

# **GAS REACTORS – A REVIEW OF THE PAST, AN OVERVIEW OF THE PRESENT AND A VIEW OF THE FUTURE**

**Thomas J. O'Connor**

Office of Gas Reactor Development, U.S. Department of Energy – Office of Nuclear Energy  
(*tom.oconnor@nuclear.energy.gov*)

*Paper presented by W. Von Lensa*

## **Abstract**

Gas-cooled reactors have a rich history and a promising future. They were among the first nuclear plants to be commercially deployed and are now the subject of revitalized interest for future deployment. Gas-cooled reactors may be critical to the management of climate change and energy security in the coming decades. This paper reviews the history of gas-cooled reactors from the carbon dioxide (CO<sub>2</sub>) cooled reactors in the United Kingdom and France to the prototype helium cooled reactors in the United States and Germany. The paper summarizes the current research and development (R&D) work supported by the Generation IV International Forum (GIF) Gas Cooled Reactor Program in general and discusses the on-going gas reactor R&D and demonstration work in the United States, People's Republic of China, and Republic of South Africa. Finally, the paper summarizes the broad range of potential applications of high temperature gas-cooled reactors including electricity generation, process heat production, unconventional hydrocarbon development, and hydrogen generation.

## **I. INTRODUCTION**

This paper documents the evolving applications of gas-cooled reactors; past, present and future. An overview of the past covers the experience with commercial gas-cooled reactors to date. An assessment of the present focuses on the technical work coordinated by GIF to support the future deployment of the Very-High Temperature Reactor (VHTR) and associated national programs to support nearer term deployment of High-Temperature Reactors (HTR). A forecast of the future describes the potential applications of high-temperature gas cooled reactors in a world that is concerned with global climate change and the utilization of

scarce resources. The gas reactor has a rich history and a promising future.

Gas-cooled reactors were among the first nuclear plants to be commercialized from military applications, which used natural uranium to produce plutonium for nuclear devices. The temperature of the core outlet has risen steadily from the earliest CO<sub>2</sub> reactor (340°C) to nearly 1 000°C. This increase in temperature will enable the application of gas-cooled reactors to expand from the generation of electricity to the production of process heat, and the production of nonconventional hydrocarbons, and ultimately, to the production of hydrogen.

## **II. EXPERIENCE WITH GAS-COOLED REACTORS**

### **II.A. CO<sub>2</sub> Cooled Reactors**

The earliest commercial gas-cooled reactors were derived from plutonium production reactors. They used natural uranium, thus not requiring expensive enrichment facilities. They also used CO<sub>2</sub> as a coolant and graphite as a moderator. The United Kingdom and France were the primary developers and users of the technology. Gas reactors still provide most of the UK electricity generated with nuclear energy, which is almost 20% of the UK's total electricity. France has decommissioned all of its gas-cooled reactors and replaced them with light water reactors. The "lessons learned" from the deployment of the CO<sub>2</sub> reactors are discussed in the following sections.

#### **II.A.1 United Kingdom**

##### *II.A.1.a. Magnox Reactors*

The earliest gas-cooled reactors in the UK were called Magnox reactors, because they utilized magnesium (Mg) as the cladding for the fuel. The first Magnox plant was the Calder Hall station with four 220 MWt (51 MWe) reactors. Calder Hall operated from 1956 to 2003 with very good performance. The CO<sub>2</sub> coolant left the core at 340°C and 0.66 MPa pressure. There were ten additional Magnox stations. The Magnox reactors represented almost 4.3 GWe of generation. The average station life was almost 40 years. Two Magnox stations remain in operation. In general, the Magnox plants performed very well for the UK. The life-time fleet average capacity factor was 70.3%. Similar reactors were deployed in Italy and Japan.

##### *II.A.1.b. Advanced Gas Reactors (AGR)*

In order to improve the performance of the Magnox plants, the UK developed a second generation CO<sub>2</sub> cooled design, the advanced gas reactor. The increase in thermal power level resulted in the core outlet temperature increasing to 640°C and pressure to 4.0 MPa, the temperature being limited by the chemical activity of the CO<sub>2</sub>. The resulting fuel temperature required the use of

stainless steel cladding, and the uranium in the fuel had to be enriched to between 2.5 and 3.5% uranium 235 (U<sup>235</sup>). AGRs with almost 8.4 GWe of capacity were built at six sites in the UK.

The overall performance of the AGRs has been adequate. The on-line refueling feature had to be abandoned due to unacceptable vibrations. Graphite moderator blocks experienced cracking. Boiler issues at Hinkley Point and Hunterston have limited the output of the plants to 70% normal capacity. Following the AGR construction, the CEBG elected to pursue light water technology for Sizewell B and subsequent nuclear stations.

#### **II.A.2. France**

France initially followed a similar path to the UK in their development of CO<sub>2</sub> cooled, natural uranium reactors. The initial designs were used by the Commissariat à l'Energie Atomique of France (CEA) for dual purposes to produce plutonium for the French weapons program and power for the grid. Subsequently, Electricité de France (EdF) owned and operated six gas-cooled power reactors with a generating capacity in excess of 2.2 GWe. The natural uranium fuel was clad in Mg/zirconium alloy. The core outlet temperatures reached 385°C with a 2.45 MPa system pressure in the later reactors.

