017 in phase with Gen-IV International Forum projects and the NHDD project. The NHDD project is to design and construct a nuclear hydrogen demonstration system and to demonstrate its hydrogen production and safety. The project is expected to start in 2010 aiming at the completion of construction in 2022 and the demonstration by 2026. Commercial venture for the NHDD project is being discussed. Final goal is to commercialize the nuclear hydrogen technology before 2030.

Fig. 12 illustrates a reference nuclear hydrogen demonstration system. It is fully dedicated to the hydrogen production and consists of a VHTR at 950°C, 5 modules of Sulfur-Iodine (SI) water-split hydrogen production processes and an intermediate loop that transports the nuclear heat to the hydrogen production process. Underground reactor and indirect loop configuration is adopted for ensuring the safety. Power level of 200MW$_{th}$ is selected and a cooled-vessel design is adopted, which enables the use of a domestic fabricated reactor pressure vessel and ensuring the operation and maintenance cost. Both the block and pebble cores are the candidates and the selection is expected in 2012 [31,32]. And, the ranges of operating parameters are being studied for maximizing

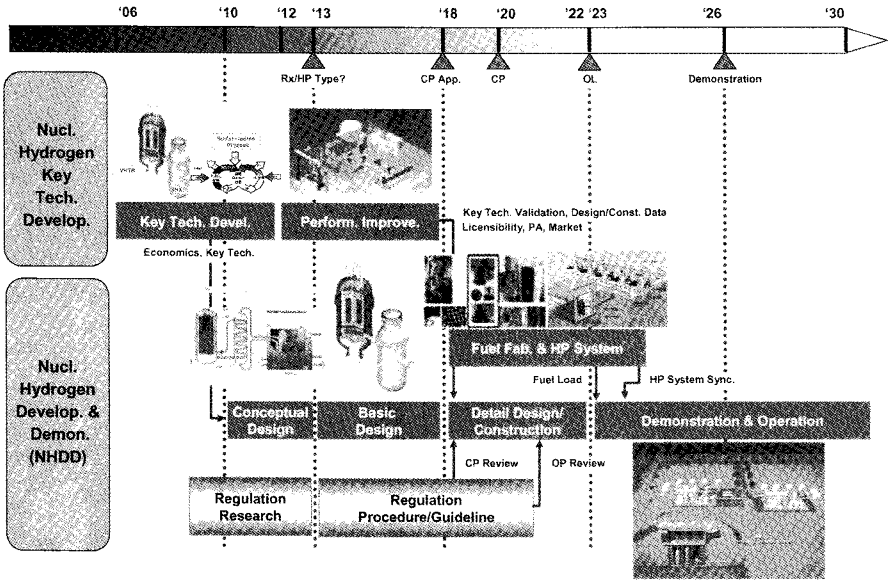


Fig. 11. National Nuclear Hydrogen Project Plan (approved by AEC in Dec. 2008)

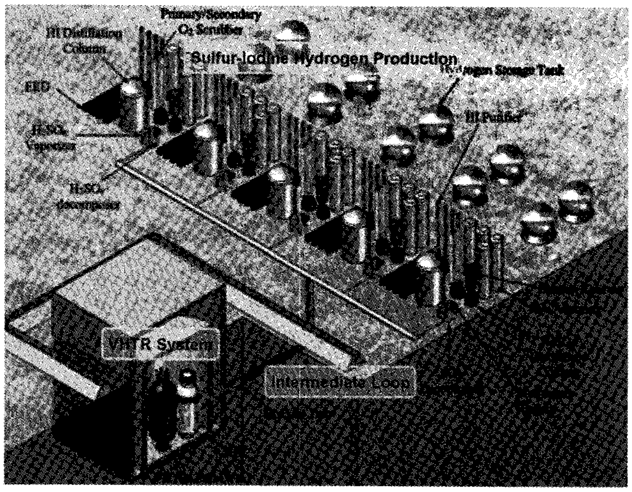


Fig. 12. Nuclear Hydrogen Demonstration System

the hydrogen production efficiency considering the integrity, sizing and manufacturing capability of components [33].

