H2-MHR PRE-CONCEPTUAL DESIGN SUMMARY FOR HYDROGEN PRODUCTION

MATT RICHARDS* and ARKAL SHENOY
General Atomics, United States of America, P.O. Box 85608, San Diego, CA 92186
*Corresponding author. E-mail : matt.richards@gat.com

Received December 13, 2006

Hydrogen and electricity are expected to dominate the world energy system in the long term. The world currently consumes about 50 million metric tons of hydrogen per year, with the bulk of it being consumed by the chemical and refining industries. The demand for hydrogen is expected to increase, especially if the U.S. and other countries shift their energy usage towards a hydrogen economy, with hydrogen consumed as an energy commodity by the transportation, residential and commercial sectors. However, there is strong motivation to not use fossil fuels in the future as a feedstock for hydrogen production, because the greenhouse gas carbon dioxide is a byproduct and fossil fuel prices are expected to increase significantly. An advanced reactor technology receiving considerable international interest for both electricity and hydrogen production, is the modular helium reactor (MHR), which is a passively safe concept that has evolved from earlier high-temperature gas-cooled reactor (HTGR) designs. For hydrogen production, this concept is referred to as the H2-MHR. Two different hydrogen production technologies are being investigated for the H2-MHR; an advanced sulfur-iodine (SI) thermochemical water splitting process and high-temperature electrolysis (HTE). This paper describes pre-conceptual design descriptions and economic evaluations of full-scale, nth-of-a-kind SI-Based and HTE-Based H2-MHR plants. Hydrogen production costs for both types of plants are estimated to be approximately $2 per kilogram.

KEYWORDS : Hydrogen, Electricity, Thermochemical, Electrolysis, Nuclear

1. INTRODUCTION

For electricity and hydrogen production, an advanced reactor technology receiving considerable international interest is a modular, passively-safe version of the high-temperature, gas-cooled reactor (HTGR), known in the U.S. as the Modular Helium Reactor (MHR), which operates at a power level of 600 MW(t). For electricity production, the MHR operates with an outlet helium temperature of 850° C or higher to drive a direct, Brayton-cycle power-conversion system (PCS) with a thermal-to-electrical conversion efficiency of 48 percent or greater. This concept is referred to as the Gas Turbine MHR (GT-MHR). For hydrogen production, both electricity and process heat from the MHR are used to produce hydrogen. This concept is referred to as the H2-MHR. The growing international interest in the MHR concept is the direct result of MHR design features, which include: (1) passive or intrinsic safety, competitive economics, and siting flexibility because of reduced water cooling requirements; (2) high temperature capability and flexible energy outputs; and (3) flexible fuel cycles.

In principle, nuclear electricity can be used to split water using conventional low-temperature electrolyzers. For a conventional LWR that produces electricity with approximately 33% thermal efficiency and current generation electrolyzers operating with an efficiency of about 75% to convert electricity to high-pressure hydrogen, the overall efficiency for hydrogen production is approximately 25%. If a GT-MHR is used to produce the electricity with 48% thermal efficiency, the overall efficiency for hydrogen production improves to 36%. However, even with high-efficiency electricity production, economic evaluations of coupling nuclear energy to low-temperature electrolysis have generally not been favorable when compared to steam-methane reforming (SMR). For these reasons, two concepts that make direct use of the MHR high-temperature process heat are being investigated in order to improve the efficiency and economics of hydrogen production. The first concept involves coupling the MHR to the Sulfur-Iodine (SI) thermochemical water splitting process and is referred to as the SI-Based H2-MHR. The second concept involves coupling the MHR to high-temperature electrolysis (HTE) and is referred to as the HTE-Based H2-MHR. Both processes have the potential to produce hydrogen with high efficiency and have been proven to work at the laboratory scale [1]. An effort is also underway to develop conceptual, commercial-scale designs for the SI-Based and HTE-Based H2-MHR

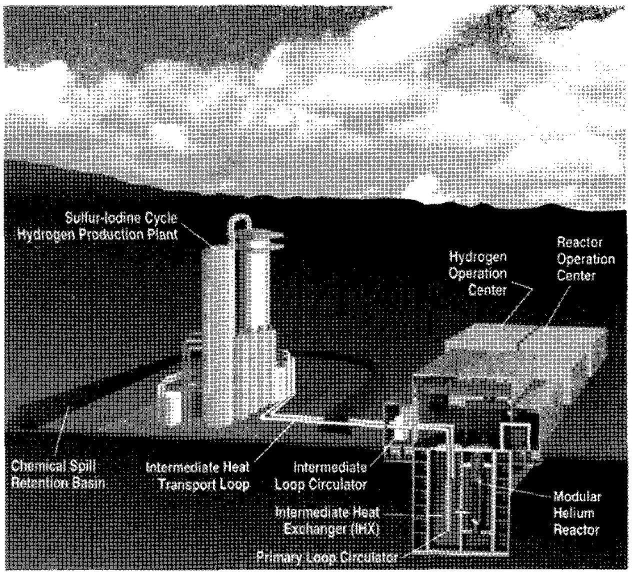

Fig. 1. SI-Based H2-MHR Concept

plants in order to better define the requirements for the related technology-development programs and to establish a basis for performing economic evaluations and assessing deployment scenarios [2-4].