All of the French reactors were shut down prior to end-of-life for economic reasons coupled with the long-term transition to light water technology that began in 1972. The St. Laurent plants had numerous problems with steam generator tube leaks. The condition was finally mitigated by changes made in the Bugey 1 plant.

The Spanish built a gas-cooled reactor at Vandellòs based upon the St. Laurent A design. This reactor was shut down prematurely due to a major turbine-generator fire.

### **II.B. Helium Cooled Reactors**

The core outlet temperature in gas-cooled reactors can be increased above the limit imposed by the CO<sub>2</sub> chemical attack of the graphite if helium is used as the coolant. Helium is much more expensive and has better heat transfer properties than CO<sub>2</sub>. Helium is much

more demanding from a system leak tightness perspective due to its small molecular size. Helium is the coolant of choice for future gas cooled reactors.

### II.B.1. United Kingdom

One of the earliest developers of the high temperature gas-cooled reactors using helium as a coolant was the UK's Atomic Energy Authority (UKAEA). As part of an Organization for Economic Co-operation and Development (OECD) project, the UKAEA developed and built the Dragon demonstration reactor. The Dragon reactor was a 20 MWt helium cooled, graphite-moderated reactor with a core outlet temperature of 750°C and pressure of 2.06 MPa. The reactor operated from 1959 to 1976. While the reactor had no means for producing electricity, it was a valuable demonstration for the use of helium as a coolant. The UK did not pursue the use of helium beyond the Dragon reactor.

### II.B.2. United States

There were two major demonstration plants built and operated in the United States. The first was Peach Bottom Unit 1, followed by the larger Ft. Saint Vrain (FSV) Plant. A brief discussion of each follows.

#### *II.B.2.a. Peach Bottom Unit 1*

The Peach Bottom Unit 1 reactor was a high-temperature gas-cooled reactor designed and built by the General Atomics Company (GA) for the Philadelphia Electric Company. The reactor used helium as a coolant and graphite as a moderator. The thermal power level was 110 MWt and 48 MWe. The core outlet temperature was 794°C and pressure was 2.4 MPa. The reactor vessel was made of steel, and there were two core designs. The first core used coated fuel particles of U-235 and Thorium-232 carbide with a single layer of anisotropic carbon. Fast neutron-induced dimensional changes cracked 90 out of the 804 sleeves containing the fuel particles. The sleeve cracking did not impair reactor operation, and the coolant activity was less than 7% of the design level. The second core incorporated

buffered isotropic pyrolytic carbon (BISO) fuel particles. The second core operated its full design life with no fuel sleeve failures and one-millionth the design coolant activity. The plant went into commercial operation in mid-1967, and retired for decommissioning in October 1974. The shutdown was a planned economic decision. The overall capacity factor over its life was an impressive 74%, and the plant was available 88% of the time.

Peach Bottom 1 provided several important outcomes including excellent agreement between the design calculations and the actual performance, excellent fuel performance of the BISO fuel, and excellent steam generator performance and load following capability.

#### *II.B.2.b. Fort Saint Vrain*

The FSV reactor was part of the U.S. Atomic Energy Commission (USAEC) Power Reactor Demonstration Program with most of the funding coming from the owner/operator, Public Service of Colorado. While the FSV reactor was designed by GA, it was very different from the Peach Bottom Unit 1 design. FSV used helium as the coolant and graphite as the moderator. The power output was much greater, 842 MWt and 330 MWe, the core outlet temperature was 778°C, and the system pressure was increased to 4.83 MPa. The reactor vessel was reinforced concrete, and the core was comprised of fuel compacts containing three layer (TRISO) fuel particles in graphite blocks. The operating license was issued by the USAEC in 1973; and full power was reached in November 1981. FSV was shut down in 1989 due to financial reasons, as the operating and maintenance costs exceeded the plant revenues. The overall capacity factor for FSV was less than 30%.

There were numerous problems with the FSV. These problems included core outlet temperature fluctuations (fixed by adding core restraints); leakage of water into the core from the helium circulator water bearings; steam generator leaks and header cracks discovered at end-of-life; reserve shutdown system malfunction, emergency pump cavitation (one-year delay); hot helium bypass on control rod drives, and a hot spot on the core support floor. In spite

of the problems, there were a number of valuable lessons learned from the design, construction and operation of FSV. These positive lessons included a much lower fission product release (than expected); an excellent agreement between calculations and actual performance; the computer control of fuel handling worked well; the helium purification system worked well; and the reinforced concrete reactor vessel performed well and systems, in general, performed as designed.

GA received orders for ten, large commercial plants, which were cancelled in the early 1970s due to a combination of the oil embargo and reduced electricity demand. The commercial designs were larger, improved versions of the FSV reactor. GA withdrew from the commercial nuclear business in 1975.

### II.B.3. Germany

The high-temperature gas reactor program in Germany was similar to the U.S. program in that it pursued high temperatures using helium as a coolant and graphite as a moderator. The primary difference was in the fuel configurations. The United States used fixed graphite blocks with fuel compacts containing coated fuel particles. The German program used a mobile pebble fuel configuration that permitted on-line refueling. The pebbles contained similar coated particle. There were two major demonstrations of the technology, the Arbeits-gemeinschaft Versuch Reaktor (AVR) and the Thorium High Temperature Reactor (THTR).