## 4.4 Nuclear Hydrogen Key Technologies Development Project

Through a pre-conceptual design study in 2004 and 2005, key technological areas in the VHTR core and system, hydrogen production process, coupling between reactor and chemical side, and the coated fuel were identified. Base on this, the nuclear hydrogen key technologies development project was launched at KAERI in 2006 as a national program of Ministry of Education, Science and Technology. It aims at the development and validation of key and challenging technologies that are required for the realization of the nuclear hydrogen system. KAERI takes the leading role of the project and the development of the VHTR technologies. Korea Institute of Energy Research (KIER) and Korea Institute of Science and Technology (KIST) takes the role of developing the SI hydrogen production technologies.

The project consists of two stages; the 1st stage (2006~2011) for the development of technologies and the 2nd stage (2012~2017) for the performance improvement and validation of technologies. The 1st phase study (2006~2008) of the development stage was completed in February 2009 and the 2nd phase study (2009~2011) had just started. The project is a 12 year project and run in phase with Gen-IV International Forum and the NHDD projects.

From the 1st phase study, key basic technologies in the design and computational tools, high-temperature materials and components, TRISO fuel manufacturing and the SI thermo-chemical hydrogen production process were developed. The technologies developed can be used for the conceptual design of the NHDD system. Major outcomes of the 1st phase study are:

1) Design and computational tools
  - Design concepts of the block and pebble cores at 950°C satisfying safety and economy
  - Design concept of a cooled-vessel for use of conventional reactor pressure vessel
  - Computational tools for nuclear design and thermo-fluid and safety analysis, etc.
2) Materials and Components
  - High temperature material tests in Helium environment
  - Graphite oxidation tests
  - Design concept of process heat exchanger ($SO_3$ decomposer) metal-based and surface-coated for manufacturing corrosion resistance
  - 10kW high pressure and temperature nitrogen/sulfuric acid gas loop
3) Fuel
  - Fuel manufacturing and qualification technology at 20g/batch scale
  - Fuel performance analysis module
4) SI hydrogen production
  - Demonstration of 3.5L/hr at atmospheric pressure and continuous operation
  - Basic technologies for catalysts, corrosion and vapor-liquid equilibrium data
  - Basic technologies of individual process unit at pressurized conditions

The 2nd phase study focuses on the improvement and validation of the selected technologies developed in the 1st phase study to the level that can be applied to the basic design of the NHDD system. The following study is planned and being performed:

1) Design and computational tools
  - Design concepts of the system configuration and optimization of operating parameters
  - Verification and validation and the documentation of computational tools
2) Materials and Components
  - Continuation of material tests
  - Design validation and manufacturing technology of process heat exchanger
  - Construction of 150kW high pressure and temperature Helium loop
3) Fuel
  - Optimization of fuel manufacturing and qualification technology at 20g/batch scale
  - Verification and validation and the documentation of fuel performance code
  - Preparation and initiation of fuel irradiation tests
4) Pressurized SI hydrogen production
  - Construction of Bunsen skid at 200L/hr
  - Construction of HI decomposition skid at 200L/hr
  - Construction of $H_2SO_4$ decomposition skid at 200L/hr
  - Integration of SI process for continued operation

In order to resolve technical challenges and to improve associated technologies in the VHTR and SI process, various multi-lateral and bi-lateral international collaborations are in progress. As multi-lateral collaborations, KAERI participates in the fuel, hydrogen, materials and computational methods validation and benchmark projects of the Generation-IV International Forum (GIF) VHTR system and in the OECD and IAEA code benchmarks. As bi-lateral collaborations, I-NERI projects with INL and ANL of USA are being performed. Nuclear hydrogen joint development center with General Atomics of USA and the nuclear hydrogen joint research center with INET of China were established for joint research and development projects. Information exchange and joint collaborations are in progress with JAEA of Japan, PBMR of South Africa and CEA of France respectively. Fuel manufacturing technologies at 2~3kg/batch scale are being transferred from FZJ of Germany. In order for planning the joint commercial venture of the NHDD project, a domestic council consisting of industries, research organizations and universities is being established. Such international and domestic collaboration will contribute a lot in ensuring the soundness and integrity of the technologies developed and in mitigating the risk on the NHDD project.