2. PLANT DESIGN DESCRIPTIONS

2.1 SI-Based Overall Plant Design Description

As shown in Fig. 1, the heat required to drive the SI process is supplied by Modular Helium Reactors (MHRs). The plant consists of four 600 MW(t) MHR modules, with each module coupled to an Intermediate Heat Exchanger (IHX) to transfer the heat to a secondary helium loop. The heat is then transferred to the SI-based Hydrogen Production System. Waste heat is rejected using cooling towers in a manner similar to that for electricity-producing plants. In addition to the heat required to drive the SI process, the plant requires approximately 800 MW(e) Most of this electricity is needed to power pumps and compressors that are part of the Hydrogen Production System design. For this study, it is assumed that the H2-MHR plant is part of an energy park that also includes GT-MHRs that provide the necessary electricity. Nominal plant design parameters are given in Table 1. At a 90% capacity factor, the plant produces 3.68 × 10^5 metric tons of hydrogen per year at an efficiency of 45.0% (based on the higher heating value of hydrogen) with a product gas pressure of 4.0 MPa.

Table 1. SI-Based H2-MHR Nominal Plant Design Parameters

MHR System	
Number of modules	4
Module power rating	600 MW(t)
Core inlet/outlet temperatures	590°C / 950°C
Peak fuel temperature – normal operation	1250°C - 1350°C
Peak fuel temperature – accident conditions	< 1600°C
Heat Transport System	
Primary coolant fluid	helium
Primary coolant pressure	7.0 MPa
Primary coolant flow rate	320 kg/s
Total pressure drop – primary circuit	100 kPa
Secondary coolant fluid	helium
Secondary coolant pressure	7.1 MPa
Secondary coolant flow rate	320 kg/s
Secondary coolant cold leg/hot leg temperatures	565°C / 925°C
Total pressure drop – secondary circuit	146 kPa
Hydrogen Production System	
Peak process temperature	900°C
Peak process pressure	7.0 MPa
Product hydrogen pressure	4.0 MPa
Annual hydrogen production[*]	3.68 × 10^5 metric tons
Plant hydrogen production efficiency[**]	45.0%

[*] Based on an overall plant capacity factor of 90%.

[**] Based on the higher heating value of hydrogen (141.9 MJ/kg)

In the SI process, water thermally dissociates at significant rates into hydrogen and oxygen at temperatures approaching 4000° C. As indicated in Fig. 2, the SI process consists of three primary chemical reactions that accomplish the same result at much lower temperatures. The process involves decomposition of sulfuric acid and hydrogen iodide, and regeneration of these reagents using the Bunsen reaction. Process heat is supplied at temperatures greater than 800° C to concentrate and decompose sulfuric acid. The exothermic Bunsen reaction is performed at temperatures below 120° C and releases waste heat to the environment. Hydrogen is generated during the decomposition of hydrogen iodide, using process heat at temperatures greater than 300°C. The product hydrogen gas is produced at a pressure of 4.0 MPa.

2.2 HTE-Based Overall Plant Design Description

As shown in Fig. 3, MHRs can supply both the heat to generate steam and the electricity to split the steam into hydrogen and oxygen. Electricity is generated using a direct, Brayton-cycle power-conversion system (PCS). Approxi-