#### *II.B.3.a. The Arbeitsgemeinschaft Versuch Reaktor (AVR)*

The AVR was a Federal Republic of Germany project at the Julich Research Center designed to demonstrate the feasibility of using spherical fuel elements (pebbles) and high temperatures. The AVR operated from 1967 to the end of 1988, when it was closed in response to the political pressures raised by the Chernobyl nuclear accident. The AVR had a thermal output of 49 MWt and an electrical output of 15 MWe. The AVR used a steel reactor vessel. The initial core outlet temperature was 850°C, which was subsequently raised to 950°C in 1974. The

system pressure was 1.1 MPa. Several fuel designs were used at the AVR. The initial fuel did not perform as well as expected. The three-layer TRISO fuel was ultimately used with very good success. In spite of a major repair outage to repair damage from a steam generator leak in 1978, the AVR returned to service in 1980 and achieved a respectful 66.4% overall availability.

There were a number of lesson learned from the AVR experience. These include pebble bed reactors work; Light Water Reactor (LWR)-type containments are not required for future high-temperature gas-cooled reactors; modular reactors are feasible. In addition, success was demonstrated in reactor operations (normal, transient and accident conditions), materials (fuel, graphite, ceramics, metallics), design (control, vessel and auxiliary systems), and pebble bed fuel manufacture and handling.

The AVR technology was transferred to South Africa in the late 1990s and became the basis for the Pebble Bed Modular Reactor. The technology was also transferred to China, where it became the basis for the High-Temperature Reactor (HTR) Program.

#### *II.B.3.b. Thorium High Temperature Reactor (THTR)*

The second German pebble bed reactor was similar in power level to the FSV and was intended to be a building block for the German high-temperature gas-cooled reactor program to achieve commercial scale power plants. The plant thermal output was 750 MWt and 300 MWe. The core outlet temperature was 750°C, and the system pressure was 3.9 MPa. Like the FSV, the THTR used a reinforced concrete reactor vessel with integral cooling circuit. The construction of THTR began in 1971 but was not completed and licensed until 1984. The THTR was shut down in 1989 in part due a shortfall in funding and also in response to the political pressures raised by the Chernobyl nuclear accident

The lessons learned from the operation of the THTR include plant maintenance workers encountered very low doses of radiation; control rods can be safely inserted into a bed of fuel

pebbles, and reliable on-line refueling and pebble discharge systems can be designed and operated. Finally, as for all reactors, licensing delays can result in major redesign and costly delays.

#### II.B.4. Japan

The High Temperature Engineering Test Reactor (HTTR) is the center piece of the Japanese high-temperature gas-cooled reactor program. The HTTR is a 30 MWt prismatic block with outlet temperatures as high as 950°C. The HTTR construction began in 1990, and criticality was achieved in 1998 with very good operating experience. The HTTR was designed to establish gas reactor technology and nuclear heat utilization technology including the production of hydrogen using the sulfur iodine process.

#### II.B.5. People's Republic of China

The Chinese high-temperature gas-cooled reactor program is based on the pebble bed design imported from Germany. The center piece of the Chinese program is the 10 MWt test reactor called the HTR-10. The HTR-10 is 10 MWt pebble bed reactor with an outlet temperature of 700°C (up to 900°C) and a system pressure of 3 MPa. The reactor construction began in 2000, and full power operation was achieved in 2003. The test reactor has performed well and significant safety tests demonstrate the passive cooling capability of the HTR. Their program also includes the HTR-PM, a commercial prototype presently under design and construction.

### III CURRENT DEVELOPMENT AREAS

#### III.A. The GIF Gas-Cooled Reactor Program

The GIF Program encompasses the development of advanced reactors and fuel cycles to support the broader deployment of nuclear energy to help reduce greenhouse gas emissions and increase global energy security. One of the advanced reactors selected by GIF is the very high-temperature reactor (VHTR). The VHTR is defined as a helium-cooled, graphite moderated reactor with a core outlet temperature in excess of 900°C and a long-term goal of achieving an outlet temperature of 1 000°C. The

VHTR is suited for a broad range of applications, including the production of hydrogen from water. Members of the GIF VHTR System Arrangement include the United States, France, Japan, United Kingdom, People's Republic of China, the Republic of Korea, Canada, Switzerland, and EURATOM.

In order to achieve the ambitious goals of the VHTR, GIF has established a research plan. The main R&D areas of the VHTR System Research Plan are briefly summarized below.

#### III.A.1. Computational Methods Development and Validation

Computational methods development and validation are major activities for the assessment of the reactor performance, in normal, incidental and accidental conditions. Computational tools are needed in areas such as thermal-hydraulics, thermal mechanics, core physics, chemical transport, and the derivate couplings. Numerical models will be specifically developed and validated to meet the pebble bed and the prismatic type core reactors requirements. Extension and validation of existing engineering and safety analysis methods are especially required to yield new design and safety approaches, new materials, operating regimes, and component configuration in the models.

Code calculations will be validated through benchmark tests and code-to-code comparisons from basic phenomena to integrated experiments, supported by HTTR (30 MW) tests, or HTR-10 (10 MW) tests or by past technology high temperature reactor data (*e.g.* AVR, Fort St Vrain, etc.).