## 5. SUMMARY AND CONCLUSION

The HTGRs, nuclear process heat applications and nuclear hydrogen production were introduced and discussed in this paper. Due to its high temperature and inherent safety, the HTGRs can provide effective resolution against the exhaustion of fossil fuels and help to reduce the carbon emissions that contribute to climate change. Heat from AHTGRs can replace heat from fossil fuels in the existing process heat markets such as steam-methane reforming hydrogen production, central steam production, oil refinery heat supply and coal-to-liquid synthetic fuel production. AHTGRs can supply heat to emerging markets such as methanol production by recycling captured $CO_2$ and clean reduction of iron ore. In addition, the HTGR is a viable option for high-efficiency electricity generation in arid countries with small electrical grids and for the effective use of fuel resources. Massive, safe, clean and efficient production of hydrogen by water splitting using the VHTR can provide a practical path to the future hydrogen economy. Recent government approval of the nuclear hydrogen program in Korea has laid a cornerstone for the foundation of the hydrogen economy. In conclusion, the HTGRs and their applications to the industrial process heat and clean hydrogen production will contribute to the low-carbon green growth, clean environment and energy security of Korea.

## ACKNOWLEDGMENTS

This work was supported by the Nuclear Research & Development Program of the Korea Science and Engineering Foundation (KOSEF) grant funded by the Korean government (MEST).

## REFERENCES

[1] R. Jeremy, *The Hydrogen Economy*, (2002)

[2] Energy Information Administration, http://www.eia.doe.gov/

[3] K.J. Bu, "National Vision for Hydrogen Economy and Its Action plan Set up," *Energy Economy Research*, **4**(2), 129-147, (2005)

[4] J. Chang, Y.W. Kim, K.Y. Lee, Y.W. Lee, W.J. Lee, J.M. Noh, M.H. Kim, H.S. Lim, Y.J. Shin, K.K. Bae, and K.D. Jung, "A Study of a Nuclear Hydrogen production Demonstration Plant," *Nuclear Engineering and Technology*, **39**(2), 111-122, (2007).

[5] M. Richards and A. Shenoy, "H2-MHR Pre-conceptual Design Summary for Hydrogen Production," *Nuclear Engineering and Technology*, **39**(1), 1-8(2007).

[6] H. Nabielek, W. Kuhnlein, W. Schenk, W. Heit, A. Christ, H. Ragoss, "Development of Advanced HTR Fuel Elements," *Nuclear Engineering and Design*, **121**, 199-210, (1990)

[7] R. A. Simon and P. D. Capp, "Operating Experience with the Dragon High Temperature Reactor Experiment) by Reverses Osmosis(RO)," *Proceedings of 1st International Topical Meeting on HTR*, Petten, April.22-24, (2002)

[8] K.I. Kingrey, *Fuel Summary for Peach Bottom Unit 1 High-Temperature Gas-Cooled Reactor Cores 1 and 2*, INEEL/EXT-03-00103, (2003)

[9] E. Wahlen and P. Pohl, *AVR Operational Experience, Overview*, FZJ, (2001)

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

[11] D. Zhong and Y. Xu, *Progress of the HTR-10 project*, IAEA-TECDOC-899, (1995)

[12] F.A.Silady, J.C.Cunliffe, and L.P.Walker, "The Licensing Experience of the Modular High-Temperature Gas-Cooled Reactor (MHTGR)," *Proc. of TCM*, SanDiego, 21-23 Sept. (1988).