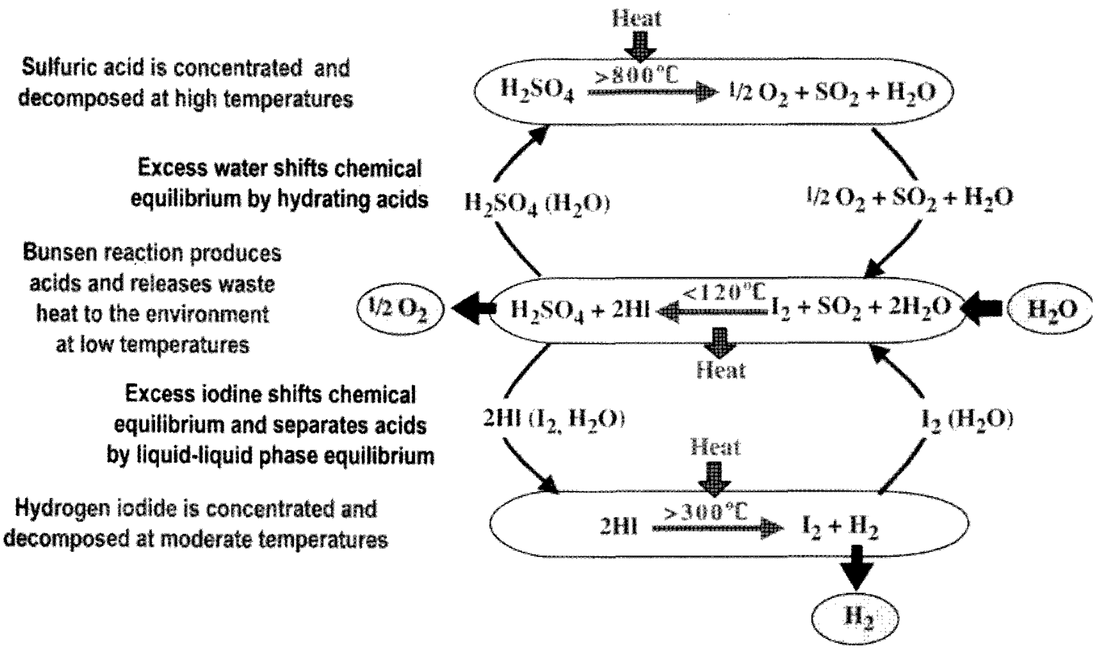

Fig. 2. The SI Thermochemical Water Splitting Process

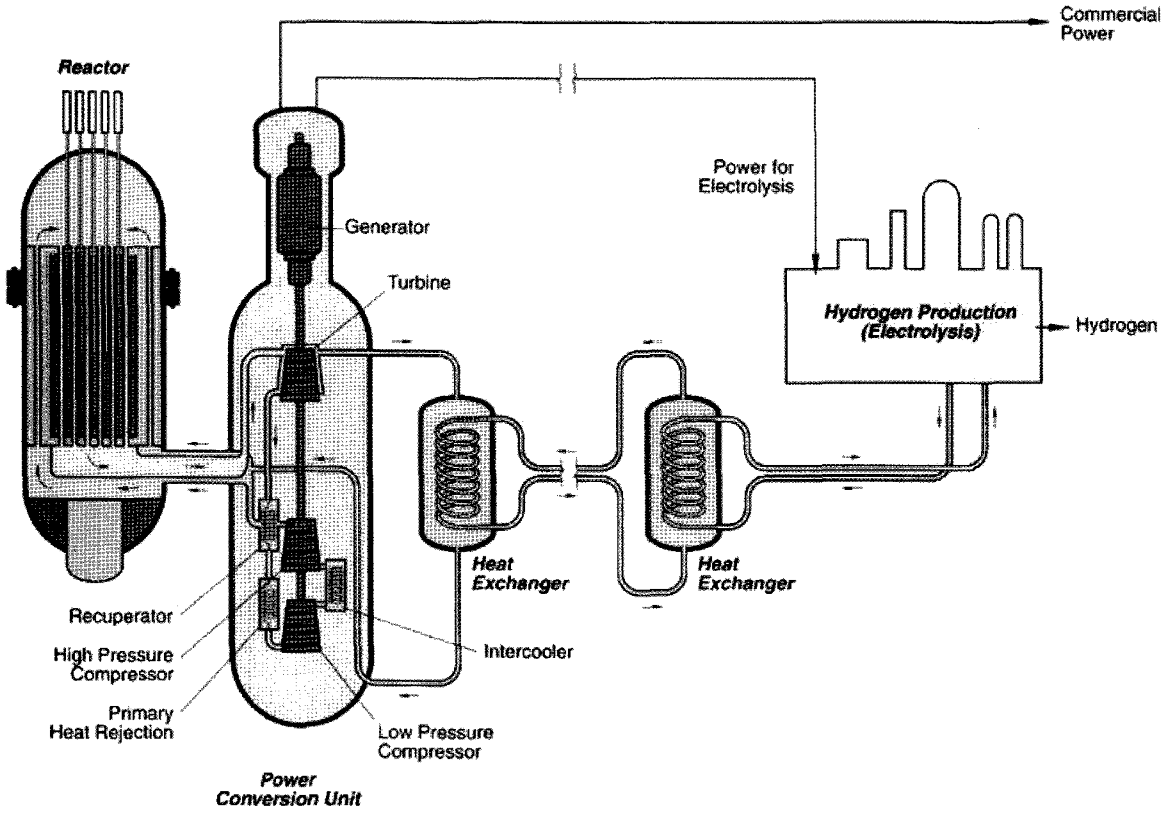

Fig. 3. HTE-Based H2-MHR Concept

Table 2. HTE-Based H2-MHR Nominal Plant Design Parameters

MHR System	
Number of modules	4
Module power rating	600 MW(t)
Core inlet/outlet temperatures	590°C / 950°C
Peak fuel temperature – normal operation	1250°C - 1350°C
Peak fuel temperature – accident conditions	< 1600°C
Helium mass flow rate	321 kg/s
Total MHR System pressure drop	80 kPa
Power Conversion System	
Mass flow rate	280 kg/s
Heat supplied from MHR System	542 MW(t)
Turbine inlet/outlet temperatures	950°C / 600°C
Turbine inlet/outlet pressures	7.0 MPa / 2.8 MPa
Generator efficiency	98 %
Electricity generated	292 MW(e)
Electricity generation efficiency[*]	53.9%
Heat Transport and Recovery System	
Primary helium flow rate	42 kg/s
Secondary helium flow rate	18.1 kg/s
IHX heat duty	59 MW(t)
IHX primary side inlet/outlet temperatures	950°C / 679°C
IHX secondary side inlet/outlet temperatures	292°C / 917°C
Steam production rate	23.6 kg/s
Mass flow rate of hydrogen added to steam	0.3 kg/s
Temperature of steam/ hydrogen supplied to SOE	827°C
Hydrogen Production System	
Peak SOE temperature	862°C
Peak SOE pressure	5.0 MPa
Product hydrogen pressure	4.95 MPa
Annual hydrogen production[**]	2.68×10^5 metric tons
Plant hydrogen production efficiency[*, ***]	55.8%

[*] Neglects parasitic heat losses from the Reactor Cavity Cooling System and Shutdown Cooling System.

[**] Based on a 4-module plant and an overall plant capacity factor of 90%.

[***] Based on the higher heating value of hydrogen (141.9 MJ/kg).

mately 90% of the heat generated by the MHR modules is used to produce electricity. The remainder of the heat is transferred though an intermediate heat exchanger (IHX) to produce steam. As indicated in Fig. 4, steam is supplied to both the anode and cathodes sides of the electrolyzers. The steam supplied to the cathode side is split into hydrogen and oxygen. The oxygen is transferred through the electrolyte to the anode side. The steam supplied to the anode side is used to sweep the oxygen from electrolyzer modules. The steam supplied to the cathode side is first mixed with a small portion of the hydrogen stream in order to ensure reducing conditions and prevent oxidation of the electrodes. Heat is recuperated from