#### III.A.2. Fuel and Fuel cycle

TRISO coated particles, which are the basic fuel concept for the VHTR, need to be qualified for relevant service conditions. Furthermore, the standard design using uranium dioxide can evolve along with the improvement of its performance through the use of a uranium oxycarbide fuel kernel or a zirconium-carbide coating for enhanced burn-up capability, reduced fission product permeation and increased resistance to core heat-up accidents (above

1 600°C). The research will include fuel characterization, post-irradiation examination, safety testing, and fission product release evaluation as well as chemical and thermo-mechanical materials properties in representative conditions.

Fuel cycle back-end R&D will encompass spent fuel treatment and disposal, as well as used graphite management. A “once through” cycle is initially envisioned. However, the potential for deep-burning of plutonium and minor actinides in a VHTR, and the use of thorium-based fuel will be included in future R&D as important steps toward a closed cycle.

### III.A.3. Materials

Reliable materials performance is key to the viability of the VHTR. The projected R&D for improved materials includes materials development and qualification; development of design codes and standards; improved manufacturing, installation, and construction techniques for key components. The service temperatures range from a near-term core outlet temperature between 750 and 900°C, for which existing materials may be used. The longer-term goal of 1 000°C requires the development and qualification of new materials.

The materials of particular interest include:

- Graphite for the reactor core and internals.
- High-temperature metallic materials for internals, piping, circulators, valves, heat exchangers, steam generators, gas turbine sub-components.
- Ceramics and composites (C-C, SiC-SiC, etc.) for control rod cladding and other specific reactor internals, as well as for advanced intermediate heat exchangers and gas turbine components for very-high temperature conditions.

### III.A.4. Components and High Performance Turbomachinery

Design and construction investigations will address key components of the VHTR

system such as the reactor pressure vessel, core, internals, circulators, valves, hot duct and heat exchangers, reactor cavity cooling system (RCCS) and other subsystems. Highly efficient generation of electricity with a VHTR requires a closed Brayton power conversion system. Anticipated R&D tasks include gas turbine and compressor system design and manufacturing, rotor dynamics, magnetic bearing technology, system layout, maintainability, and control system. In conjunction with these above efforts, new welding techniques shall be developed, and dedicated test loops will be needed to support the component design work

### III.A.5 Hydrogen Production and Other Process Heat Applications

The principal candidates for hydrogen production from water are (1) the sulphur/iodine (S/I) thermo-chemical cycle and (2) the high-temperature electrolysis (HTE) process. Integrated test loops will help assess the performance and optimize the processes prior to building a demonstration scale prototype. Such test loops will assist the development heat exchange and transport components.

Coupling the hydrogen process technology with the nuclear reactor is another key element in the VHTR development. Considerations include interfacing events between nuclear and nonnuclear plants, areas of particular interest include thermal load management, hydrogen fires and explosions, toxic and hazardous material releases, tritium permeation and thermal disturbances caused by the hydrogen production system transients.

Additional process heat applications for the VHTR are extremely important to both energy security and global climate change management. These applications are discussed in more detail in Section IV of this paper.

### III.B The U.S. Gas Cooled Reactor Program

In the United States, high-temperature gas-cooled reactor (HTR) development work is funded by the U.S. Department of Energy’s (DOE) Office of Nuclear Energy (NE) Generation IV Program. Two tracks are being

pursued. The first is to support the technologies required for near-term commercialization, the second is to extend the capabilities into even higher temperature regimes. The reference near-term concept is a helium-cooled, graphite-moderated, thermal neutron spectrum reactor with an outlet temperature of 750 to 850°C. The reactor core configuration may be either a prismatic graphite block or pebble bed. These near-term concepts have the potential to extend the benefits of nuclear energy beyond the electrical grid by providing industry with carbon-free, high temperature process heat for a variety of applications including petroleum refining, bio-fuels production, and production of feedstock for use in the fertilizer and chemical industries. The reactor thermal power and core configuration will be designed to assure passive decay heat removal without fuel damage during any potential accident. An integral part of the U.S. Generation IV VHTR Program is the development of a regulatory framework with the U.S. Nuclear Regulatory Commission

The U.S. Generation IV VHTR R&D activities are closely integrated with the GIF VHTR activities. Key aspects of the U.S. Generation IV VHTR R&D are discussed below.

### III.B.1 Fuels

The U.S. Generation IV VHTR's AGR Fuel Development and Qualification Program are designed to provide a fuel qualification baseline to support regulatory acceptance. The AGR Fuel Development and Qualification Program supports the near-term deployment of gas reactor technology by reducing market entry risks posed by technical uncertainties associated with fuel production and performance.

The program is: (1) developing technologies for the manufacture of very high-quality fuel kernels, TRISO-coated particles, and compacts; (2) irradiating fuel to high burnup at prototypical powers; (3) testing the irradiated fuel during worst-case accident simulations, and (4) developing and validating physically based computer models of the fuel and fission product transport behaviour.

### III.B.2 Materials

The VHTR Materials R&D Program is testing and qualifying the key materials commonly used in very high-temperature designs. The materials R&D Program encompasses the materials needed for the VHTR reactor system, power conversion unit, intermediate heat exchanger, and associated balance of plant. The order of priority for the VHTR materials R&D is as follows:

- Test and qualify core graphite materials.
- Develop an improved high-temperature design methodology for use of selected metals at very high temperatures.
- Develop American Society of Mechanical Engineers (ASME) and American Society for Testing and Materials (ASTM) codes and standards.
- Perform environmental testing and thermal aging of selected hightemperature metals.
- Irradiate, test, and qualify reactor pressure vessel (RPV) materials.
- Develop and qualify composites for use in control rod cladding and guide tubes.
- Resolve RPV fabrication and transportation issues.

