European Research and Development on HTGR Process Heat Applications

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The High-Temperature Gas-Cooled Reactor represents a suitable and safe concept of a future nuclear power plant with the potential to produce process heat to be utilized in many industrial processes such as reforming of natural gas, coal gasification and liquefaction, heavy oil recovery to serve for the production of the storable commodities hydrogen or energy alcohols as future transportation fuels. The paper will include a description of the broad range of applications for HTGR process heat and describe the results of the German long-term projects “Prototype Nuclear Process Heat Reactor Project” (PNP), in which the technical feasibility of an HTGR in combination with a chemical facility for coal gasification processes has been proven, and “Nuclear Long-Distance Energy Transportation” (NFE), which was the demonstration and verification of the closed-cycle, long-distance energy transmission system EVA/ADAM. Furthermore, new European research initiatives are shortly described. A particular concern is the safety of a combined nuclear/chemical facility requiring a concept against potential fire and explosion hazards.

KEYWORDS: high-temperature reactor, process heat, hydrogen production, steam reforming, safety

I. Introduction

In the last 50 years, nuclear power has evolved to a key component in the world’s mix of energy sources. Some 30 countries operate nuclear power plants for commercial electricity production provided by 441 reactors with a total capacity of more than 350 GW(e) and the experience of approx. 10,500 years of operation (end of 2002). A market potential for 50 to 90 more units to be implemented by 2015 has been assessed by the IAEA1). More than 90 % of the nuclear capacity are concentrated in industrialized countries. In the European Union (EU), a total of about 860 TWh or 33 % of the electricity demand (2001 data) is covered by nuclear power comprising 145 nuclear power plants in operation. Apart from avoiding the further liberation of climate-sensitive CO₂ emissions, nuclear power production in the EU is a vital contribution to the competitiveness of the European economy and to the reduction of the EU dependency on energy imports with fluctuating cost.

But there is also a large potential for nuclear power to play a major and important role in the non-electric sector as a provider of process heat and steam in a great variety of industrial processes. Presently used in principle as base load power plants for electricity production, future nuclear power plant (NPP) designs must be flexible to be adjustable to multiple needs in terms of both size (including small and medium) and application, i.e., the expansion of the market potential to the wide fields of cogeneration of electricity and heat (CHP) and of non-electric applications like process heat provision for chemical processes (synfuel production), desalination, district heating, etc., but also destruction of existing Pu stockpiles and transmutation of radiotoxic waste.

Nuclear power is considered by many to be the most promising CO₂-free energy technology with long-term fuel supply security, the absence of most air emissions, and a saving of the existing fossil resources. As of 1996, the worldwide installed nuclear capacity saved an additional impact on the atmosphere of 2.3 billion tons of CO₂ per year corresponding to 8 % of additional release2).

Hydrogen is already a significant chemical product. As a powerful and clean fuel, it could play an essential role in the world’s future energy economy as a secondary energy carrier in addition to electricity. The transportation sector will be among the first to begin a transition to H₂-rich fuel. Nuclear production of H₂ has the potential to contribute significantly to the global energy supply in the 21st century in a sustainable, competitive and environmentally friendly manner.

II. Nuclear Power for Non-Electric Applications

Since the beginning of the development of nuclear power, the direct use of the generated heat for district heating or in industrial processes has been considered convenient and practiced in many countries. Still, it is less than 1 % of the nuclear heat worldwide which is presently used for non-electric applications, but there are signs of increasing interest3).

1. Experience

The experience up to now gained with nuclear process heat/steam extraction is from 60 reactors and about 600 reactor-years, respectively1). Most nuclear non-electric applications are found in the area of district heating, predominantly required in climate zones with relatively long

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and cold winters. Typical district heating networks are in the range of 600 - 1200 MW(th) in large cities down to 10 - 50 MW(th) in smaller communities, providing heat in the temperature range of 100 - 150 °C. Up to now, some 50 commercial NPP are being used or have been used for heating purposes with a heat output between 5 and 240 MW.