both the hydrogen/steam and oxygen/steam streams exiting the electrolyzer. A small quantity of electricity is generated from the oxygen/steam stream to provide power for plant house loads. The full-scale plant includes four, 600-MW(t) MHR modules. The reactor design and PCS are essentially the same as that for the GT-MHR, but with some minor modifications to allow operation with a higher coolant-outlet temperature of 950°C in order to increase hydrogen-production efficiency. Nominal plant design parameters are given in Table 2. At a 90% capacity factor, the plant produces 2.68×10^5 metric tons of hydrogen per year at an efficiency of 55.8% (based on the higher heating value of hydrogen [5]) with a product gas pressure of 4.95 MPa.

Electrolysis is performed at high temperatures using solid oxide electrolyzer (SOE) modules. The module design is based on planar cell technology being developed as part of a collaborative project between Idaho National Laboratory (INL) and Ceramatec of Salt Lake City, UT. Stacked assemblies of 100-mm × 100-mm cells have been tested successfully at INL and design parameters have been developed for a 12.5 kW(e), 500-cell stack. An SOE module would contain 40 500-cell stacks and consume 500 kW(e). Eight modules could be installed within a structure that is similar in size to the trailer portion of a typical tractor-trailer. Approximately 292 of these 8-module units would be required for a full-scale plant with four 600-MW(t) MHR modules.

3. MHR DESIGN AND PASSIVE SAFETY FEATURES

The GT-MHR design is shown in Fig. 5. Passive safety features of the MHR include the (1) ceramic, coated-particle fuel that maintains its integrity at high temperatures during normal operation and loss of coolant accidents (LOCAs); (2) an annular graphite core with high heat capacity that limits the temperature rise during a LOCA; (3) a relatively low power density that helps to maintain acceptable temperatures during normal operation and accidents; (4) an inert helium coolant, which reduces circulating and plateout activity; and (5) a negative temperature coefficient of reactivity that ensures control of the reactor for all credible reactivity insertion events. The fuel, the graphite, the primary coolant pressure boundary, and the low-pressure vented containment building provide multiple barriers to the release of fission products.