### III.B.3. Computational Methods

Included in the U.S. Generation IV VHTR R&D effort is the advancement of analytical methods and modelling to support gas reactor design including establishing qualification and validation criteria and experiments. The methods efforts will develop improved analytical codes and validate applications of these codes using data from scaled experiments and prior experience. A major focus will be on the development of tools to assess the reactor core neutronic and thermal hydraulic behaviour. Fuel behaviour and fission product transport models will be developed within the fuels program and graphite performance models within the materials program.

### III.C The People's Republic of China

The Chinese high-temperature gas reactor R&D program is directed toward the development of the prototype modular reactor and conversion of the HTR-10 to a vertical shaft direct Brayton cycle electricity generator. The modular reactor R&D includes fuel fabrication, optimizing the Rankine cycle, and improved constructability. Much of the technology used in the modular reactor is based upon proven fossil power conversion technology. The HTR-10 modification replaces the existing steam generator Rankine cycle with a vertical Brayton cycle power conversion unit using active magnetic bearings. The R&D includes the development of test loops for the helium compressor and active magnetic bearings. Managing the damping, critical speeds, and system stiffness are critical elements in the successful deployment of such a vertical shaft machine. These issues will be evaluated in the R&D program.

The prototype pebble bed reactor (HTR-PM) is a modular 200 MWe reactor. The HTR-PM project received environmental clearance in March 2008 for construction start in 2009 and commissioning by 2013. Additional gas reactor modules are proposed for the HTR-PM site in the Shandong Province.

### III.D. The Republic of South Africa

The South African R&D program is structured to support the deployment of the PBMR for either electricity generation purposes or process heat.

The R&D includes fuel manufacturing development, irradiation and testing, testing of key active components in their Helium Test Facility, testing of heat transfer mechanisms, and thermal hydraulic phenomena in their Heat Transfer Test Facilities (high temperature and high pressure). In the safety assurance area, R&D tasks include the effects of corrosion due to air ingress on the natural circulation potential of the PBMR primary circuit. Experiments with the critical facility and the PBMR micro-model have assisted in the development of the overall safety

case through benchmarking of the analysis software.

PBMR is evaluating a move in product emphasis from a direct Brayton cycle to a steam co-generation Rankine cycle to match nearer term applications in process heat. This switch includes lowering the reactor outlet temperature to approximately 750°C and smaller power output around 200 MWt. This strategy is being made with consultation of potential customers in both South Africa and the United States. It also brings the South African development effort in better alignment with the Chinese HTR Program. The decision should be finalized in June 2009 after it is reviewed with the PBMR Board of Directors and the South Africa government, assuming the business case for this product design is positive.

## IV. FUTURE USE OF GAS REACTORS

In all reasonable forecasts, nuclear energy must play an ever increasing role in the generation of electricity, which accounts for roughly one-third of the global, man-made CO<sub>2</sub> emissions. However, if we are to deal effectively with the combined threat of climate change and energy security, nuclear energy must expand its role beyond the generation of electricity. In the form of HTRs and VHTRs, nuclear energy can provide CO<sub>2</sub> emission-free process heat for chemical plants, refineries, and for the development of unconventional, hydrocarbon resources. In this context, a gas reactor is helium cooled, graphite moderated reactor with core outlet temperatures equal to or in excess of 750°C. Eventually, gas reactors will have sufficiently high core outlet temperatures to produce hydrogen from water to provide transportation fuels and serve as an excellent energy carrier, similar to the role of high-voltage transmission systems. Similarly, hydrogen permits the production of gases and liquids from the world's most abundant unconventional hydrocarbon, coal, without the emission of large quantities of CO<sub>2</sub>.

These are not new ideas. In a 1982 overview paper, [1] the incentives for developing and deploying high-temperature gas-cooled

reactors include “the efficient application of nuclear heat to:

1. Replace fossil fuels in a substantial portion of industrial process heat energy needs.
2. Significantly reduce the potential for the adverse environmental impact of CO<sub>2</sub> and other pollutants from burning fossil fuels for the production of process steam and heat.
3. Directly substitute for the heat formed by burning fossil feedstock fuels in the production of syngases, syngas, and hydrogen.
4. Provide a path to nearly inexhaustible hydrogen fuel economy through thermochemical water splitting.

More recently, Konefal [2] produced an excellent overview of the potential applications of gas reactors for process energy applications. The report is a thorough, state-of-the-art assessment of the theoretical deployment of gas reactors for use in the following applications.

- Petroleum refining.
- Oil recovery.
- Coal and natural gas derivatives.
- Petrochemicals.
- Industrial gases, particularly hydrogen.

- Ammonia and nitrates production for inorganic fertilizers.
- Metals.
- Polymers.
- Cement.
- Pharmaceuticals.
- Paper and Glass.

Of the applications, the first seven are considered to be high priority. The application of nuclear energy to the generation of electricity, process heat, nonconventional hydrocarbon, and hydrogen are briefly discussed in the following sections.

Steve Aumier [3] of the Idaho National Laboratory proposes a vision of hybrid nuclear/conventional energy as a means to address the key aspects of energy security and climate change. Figure 1 illustrates some key elements of this vision.