In industrial processes, energy supply security is very important demanding a very high degree of reliability and availability approaching 100 %. The temperatures required are covering a wide spectrum. With respect to the size of the power plant, 99 % of the industrial users need a thermal power less than 300 MW, which accounts for about 80 % of the total energy consumed. Half of the industrial users even demand thermal power in the range less than 10 MW. Experience with nuclear process heat/steam applications has been obtained, e.g., from desalination (most in Japan) or D₂O production (Canada).

The High-Temperature Gas-Cooled Reactor (HTGR) reaching a coolant exit temperature of up to about 1000 °C, represents a suitable concept. It is a nuclear energy source to provide in an efficient way both electricity and steam and heat to be utilized directly in many important industrial processes where high-temperature (HT) heat is required. Furthermore it meets customer requirements in terms of flexible operating parameters and small modular reactor sizes. Employed in the fossil fuel conversion, it allows to open new markets for gaseous and liquid fuels.

The today’s concept of a modular-type HTGR is characterized by low power, low power density, graphite core structures, coated particle fuel, and helium gas as coolant. While passing the active core, the helium gas is heated up to 950 °C or even higher and then routed to a gas turbine or heat-exchanging components.

Up to now, five HTGRs have been operated in Germany, the UK, and the USA, designed for the generation of electricity. All have stopped operation in the meantime. Reactor No. 6 is the Japanese High-Temperature Engineering Test Reactor, HTTR, with 30 MW(th) power, which has reached first criticality in 1998. The HTTR is foreseen to be the first demonstration of a nuclear heat utilization system for hydrogen production via steam reforming of natural gas. HTGR No. 7 is the Chinese HTR-10 based on a pebble-bed core with a power of 10 MW(th); it has reached criticality in 2000 and is presently in the commissioning phase. For this reactor, a long-term test program for nuclear heat application is planned in future. An IHX will be installed for this purpose, following a phase of demonstration of reactor operation. Steam reforming of methane and coal gasification are the competing processes to be studied.

Modern HTGRs offer a high degree of safety at a comparatively low risk owing to the low power density and an inherent limitation of the thermal load on the fuel to a non-dangerous level. The trend towards small modular units and a design that relies on the inherent safety features such as natural heat transport mechanisms has resulted in a “catastrophe-free” concept that excludes any danger to the environment both during normal operation and after accidents. Low enrichment with fissile uranium avoids problem of proliferation of nuclear materials.

2. Process Heat Production with HTGR

In principle, any type and size of nuclear reactor can be used as heat source for district or process heating. Different types of nuclear reactors provide a different range of coolant temperatures (see Fig.1). Light Water Reactors (LWR), because of their lower temperature level, allow steam production of lower quality only; therefore they are principally used for electricity generation with occasional steam extraction. Coolants of Fast Breeder Reactors (FBR) and Advanced Gas-Cooled Reactors (AGR) reach higher temperature levels around 500 °C.

The electricity producing variant of an HTGR can be operated at an efficiency of 40 %, which was demonstrated, e.g., with the German reactors AVR and THTR-300. The possibility to run an HTGR in the Combined Heat and Power (CHP) operation mode, allows electricity production plus the generation of high-quality process steam and district heat, thus further increasing the efficiency. The production of high-quality steam at 530 °C and 15 MPa would be provided by the operation of a steam turbine prior to the “normal” steam application system for electricity production. The unique potential of an HTGR, however, is given with the nuclear process heat reactor and its large spectrum of industrial applications (see Fig.2).

The most interesting application is the production of synthesis gas by steam reforming of natural gas or other
hydrocarbons. Also for coal gasification, nuclear process heat from an HTGR could act as a substitute for conventional firing, thus saving coal resources and avoiding additional environmental effects. Two different processes have been investigated in more detail: hydro-gasification of brown coal and steam-coal gasification of hard coal. A particular suitability of the HTGR is given in the enhanced oil recovery via steam flooding, where high-pressure steam is pressed into oil fields lowering the oil viscosity and enhancing its recovery. About 4 - 6 tons of steam is needed for 1 ton of oil and liquefaction, or heavy oil for the production of the fuels hydrogen or methanol (or higher alcohols), thus being able of serving both heat market and traffic sector.