The MHR fuel element and its components are shown

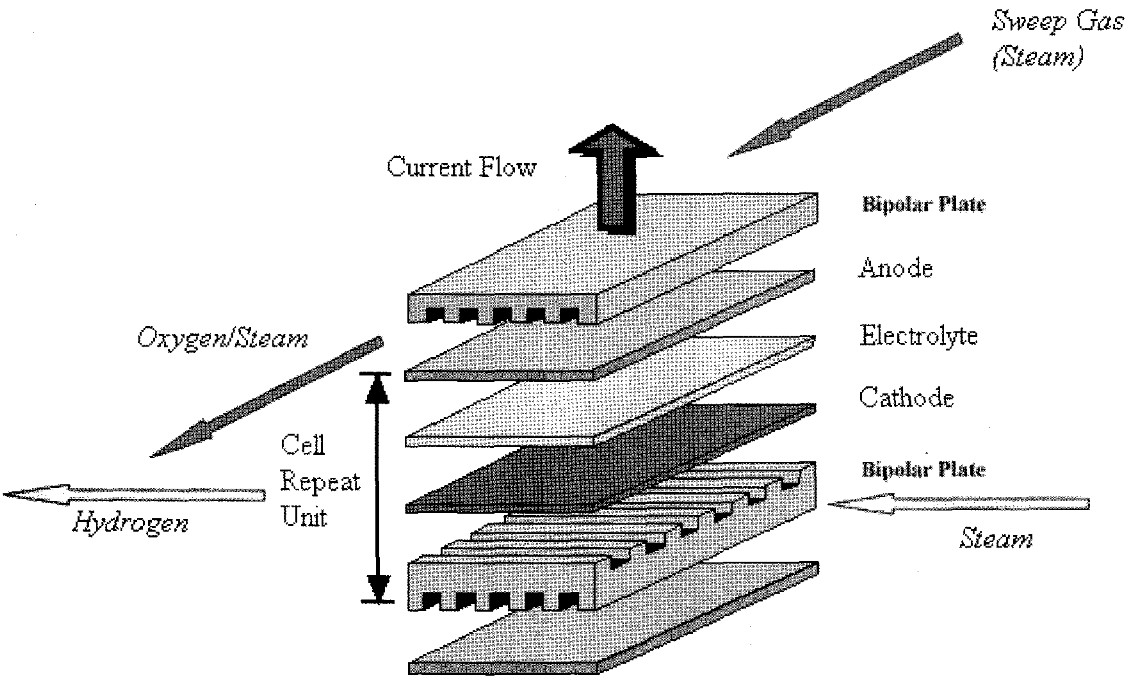

Fig. 4. SOE Unit Cell Schematic

in Fig. 6. The fuel for the H2-MHR consists of microspheres of uranium oxycarbide that are coated with multiple layers of pyrocarbon and silicon carbide. The H2-MHR core is designed to use a blend of two different particle types; a fissile particle that is enriched to 19.8% U-235 and fertile particle with natural uranium (0.7% U-235). The fissile/fertile loading ratio is varied with location in the core, in order to optimize reactivity control, minimize power peaking, and maximize fuel cycle length. The buffer, inner pyrolytic carbon (IPyC), silicon carbide (SiC), and outer pyrolytic carbon (OPyC) layers are referred to collectively as a TRISO coating. The coating system can be viewed as a miniature pressure vessel that provides containment of radionuclides and gases. This coating system is also an excellent engineered barrier for long-term retention of radionuclides in a repository environment.

The H2-MHR is not expected to present any significant licensing challenges relative to the GT-MHR or other reactor concepts. However, a key consideration for safety and licensing of the H2-MHR is co-location of the MHR modules with a hydrogen production plant. It is proposed to locate the two facilities as close as possible (within 100 m or less) in order to minimize the distance over which high-temperature heat is transferred. Idaho National Laboratory (INL) has recently performed an engineering evaluation for these separation requirements and has concluded separation distances in the range of 60 m to 120 m should be adequate in terms of safety.