#### IV.A. Electricity Generation

Electricity is the one area where nuclear energy is currently used commercially. Traditionally, commercial nuclear power plants are among the largest of the central generating stations. The Advanced LWRs are under construction for baseload electricity generation

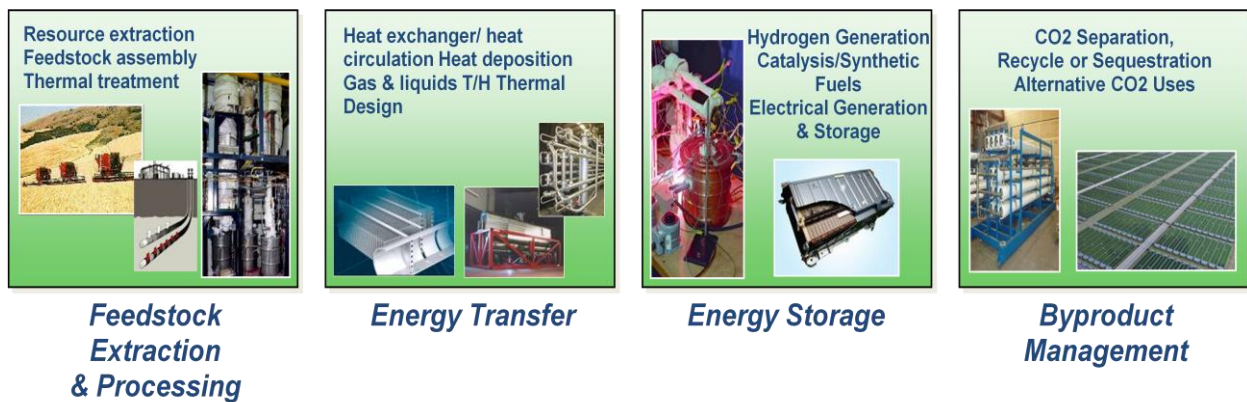


Figure 1: Potential Application of High Temperature Gas cooled Reactors for a Broad Range of Hybrid Energy Applications

with capacity greater than 1 200 MWe. These proven, safe and reliable units will be the nuclear generation option of choice for most of the world's large utilities. However, other utilities prefer to build plants of a smaller scale, in increments of 250 MWe, as seen in the large number of natural gas-fired plants deployed in the 1990s throughout the world. If smaller nuclear plants can be licensed and built economically, the displacement of natural gas-fired combined cycle (NGCC) generation plants is likely to be significant in the future. This displacement will occur if the price of natural gas remains high and the price of CO<sub>2</sub> becomes significant. Proposed gas reactors are of a similar size as the current NGCC plants. In this vein, the smaller gas reactors can fill one or more important niches. These niches include either a situation where an electric utility does not need 1 200 MWe or more of generation or one where a large investment of 4B€ provides too great an exposure for the corporation. Another potential niche is for regions of the world where water usage is a critical issue for power generation, such as in the U.S., west and southwest. A gas reactor is small enough and efficient enough to use air-cooled condensers without a severe heat rate penalty. Air condensers are currently coupled to generating units with capacities as high as 500 MWe. The water situation will only exacerbate the energy crisis with time.

#### IV.B. Process Heat Applications

The second area of applications for future gas reactors is in the refining of crude and other feedstocks into transportation fuels. Worldwide, refineries produce 13% of all of the manmade CO<sub>2</sub> and consume large amounts of energy. For example, refineries use about 7.5% of the entire U.S. energy supply. The potential substitution of nuclear produced process heat for process heat produced by the combustion of high-quality fossil fuels, such as natural gas is potentially significant, if the economics are sensible.

The potential use of nuclear energy to displace the use of natural gas in an oil refinery and to reduce CO<sub>2</sub> emissions can be assessed by investigating the types of fuels and energy usage in a typical U.S. refinery, see Figure 2.

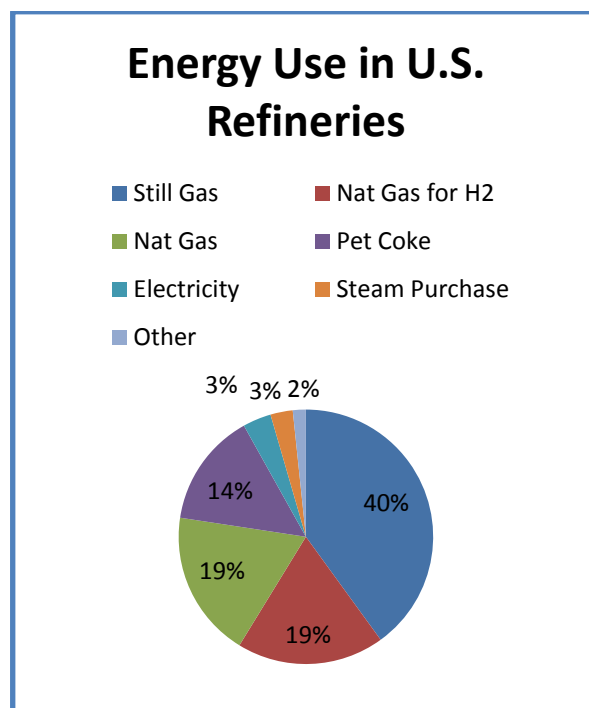


Figure 2: Sources of energy for the refining of crude oil in the average U.S. refinery

Discussions with oil companies suggest that nuclear energy could replace some but not all of the energy requirements of an oil refinery. At a minimum, 25% of the energy, the natural gas, the purchased steam and electricity can be replaced with nuclear energy in the largest refineries. In the United States alone, refineries use over 2.70 trillion cubic feet (TCF) of natural gas per year. Reference [8] identifies the thermal load (steam, heat and electricity) for a 200 000 bbl/d refinery as about 1 100 MWt. It is expected that economically replaceable energy is at most one-half the total, based upon these end-user discussions.