![Concept of a high temperature gas-cooled reactor for process heat production](image)

**Fig.2** Concept of a high temperature gas-cooled reactor for process heat production

Other close-to-the-market processes suitable to supply process heat from an HTGR are the aluminum oxide production requiring a temperature range of 950 - 1000 °C and crude oil refining (600 - 700 °C). A refinery with a typical throughput of 6 - 7 million tons of crude oil per year consists of a large number of individual plants. Process heat must be transmitted using an intermediate heat transfer loop. For economical reasons, all necessary heat exchanger plants should be built, maintained, and repaired according to conventional, not nuclear, specifications.

The operation of a process heat HTGR is flexible in the choice of the coolant temperature at steam generator inlet such that a chemical industrial complex could be optimized in terms of product spectrum and product volume.

Various designs of nuclear process heat HTGRs of different sizes have been proposed in the past. They include the process heat reactor concepts PNP-3000, PR-500, as well as the modified versions of the HTR-Module and the AVR reactor. All are characterized by a supply of energy at high temperature levels in the order of 950 °C, which allows the yield of high chemical reaction rates. The main components in the primary circuit for decoupling the HT heat are a steam reformer with a steam generator installed in series or a He/He intermediate heat exchanger (IHX).

In comparison to the electricity generating nuclear plant, several modifications are necessary for a process heat reactor:

- Reduced power density to compensate for the higher core outlet temperature level (for the HTR-Module: 3 → 2.55 MW/m³, 200 → 170 MW(th) for the same volume of the active core);
- Reduced system pressure as compromise between a high pressure desired for its favorable effect on operating and accident conditions of the nuclear reactor and a low pressure desired for chemical process reasons in the secondary and tertiary circuit. The pressures in the different circuits should be in the same range, slightly increasing towards the outside (for the HTR-Module: 7 → 5 MPa (4 MPa with IHX));
- Two fuel zones in the pebble bed to minimize the occurrence of hot/cold gas strains in the core to achieve a radial temperature profile as uniform as possible;
- Ceramic (graphite) liner to replace the metallic liner because of the higher temperatures.

Since focusing more and more on small-sized HTGRs, strong emphasis has been put on the fuel element as the most efficient barrier against radioactivity release. The high level of fuel quality that has been reached in the German fuel qualification program, could be demonstrated in numerous irradiation and post-irradiation experiments.

The IHX represents an interface component to connect the nuclear with the chemical system. It serves the purpose to

- Minimize contamination of the process heat exchanger allowing it to be placed outside the nuclear containment,
- Prevent an ingress of water or process gas into the nuclear primary system in case of a tube rupture,
- Reduce hydrogen permeation from the process gas into the primary helium as well as tritium permeation in the reverse direction.

### 3. Nuclear Hydrogen Production Methods

The world hydrogen production is around 560 billion Nm³ per year. It requires a substantial amount of primary energy with presently 96% being taken from fossil fuels (48% from natural gas, 30% from oil, 18% from coal) with subsequent release of CO₂ at the hydrogen generation plant. Only a small share is electrolytically produced hydrogen. The rapidly growing demand favors technologies with low fuel costs and
the scale of hydrogen is appropriate to its production by nuclear power.

The main fraction of the hydrogen (70 %) is consumed in the fertilizer and petroleum industries as well as in the iron and steel industries, used as chemical raw material and intermediate product or directly as fuel, e.g., for process heat production. Most of the growth in hydrogen consumption is used to convert heavy, high-sulphur crude oil into transportation (gasoline, diesel, jet) fuel, because sources of high-grade low-sulphur crude oil are being exhausted. In future, hydrogen and other synthetic fuels are expected to find broadening application on world energy markets.

A widely applied method for the production of hydrogen is the decomposition and gasification of fossil fuels with reaction temperatures typically in the range beyond 500 °C. An HTGR would be suitable to provide the process heat required.