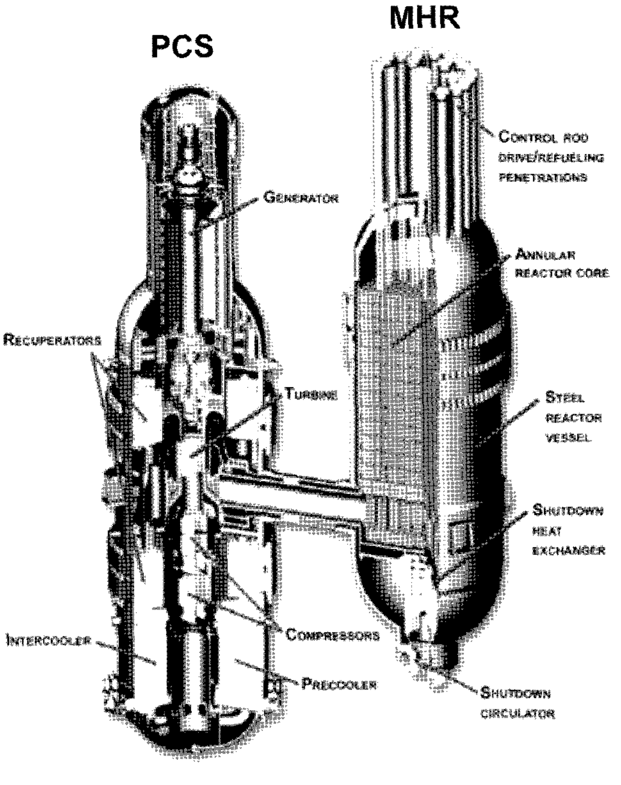

Fig. 5. GT-MHR Design

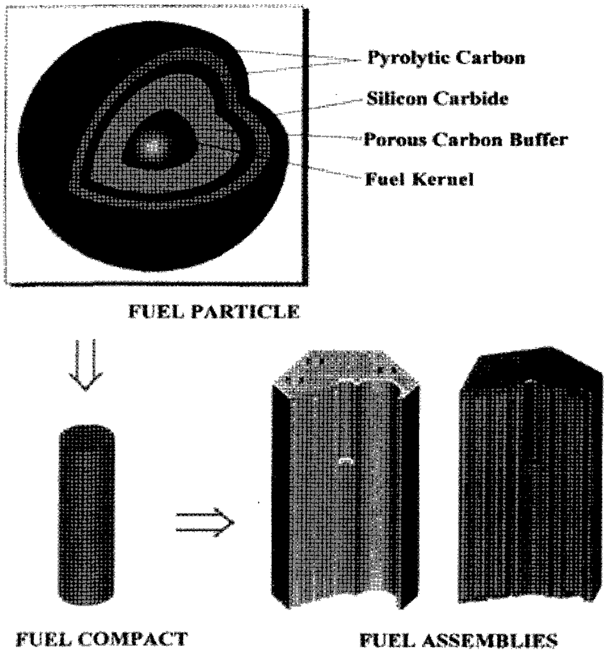

Fig. 6. MHR Fuel Element Components

4. ECONOMIC EVALUATION

Fig. 7 shows a comparison of nuclear hydrogen production costs with the costs for producing hydrogen using SMR. In December 2005 the wellhead price for natural gas was \$10.02 per 1000 cubic feet, which corresponds to \$9.72/MMBtu, a value consistent with when this design analysis was performed. At this price, nuclear hydrogen production is economically competitive with SMR. Nuclear hydrogen production is economically competitive with SMR for natural gas prices in the range \$6 to \$8/MMBtu, if a CO_2 sequestration/disposal cost for SMR and an O_2 credit for nuclear hydrogen production are assumed.

4.1. SI-Based H2-MHR Economic Evaluation

An economic evaluation was performed assuming the plant could be constructed in 36 months with an annual interest rate of 7% and a fixed charge rate of 12.6% (corresponding to a regulated utility). The capital costs of the MHR System and Hydrogen Production System were estimated to be \$1.44 billion and \$1.07 billion, respectively, for a total H2-MHR plant capital cost of \$2.51 billion. The installed