[13] A. Shenoy, *Gas Turbine Modular Helium Reactor (GT-MHR) Conceptual Design Description Report*, GA report 910720, (1996)

[14] Z. Wu and Y. Dong, "Introduction of HTR-PM Demonstration Project," *Proceedings of IAEA TM on Safety Aspects of Modular HTGRs*, Beijing, 23-26 Oct. (2007)

[15] K. Weaver, et.al, NGNP Preliminary Project Management Plan, INL/EXT-05-00952, (2006)

[16] K. Kunitomi, et al., "JAEA's VHTR for Hydrogen and Electricity Cogeneration: GTHTR300C," *Nuclear Engineering and Technology*, 39(1), 9-20, (2007)'

[17] S.A. Wright and P.S. Pickard, "Impact of Closed Brayton Cycle Test Results on Gas Cooled Reactor Operation and Safety," *Proceedings of ICAPP 2007*, Nice, France, May 13-18, (2007)

[18] M. Richards, et al., "VHTR Deep Burn Applications," *Proceedings of PBNC-16*, Aomori, Japan, Oct. 13-18, (2008).

[19] D. Hinttner, et al., "A New Impetus for Developing Industrial Process Heat Applications of HTR in Europe," *Proceedings of HTR 2008*, Washington DC, Sept30-Oct.1, (2008).

[20] Y.W. Kim, et al., "Gas Cooled Reactor, Its Potential Applications for Process Heat" *IAEA TM on Non electric Applications of Nuclear Energy*, Daejeon, March 3-6, (2009).

[21] W. Kriel, et al., "The Potential of the PBMR for Process Heat Applications," *Proceedings HTR-2006*, Johannesburg, RSA, Oct.1-4, 2006

[22] J. Chang "Challenges for Production of Hydrogen Using

Nuclear Energy," *IAEA TM on Non electric Applications of Nuclear Energy*, Daejeon, March 3-6, (2009).

[23] M. Ogawa, Nishihara, "Japan's HTTR, Tetsuo," *Nuclear Engineering and Design*, **233**(1-3), 5-10, (2004).

[24] R. Elder and R. Allen, "Nuclear Heat for Hydrogen Production : Coupling a Very High/High Temperature Reactor to a Hydrogen Production Plant," *Progress in Nuclear Energy*, **51**, 500-525, (2009).

[25] R. Kuhr, "HTR's Role in Process Heat Application," *Nuclear Engineering and Design*, **238**(11) 3013-3017, (2008).

[26] H. Ohashi et al., "Development of Control Technology for HTTR Hydrogen Production System with Mock-up Test Facility - System Controllability Test for Loss of Chemical Reaction." *Nuclear Engineering and Design* 236, 1396-1410, (2006).

[27] K. Suruoka, T. Inatani, T. Miyasugi, and M. Mizuno, "Design Study of Nuclear Steelmaking System," *Transaction of the Iron and Steel Institute of Japan*, **23**(12), 1091-1101, (1983).

[28] J. Astier, J.C. Krug and Y. De Lassat de Pressigny, "Technico-Economic Potentialities of Hydrogen Utilization for Steel Production," *Int. J. Hydrogen Energy*, **7**(8), 671-679, (1982).

[29] C. O. Bolthrunis, R. Kuhr, A.E. Finan, "Using a PBMR to Heat a Steam-Methane Reformer: Technology and Economics," *Proceedings of the 3rd International Topical Meeting on High Temperature Reactor Technology*, Paper 100000118, (2006).

[30] W.J. Lee, et al., "Status of Nuclear Hydrogen Project in Korea", *ANS Embedded Topical on ST-NH2*, Boston, USA, Jun 24~28 (2007)

[31] C.K. Jo and J.M Noh, "Preliminary Core Design Analysis of a 200MWth Pebble Bed-type VHTR," *Proceedings. of the Korean Nuclear Society Spring Meeting*, Jeju, Korea, (2007)

[32] M.H. Kim, et al. "Computational Assessment of the Vessel Cooling Design Options for a VHTR," *Proceedings of the Korean Nuclear Society Autumn Meeting*, Pyeongchang, Oct.30-31, Korea, (2008).

[33] Y. Shin, *Pre-evaluation of Nuclear Hydrogen process*, NHDD-HI-CA-08-06, KAERI Report, (2008).