Steam reforming of natural gas is a mature and well established technology practiced on industrial scale and presently most commonly used for H₂ production. Today’s production capacities are up to 140,000 Nm³/h. Typical operating conditions are temperatures in the range of 750 - 850 °C, pressures of 2 - 3 MPa, and steam-CH₄ ratios of 2 - 5, depending on the application of the product gas. If the primary energy required for the endothermal reaction would be provided by nuclear energy, based on the same amount of CO₂ produced, the H₂ output from the reforming process could be increased by 40 - 50 % compared with the conventional process.

To a lesser extent, higher hydrocarbons are consumed in gasification, partial oxidation, or cracking processes also with a long-term development history. Hydrogen-rich coal gas produced from the coke furnace process, was already in use more than 100 years ago in Germany, where it was fed into the municipal gas grids. The gasification of biomass may become competitive in near future.

In the coal gasification process, heat input is a pertinent cost factor. The introduction of nuclear heat requires a heat transfer via two heat exchangers in order to avoid the handling of coal and ash in the reactor containment. Primary helium of 950 °C is passed to a secondary helium circuit via a He-He IHX; secondary helium of 900 °C enters a steam gasifier; hot steam produced then is routed into a coal bed which will be gasified. The product gas, which is a mixture of H₂, CO, CH₄, and some N₂, is compressed, heated up, and can then be supplied to the methanol synthesis process. In the hydro-gasification process, coal is converted in an exothermal reaction to synthetic natural gas:

\[ \text{C} + 2 \text{H}_2 \rightarrow \text{CH}_4 + 86 \text{kJ/mol} \]

The H₂ needed as input is taken from the endothermal steam reforming of methane. About 50 - 60 % of the coal can be converted. If desired, subsequent processes would allow the generation of synthetic natural gas or methanol.

Thermal processes can also be applied to biomass such as peat, wood, gases, and agricultural residues as well as to municipal solid waste and sewage. Gasification of biomass results in a high heat value product gas containing H₂, CO₂, CO, and CH₄. A subsequent methanol synthesis is possible, if CO₂ and H₂ are added.

The electrolytical generation of hydrogen is realized on a larger scale by means of the chloralkali-water electrolysis, where the H₂ is a byproduct of the chlorine production process; it accounts for approx. 4 % of the world’s H₂ production. Water electrolysis at lower pressures has already achieved a high technological level with efficiencies in the order of 65 %. However, electrolysis is competitive only at locations, where cheap electricity, e.g., by hydro power (Norway, Canada, Brasil, Iceland), is available. Units cover a power range between 1 kW and 125 MW(e). The use of cheap off-peak electricity would allow the economical production of electrolytical hydrogen.

Nuclear thermochemical cycles offer a large economic potential. High temperature heat from an HTGR could be directly used for conversion into the chemical energy of hydrogen. In thermochemical cycles, the process of water splitting is subdivided into several partial reactions. The thermal energy required is typically at 800-900 °C. In thermochemical-electric hybrid cycles, the low temperature reactions run on electricity. Numerous potential cycles were tested and checked in terms of reaction kinetics, thermodynamics, reactant separation, material stability, flow sheeting, and cost analysis. Those based on sulfuric acid hybrid processes appear to be promising. Major problems arise by the large material flows, the introduction of impurities, the potential formation of toxic substances, and, last but not least, the still unsatisfactorily low overall energy efficiency of around 40 %.

The iodine-sulfur (I-S) thermochemical cycle, originally developed by General Atomics, is being investigated in detail by JAERI and is considered a second candidate for nuclear hydrogen production in a later stage of HTTR operation. Water decomposition is made in the following steps:

\[ \text{I}_2 + \text{SO}_2 + 2 \text{H}_2\text{O} \rightarrow 2 \text{HI} + \text{H}_2\text{SO}_4 \quad @ \text{20-100°C} \]
\[ 2 \text{HI} \rightarrow \text{H}_2 + \text{I}_2 \quad @ \text{200-700°C} \]
\[ \text{H}_2\text{SO}_4 \rightarrow \text{H}_2\text{O} + \text{SO}_2 + 0.5 \text{O}_2 \quad @ \text{850°C} \]

where the nuclear heat will be used for H₂SO₄ decomposition. Both H₂ and O₂ producing reactions can be carried out in the liquid phase employing a solid catalyst. Laboratory-scale experimental studies at JAERI have demonstrated already a continuous production of hydrogen over 24 h in a closed cycle. Further efforts will concentrate on the control of flow rate and I concentration stability, the development of appropriate
materials for the reactors and the improvement of thermal efficiency.