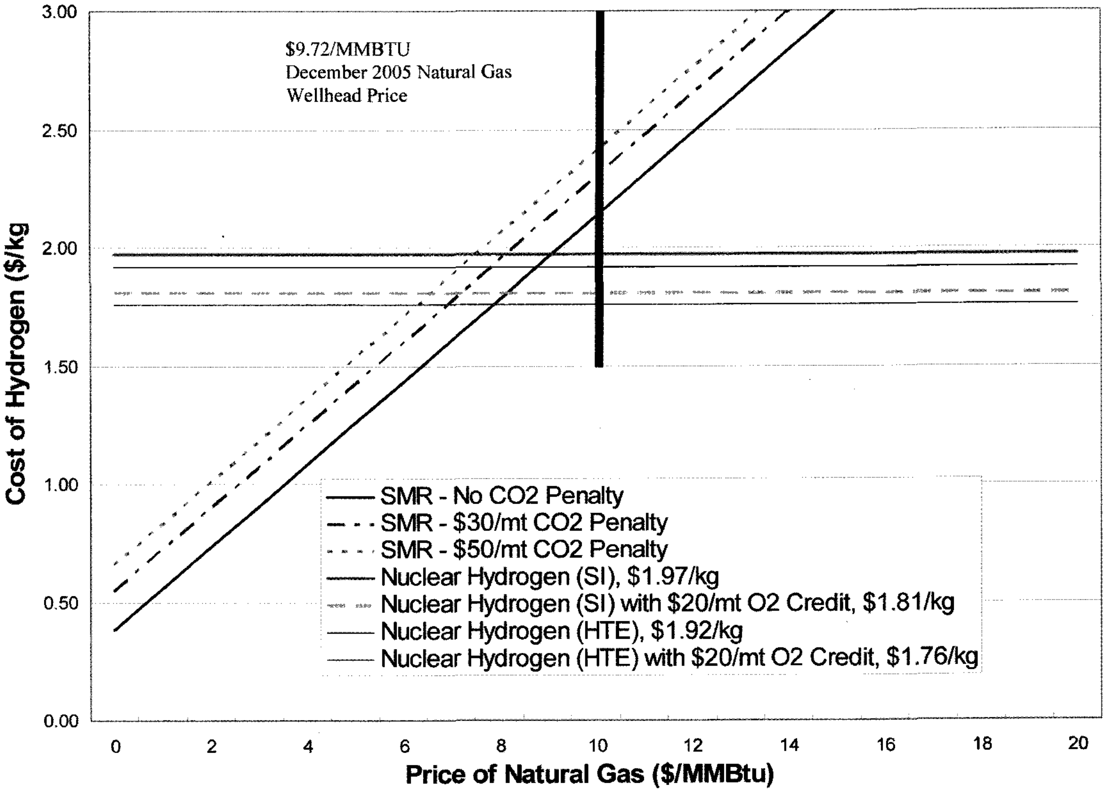

Fig. 7. Comparison of Nuclear and SMR Hydrogen Production Costs

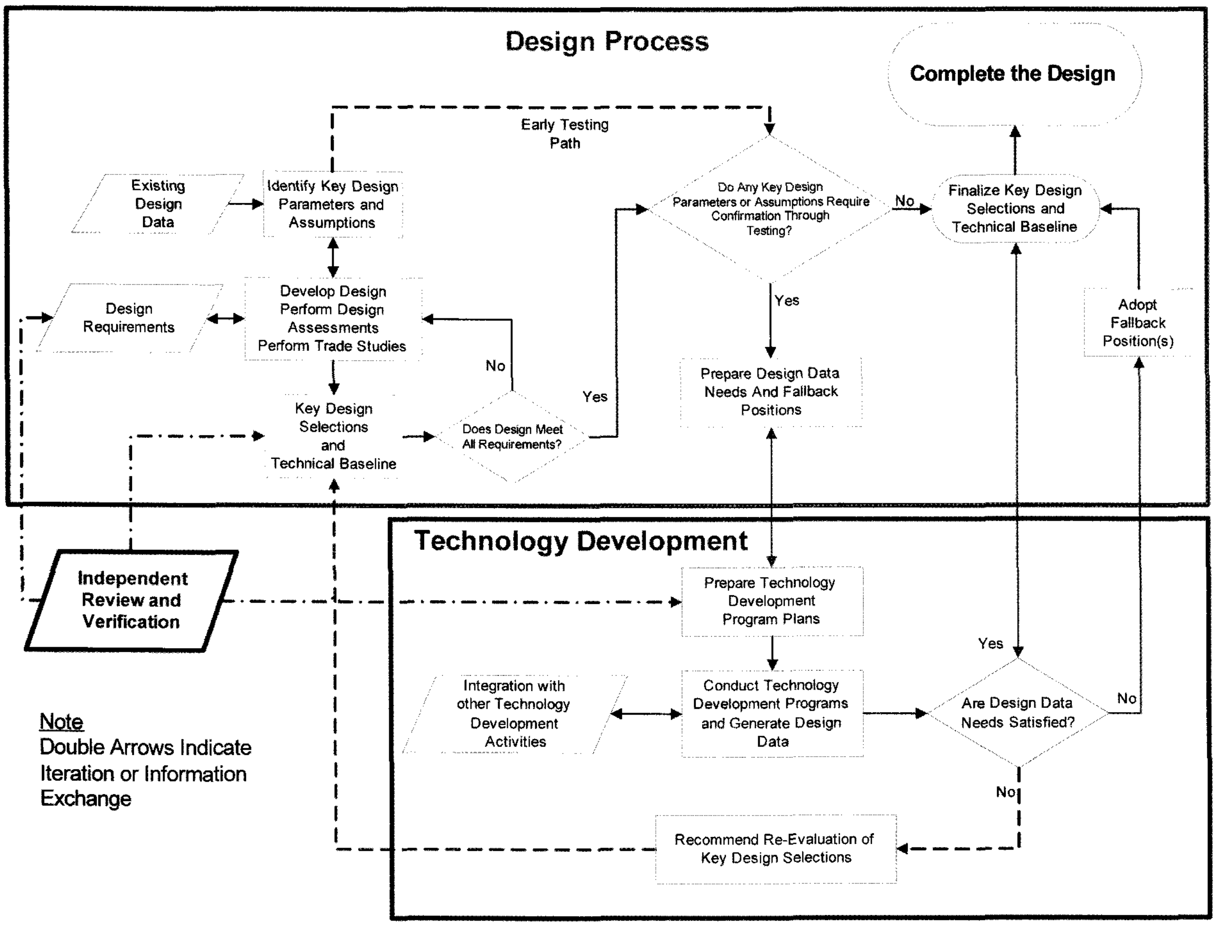

Fig. 8. Integration of Design with Technology Development

capital costs are approximately \$1,360/kW-H_2 using the higher heating value of hydrogen (141.9 MJ/kg). The total operations and maintenance (O&M) costs are estimated to be \$340 million per year, of which about two-thirds are electricity costs. The hydrogen production costs are estimated to be \$1.97/kg. Electricity costs contribute to about 30% of the hydrogen production costs. If the pumping power required by the SI process could be reduced by 50%, the hydrogen production costs could be reduced to about \$1.62/kg and the overall efficiency of the process would increase from 45% to 55%.

4.2. HTE-Based H2-MHR Economic Evaluation

An economic evaluation was performed assuming the same construction time, interest rate, and fixed-charge rate as the SI-based plant. The capital costs of the GT-MHR Plant and Hydrogen Production Plant were estimated to be \$1.42 billion and \$1.16 billion, respectively, for a total H2-MHR plant capital cost of \$2.58 billion. The SOE module cost was assumed to be \$500/kW(e). The installed capital cost is approximately \$1,920/kW-H2 using the higher heating value of hydrogen (141.9 MJ/kg). The total operations and maintenance (O&M) costs are estimated to be about \$119 million per year. The hydrogen production cost is estimated to be \$1.92/kg. Hydrogen Production Plant capital costs contribute to about 28% of the hydrogen production cost. If the SOE module cost is increased to \$1,000/kW(e), the installed capital cost and hydrogen production cost increase to \$2,560/kW-H_2 and \$2.55/kg, respectively.

5. CONCLUSIONS

Based on this pre-conceptual design study, the H2-MHR is capable of producing hydrogen economically, safely, and with minimal environmental impact. It is recommended that the H2-MHR design development be continued through the conceptual, preliminary, and final design phases. Also, it is recommended that future H2-MHR design work be closely coupled with ongoing and planned technology-development