The chemical industry is another industry in which gas reactors could play an important role in the future. The three most energy consumptive chemical processes are the production of (1) ethylene, (2) ammonia and (3) chlorine. Ammonia, a key component of inorganic fertilizer production, requires copious amounts of natural gas in its production. In a chemical plant, natural gas is used for feedstock and process heat to provide steam and electricity through co-generation. To quantify the energy use and CO<sub>2</sub> emitted in the manufacture of chemicals, key data for the U.S. are:

- The chemical industry uses about 15% of the energy used in the U.S.
- The production of ethylene, a major petrochemical product, requires about 4.9 QUAD of energy annually and represents 34% of the entire petrochemical annual energy usage.
- The total natural gas used annually in the production of ammonia is 6 TCF, with 42% burned to produce the heat necessary for ammonia production.
- Ammonia production creates about 115 million MTs/y of CO<sub>2</sub>. Annual chlorine production requires 5 QUAD of energy, mainly in the form of electricity.

#### IV.C. Unconventional Hydrocarbon Production

In order to increase the energy security of any country in the world, that country must be in a position to utilize its indigenous resources. In the United States, for example, petroleum feedstock could be produced from domestic, unconventional hydro-carbon sources, such as heavy oil and tar sands, coal, biomass and oil shale. The United States has huge deposits of both coal and oil shale and could produce as much as 1.3 billion dry tons per year of sustainable biomass from agriculture and forest residues. [4]

Chevron [4] recently completed a thorough evaluation of the potential uses of nuclear energy in the exploitation of unconventional hydrocarbons in their future business. In their evaluation, the unconventional hydrocarbons include heavy oils using steam floods, oil sands using cyclic steam stimulation and steam-assisted gravity drainage, oil shale, and coal to liquids.

##### IV.C.1. Heavy Oil and Tar Sands

The recovery of heavy oil and the bitumen recovery from tar sands require significant amounts of steam and electricity for heating and pumping the product. The top four resources of tar sands in the world are: Canada, Venezuela, Columbia and Russia. For example in North

America, if we produce 800 000 bbls/day from a combination of 50% heavy oil and 50% tar sands, Bradruzzaman [5] concludes that about 0.314 TCF of natural gas per year is required with an attendant CO<sub>2</sub> release of over 21 million MT per annum. The natural gas cost at today's price of \$6 million BTU delivered is over \$5 million per day. With a target of 0.8 MMbbls/d from heavy oil and tar sands, between 15 and 25 gas reactors are required, assuming that a 500 MWt can provide sufficient energy to produce 50 Mbbls/d. The number of reactors deployed depends upon the layout of the fields.

##### IV.C.2. Coal to Liquids and Gases

Coal is one of the most abundant hydrocarbons on earth. The top coal resources in the world are located in Russia, the United States, China, Australia, and Canada. While coal is currently used to produce electricity, it can also serve as transportation fuel. The process for converting coal to liquids (CTL) was developed in Germany in the 1920s and by World War II became the source of 90% of that nation's liquid fuel requirements. Nine indirect and 18 direct liquefaction plants produced four million metric tonnes per year. Later, as a result of the apartheid based embargoes, South Africa, using technology similar to that used by the Germans, developed their own CTL industry that now produces up to 10 million metric tonnes per year meeting about 40% of the country's current liquid fuel needs. There is also a growing interest in other countries with major coal reserves, *e.g.* the United States and China, to develop processes that can exploit the large coal deposits to meet their growing petroleum requirements. For example, if the coal deposits in the United States were converted to liquid hydrocarbons, they would represent over 60% of the world's proven oil reserves. China is experiencing growth in coal liquefaction as a way of utilizing its coal reserves and reducing its dependence on imported oil. The South African company, Sasol, is planning two CTL plants in China. [6] In the United States, some nine states are actively considering CTL plants. Global liquid coal production is expected to rise from 150 000 bpd today to 600 000 in 2020 and 1.8 million bpd in 2030. [7] Currently, the CTL plants produce over 32 million MT of CO<sub>2</sub>/year. The plants are the largest, global, single point

sources of CO<sub>2</sub> emissions. Expanded deployment of conventional CTL plants is a major environmental concern.

A modified FT CTL plant [8] can be designed and built that produces very little CO<sub>2</sub>. The large amount of CO<sub>2</sub> produced in conventional FT-CTL plants is one of the primary objections to the use of coal to make refining feedstock. In the modified FT-CTL plant, gas reactors are used to split water to produce the oxygen (O<sub>2</sub>) and hydrogen (H<sub>2</sub>), in lieu of the air separation unit and the inherent water shift reaction. The modified CTL plant uses 40% less coal to produce the same amount of product. The oxygen derived from the water-splitting process is used for coal gasification, thus eliminating the need for air separation units, which represent about 10% of the total cost of the plant. However, the modified FT-CTL process requires a large amount of H<sub>2</sub>, on the order of 0.22 kg of H<sub>2</sub> for each kg of coal.