The sulfuric acid hybrid or Westinghouse cycle was experimentally investigated at FZJ demonstrating a 10 NL/h production rate over 600 h. Cycle efficiency was found to be 40 %, an increase to 46 % is thought possible by optimizing the electrolysis step. Another thermochemical cycle, UT-3, based on the bromine-calcium-iron process appears also appropriate in connection with heat from an HTGR. All four reactions are solid-gas reactions, which take place in separate reactors connected in series in a loop. A drawback is the small conversion rate resulting in large gas flows and reactor size.

The electrochemical decomposition of steam at higher temperatures, 800 - 1000 °C, could also be considered as a future process of H2 production run by HTGR. It offers the advantages of a reduction of electricity demand (minus 30 % compared to room temperature) and a lowering of the activation barriers at the electrolyte surfaces resulting in efficiency improvement. The development of electrolysis cells of either tubular or planar shape has started in several countries. In Germany, the technology has been successfully demonstrated with the operation of a 2 kW laboratory scale pilot plant known under the name „Hot Elly“.

Also from the Japanese HTTR, a concept of hydrogen/methanol co-production including CO2 recycling has been elaborated. Using 10 MW of process heat and 950 kg/h of natural gas as input, the resulting material output streams have been assessed to be 1390 Nm³ of H2 plus 1930 kg/h of methanol.

III. Research Initiatives on Process Heat HTGRs

The Federal Republic of Germany has spent around 4 billion US $ on R&D for HTGRs. Two reactors have been constructed and operated. The 45 MW(th) research reactor AVR in Jülich was the first pebble-bed reactor and was operated over more than 20 years until shutdown in 1988. It tested both the components and the spherical fuel elements, successfully demonstrating the feasibility of the concept with a high availability of 90 % in some years. Apart from proving the inherent safety features of an HTGR such as a passively safe decay heat removal, the operation with a 950 °C (and partly higher) average coolant outlet temperature since 1974 verified process heat conditions and demonstrated the good quality of the TRISO fuel.

1. German Long-Term Projects on HTGR Nuclear Process Heat Applications

In several long-term projects in Germany in the 1970s and 1980s, the technical feasibility of a nuclear process heat reactor has been established. The main components developed and tested are the nuclear steam reformer and the intermediate He-He heat exchanger (IHX) as well as the hot gas ducting between the nuclear core and the heat exchanger. Unlike conventional fossil-fueled components, the helium-heated components of the HTGR have to meet the more stringent requirements of a „nuclear“ component in terms of construction, quality assurance, and scheduled re-testing. They have the important function of forming a radioactivity barrier between the primary helium and the process gas.

In 1977, a joint design and development program for a nuclear process heat prototype plant (PNP) was initiated by partners of the coal industry, the nuclear industry, and the Research Center Jülich, and mainly funded by the Federal State of Northrhine-Westphalia. The main objective was the provision of an energy system based on a combination of German coal and nuclear power, including the developing and testing of a nuclear heat generating system to be operated at a 950 °C gas outlet temperature, intermediate circuit, heat extraction, coal gasification processes and nuclear energy transport. The design work for a nuclear process heat reactor was based on a thermal power size of 500 MW (PNP-500) and 3000 MW (PR-3000), respectively. Important aspects such as heat transfer under varying operational load conditions, hot gas mixing in the core bottom, or the lifetime of hot gas thermal insulation have been comprehensively investigated in experiment. Seismic behavior of the core structures was examined using the SAMSON three-axial vibrational test facility. Tests on core models confirmed the good-natured behavior of the pebble bed, which shows a high damping effect under dynamic excitation.