programs, in order to ensure that the data obtained by these programs satisfies specific needs of the H2-MHR design. This model for integration of design with technology development is illustrated in Fig. 8 and is based on successful Engineering Development and Demonstration (ED&D) programs conducted and managed by General Atomics for Department of Energy projects, including the commercial GT-MHR and other gas-reactor programs.

ACKNOWLEDGEMENT

This work was funded by the U.S. Department of Energy Nuclear Energy Research Initiative (NERI), under grant DE-FG03-02SF22609/A000. The authors would also like to acknowledge the contributions and assistance provided by Toshiba Corporation, Fuji Electric Systems, Japan Atomic Energy Agency, and Savannah River National Laboratory.

REFERENCES

[1] S. SHIOZAWA, "Development Status of Hydrogen Production Technology Using High Temperature Gas-Cooled Reactor," *Proceedings of the 6th International Conference on Nuclear Thermal Hydraulics, Operations and Safety (NUTHOS-6)*, October 4-8, 2004, Nara, Japan, Atomic Energy Society of Japan, Tokyo, Japan (2004).

[2] M. RICHARDS, A. SHENOY, Y. KISO, N. TSUJI, N. KODOCHIGOV, and S. SHEPELEV "Thermal Hydraulic Design of a Modular Helium Reactor Core Operating at 1000°C Coolant Outlet Temperature," *Proceedings of the 6th International Conference on Nuclear Thermal Hydraulics, Operations and Safety (NUTHOS-6)*, October 4-8, 2004, Nara, Japan, Atomic Energy Society of Japan, Tokyo, Japan (2004).

[3] M. RICHARDS and A. SHENOY, "Hydrogen Generation Using the Modular Helium Reactor Core," *Proceedings of ICONE12: 12th International Conference on Nuclear Engineering*, April 25-29, 2004, Arlington, Virginia, American Society of Mechanical Engineers, New York, NY (2004).

[4] M. RICHARDS, A. SHENOY, and K. Schultz "MHR-Based Hydrogen Production Systems," *Proceedings of the International Congress on Advances in Nuclear Power Plants (ICAPP '04)*, June 13-17, 2004, Pittsburgh, PA, American Nuclear Society, La Grange Park, IL (2004).

[5] International Atomic Energy Agency (IAEA), May 1999, *Hydrogen as an energy carrier and its production by nuclear power*, IAEA-TECDOC-1085.