The gasification processes investigated were steam coal gasification for hard coal as well as hydro-gasification for brown coal. For both types, respective pilot plants were constructed and operated under nuclear-typical conditions. Catalytic and non-catalytic steam coal gasification was tested in a 1.2 MW semi-technical scale experimental facility, where the heat was provided by helium electrically heated up to 950 °C. The plant was in hot operation for approx. 23,000 hours with more than 13,000 hours under gasification conditions. Maximum capacity was 230 kg/h of hard coal, the total quantity of coal gasified was 1600 t. The hydro gasification process was verified in a 1.5 MW test facility, which operated for about 27,000 h with more than 12,000 h under gasification conditions. The throughput was 320 kg/h of brown coal, the total quantity gasified was 1800 t. From 1983 to 1985, a follow-up plant was operated with a throughput of 9.6 t/h corresponding to a total power of 50 MW and an SNG production of about 8000 Nm³/h. The idea of construction of a PNP plant was eventually abandoned due to the given economic conditions.

Within the so-called NFE (nuclear long-distance energy) project, the production of nuclear hydrogen as energy storage, transportation, and recovery of the stored energy has been investigated (see Fig.3). Steam reforming of methane under nuclear conditions was experimentally verified in the EVA (single splitting tube) test facility at FZJ representing a complete, helium-heated system. A reaction tube with
dimensions typical for industrial plants (length: 15 m; inner diameter: 130 mm; wall thickness: 21 mm) was connected in a closed loop to an electrical heater with a power input of 10 MW(e) simulating the nuclear source.

Fig.3 EVA/ADAM long-distance energy transmission system based on methane reforming and the energy carrier hydrogen

The follow-up facility, EVA-II, consisted of a steam reformer bundle with 18 tubes. Heat transport medium was helium gas flowing at a rate of 4 kg/s and reaching a temperature at the heater exit of 950 °C and a system pressure of 4 MPa. Helium flows in a ring gap on the outside of the reaction tube and provides its heat to the process gas mixture flowing inside the tube filled with a metallic nickel catalyst. Heat source, steam reformer, and steam generator were arranged in separate steel vessels side by side, interconnected by coaxial hot gas ducts. The feed gas methane was introduced at a rate of 0.6 kg/s. The experiments confirmed the expected thermodynamic and chemical processing behavior and the validity of respective computer models.

For EVA-II, a respective ADAM (three adiabatic methanation reactors) was constructed, a test facility for the reverse process, the methanation of the synthesis gas in three steps. The peak temperature during methanation was 650 °C releasing heat at a rate of 5.3 MW(th). The helium system was operated for 13,000 h with 60 % of this time at a temperature of 900 °C. The complete EVA/ADAM system was operated for more than 10,000 hours both under steady-state and transient and partial load conditions, and thus demonstrated successfully a long-distance chemical energy transportation system based on hydrogen.

In the 10 MW „Component Experimental Loop“ (KVK), the heat-exchanging components designed for a power level representative for large and medium-sized plants were tested under nuclear coal gasification conditions. The facility consisted of a primary and a secondary helium loop. Heat sources were a natural gas fired heater and an electrical heater. Peak temperature was 1000 °C in the primary circuit and 950 °C in the secondary circuit at a system pressure of up to 4.6 MPa. The helium flow rate was 3 kg/s in both circuits. The test components examined included two designs of an IHX (U-tube, helical tube), hot gas ducts with a total length of 140 m, hot gas valves, water cooler, and a steam generator (as the heat sink). KVK was operated for 18,400 h with 7000 h above 900 °C and 11,000 h above 700 °C, respectively, demonstrating the industrial feasibility of the tested components at a high reliability and an almost 100 % availability.

In the qualification program for HT metallic materials, steam reformer lifetimes and He-He heat exchanger materials have been approved to achieve the required lifetime of 100,000 hours. Still, the experience gained so far has disclosed that the technical solution of material problems require further efforts in longer-term projects.

2. Thermochemical Conversion of Biomass

As an alternative option, nuclear process heat from an HTGR can also be utilized for the production of energy alcohols from biomass, representing a CO2-neutral production process by means of a CO2-free primary energy input. For the generation of methanol (H/C ratio = 4) from biomass, e.g., wood (H/C ratio = 1.5), additional H atoms are needed, which means additional energy. The process could also be used for synthetic natural gas (SNG) production; however, energy alcohol has the advantage to be created in the user-friendly liquid state.

A possible process flow scheme is shown in Fig.4. Apart from the HTGR reactor as the nuclear process heat source, the principal component is the gasifier for wood (SGW) heated by the primary coolant helium, and also receiving steam from the steam superheater (STS). The methanol synthesis unit (MES) receives the input flows synthesis gas from the SGW plus hydrogen from an electrolyzer (ELY). The efficiency of the total process proposed has been assessed to be 52 %; the product yield would be about 140 % [3].
Furthermore if requested by the user, the product hydrogen could be obtained from the above process by extending the flow scheme applying the so-called methane-methanol-methanal hybrid cycle\(^7\). This cycle includes, after the methanol (\(\text{CH}_3\text{OH}\)) synthesis, the subsequent steps of methanal (\(\text{CH}_2\text{O}\)) synthesis and methanal electrolysis for the generation of SNG, which is then routed to the steam reformer for further \(\text{H}_2\) production.

3. Safety Study on a Combined Nuclear/Chemical Facility

In Japan, the 30 MW(th) HTTR is presently in the commissioning phase. Its main components are a prismatic core, a 20 MW pressurized water cooler and a 10 MW IHX for process heat decoupling. It is expected to be the first-of-its-kind nuclear reactor to be connected to hydrogen production processes. The process to be tested first is the steam reforming of natural gas. Heat from the primary helium will be transferred via the IHX into the secondary circuit where helium with an inlet temperature of 880 °C at 4.1 MPa enters the SR equipped with a bundle of 30 splitting tubes of 9 m length each. The heat input to the steam reforming process is 3.6 MW from the helium plus 1.2 MW from the hot process gas. The efficiency is estimated to be 78 %. Goal is the conversion of 950 kg/h of LNG plus heat into 3800 Nm³/h of \(\text{H}_2\). Prior to the nuclear verification, a 1:30 downscaled pilot plant with a single 1:1 scaled splitting tube will be operated to investigate system characteristics, to verify (transient) operation, and to confirm safety and performance of key components under nuclear conditions. This experimental facility has started test operation in 2001. Further preparatory tests include the examination of the permeation behavior of hydrogen and tritium, and of the corrosion behavior of the nickel-based superalloy material Hastelloy XR.

Nuclear power plants must be designed and operated to current safety objectives and principles in order to achieve a high level of safety. Innovative reactor concepts are made on a design such that even in extreme accidents, radionuclide release is made impossible or, at least, restricted to the plant itself making any emergency planning obsolete.

Particular safety aspects apply, if the nuclear plant is combined with a chemical facility associated with a fire and explosion hazard, when flammable gases are present (see Fig.5). An approach to a safety analysis for the HTTR connected with a steam reformer unit has been conducted in a joint German/ Japanese effort\(^8\). Special attention was given to the potential development of a detonation pressure wave as the result of an inadvertent release of natural gas from the LNG storage tank into the environment and its ignition.

A literature study on theoretical assessments and experimental studies about methane combustion behavior has shown that methane is a comparatively slowly reacting gas and that a flammable methane-air mixture in the open atmosphere is highly unlikely to result in a detonation. JAERI calculations simulating the impact of a methane vapor cloud explosion on the HTTR has shown that no significant influence on the reactor building is expected. Also the safety distance between reactor building and LNG storage tank, which is planned to be more than 300 m, would actually meet the requirements of the German guideline on the protection of nuclear power plants against pressure waves from gas cloud explosions.

4. The EU Project MICANET

The objective of the MICHELANGELO Network (MICANET)\(^9\), a Thematic Network within the 5th EU Framework Programme (FP) (1997-2000), is the elaboration of a general European R&D strategy for the further development of the nuclear industry both in short, medium, and long term, in order to set the appropriate conditions of economic competitiveness and compatibility with the requirements of sustainable development.

To broaden the application range of nuclear power beyond dedicated electricity generation, the network will make proposals of orientation for future EURATOM R&D FPs including new aspects of nuclear energy like Combined Heat and Power (CHP), desalination, and hydrogen or other fuel production as a link to other \(\text{CO}_2\)-free energy sources.

MICANET intends to act as the European counterpart and partner to the American initiative “Generation IV” or the US-DOE Nuclear Research Initiative NERI. The potential and features of HTGRs are making this concept a serious candidate for the IV\(^{\text{th}}\) generation of future nuclear power plants. The innovative concept VHTR, Very-High-Temperature Reactor, represents an advanced HTGR system to be applied in highly effective generation of both electricity and process heat, e.g., for hydrogen production. It is a key point in the international R&D program and one out of the six reactor systems recommended for further long-term development.
5. The INNOHYP Proposal for the 6th EU FP

INNOHYP is the proposal for an Integrated Project in the 6th EU Framework Programme to deal with innovative hydrogen production methods demonstrating the viability of clean and sustainable techniques of massive hydrogen production. The primary energy is being considered to come from the CO2-free sources renewables and nuclear. The H2 production processes to be investigated are allothermal steam reforming of hydrocarbons, HT-electrolysis, thermochemical water splitting (I-S, SnO/Sn), thermochemical conversion of biomass as well as more sophisticated processes (photoelectrochemical and photobiological systems), which are still at an early stage of development.

The retrieval of valuable information from the German PNP and NFE nuclear projects to form a basis where to start from, will be an important aspect concerning the allothermal steam reforming. Considering the present Japanese activities on nuclear H2 production methods using the HTTR and – in a preceding step – out-of-pile test facilities, respectively, a strategic cooperation with Japan is of utmost importance for this EU project and of mutual benefit for both partners.

IV. Conclusion

If the problems arising with CO2 emissions and its impact on the global climate are taken seriously, a significant increase of carbon-free energy technologies within the next decades is necessary. One important option in the future mix of energy sources is nuclear. Under the conditions that long-lived radioactive wastes can be handled safely and public acceptance can be acquired by convincing safety systems, new innovative reactor designs should be introduced which do not cause any impact to the environment and restrict any radionuclide release to the plant itself.

The HTGR appears to belong to this category. It is a universal source of energy with a high degree of passive safety features. Long-term goal is the utilization of HT heat to serve the complete heat market up to 1000 °C to provide the full potential of cogeneration of electricity and process heat for the production of storageable and transportable secondary energy carriers such as hydrogen and methanol.

In Germany, designs of helium-cooled heat-exchanging components have been successfully operated under simulated nuclear conditions. Furthermore the closed-cycle EVA/ADAM chemical energy transportation system based on H2 was demonstrated. The next steps will be the realization of nuclear hydrogen and methanol production foreseen in connection with the Japanese HTTR.

By the manufacture and successful operation of HT heat-exchanging and heat-transporting components, highly valuable practical experience with high-temperature helium plants on a representative scale has been acquired.

Hydrogen from nuclear process heat assisting in the steam-reforming of natural gas should be a transition step on the way to a non-fossil H2 generation in the long term. Direct HT thermochemical processes are considered appropriate water splitting methods of the future. The candidates of choice are the I-S process and the UT-3 cycle, both of which have been identified by a screening procedure within the NERI project to be the most promising cycles.

While recognizing the significant time lag before HTGRs or thermochemical hydrogen-producing processes will become established technologies, it is considered that hydrogen production by conventional electrolysis and new technologies using existing reactor designs could be advantageous. This near-term approach can utilize existing infrastructure for electricity distribution and it currently holds competitive advantage vis-à-vis renewable energy sources.

V. References