#### IV.C.3. Oil Shale

The oil shale deposits in the world contain the oil equivalent of over twice the proven crude oil reserves. The United States has 60% of oil shale in the world, representing 7 trillion barrels of oil equivalent. Estonia, Australia, China, and Brazil have the next largest oil shale resources. It is estimated that the oil shale deposits from the Green River region of the western United States will yield over 1 million barrels per acre. While the in-situ extraction of kerogen, the useful product, from oil shale, is in the experimental stage at Shell [9], scientists estimate that it requires approximately 12 GWt to produce 1 MMbbls/d. [10] The current approach is to use electric down hole heaters to raise the temperature of the oil shale to a level sufficient (~370°C) to release the kerogen. Over 250 KW-hr of electricity is required to produce one barrel of kerogen. With the current generation mix in the United States, the annual CO<sub>2</sub> emitted in the generation of the electricity required for the in-situ oil shale production of 0.4 MMbbls/d is about 17.5 million MT. An alternate, more energy efficient approach is the use of hot fluids to heat the ground rather than incurring the conversion losses in generating electricity. One nonemitting

source of heat for the in-situ oil shale is nuclear in the form of gas reactors. If gas reactors produced the heat for the *in-situ* oil shale production of 0.4 MMbbls/d, between 10 and 15 gas reactors (500 MWt) are required, depending upon the morphology of the oil shale deposits.

#### IV.C.4. Biomass

The conversion of biomass to liquids is more confounded than the other unconventional hydrocarbon sources, because so many different ways to produce liquids exists. Forsberg [11] provides an excellent description of the different processes and biomass feedstocks available or under development. Biomass can be converted to liquids using the Fischer-Tropsch process, similar to the conversion of coal to liquids. However, in the case of biomass, the net CO<sub>2</sub> burden is substantially less than for coal. This assumes that an equivalent amount of CO<sub>2</sub> produced in the gasification process is consumed in the growing of the crops, a.k.a., terrestrial sequestration. Gas reactors could produce the steam and the electricity required for the biomass conversion plants, reducing the CO<sub>2</sub> emitted from the burning of fossil fuels.

#### IV.D. Hydrogen Production

There is a growing need for hydrogen, emission-free process heat and steam for industries and process heat and steam for the production of unconventional hydrocarbons, as shown in previous sections.

Hydrogen is required in ever-growing quantities to process the lower quality, higher sulfur crude oil that is available today. The current method for producing hydrogen is through steam methane reformation of natural gas. The increasing price volatility of natural gas and the strong potential for carbon constraints are reasons for developing alternative means for producing hydrogen. Nuclear energy can produce emission-free hydrogen in a number of ways, including:

- conventional water electrolysis (using nuclear generated electricity),

- high-temperature electrolysis (using nuclear generated electricity and steam) requires temperatures up to 900°C for 50% conversion efficiency,
- thermo-chemical cycles water splitting (using nuclear heat) requires temperatures of 850°C,
- hybrid cycles (combining thermo-chemical and electrolytic steps) also requires temperatures of 850°C, and
- steam methane reforming (SMR) (using nuclear energy for the endothermic heat of reaction and steam), requires temperatures of 800°C.

The economics of hydrogen production through water splitting, the price of natural gas and the price of CO<sub>2</sub> emissions will determine the actual deployment of gas reactors for hydrogen production.

## V. CONCLUSION

This gas reactor review concludes the following:

1. While not all of the gas-cooled reactors demonstrations and deployments satisfied every expectation, all of them did provide valuable information and experience.

Lessons learned include:

- a. Lower temperature CO<sub>2</sub> cooled, natural uranium fuelled reactors can be successfully deployed for periods in excess of original design life.
- b. Helium can be successfully used as a coolant and graphite as a moderator for temperatures up to 950°C.
- c. Coated fuel particles, particularly of the TRISO type, perform reliably to high burn up levels, when properly manufactured.
- d. Conventional LWR type containments are not required for gas-cooled reactors.

- e. Fuel handling and refuelling of both prismatic blocks and pebbles can be reliably performed.
  - f. Control rods can be confidently inserted into a bed of fuel pebbles.
  - g. Tests demonstrate the safety of gas reactors under loss-of-coolant flow without scram conditions.
2. Current research programs within GIF and specific country programs address major development, demonstration and deployment issues. These include fuel, materials, constructability and manufacturability, turbo machinery and hydrogen production.
  3. Gas reactors can reduce CO<sub>2</sub> emissions and increase energy security through their ability to:
    - a. Play a niche role in electricity generation, where larger advanced light water reactors are either too large, too capital intensive or too water consumptive.
    - b. Provide industrial process heat for oil refining, chemical, petro-chemical and fertilizer production with a minimum generation of CO<sub>2</sub> emissions and maximum conservation of strategic hydro-carbon resources, particularly natural gas.
    - c. Support the development of unconventional hydrocarbons to increase national energy security. These unconventional hydro-carbons include heavy oil and tar sands, coal (in conjunction with hydrogen production), oil shale, and biomass.
    - d. Provide the thermal energy for hydrogen production using thermal chemical, high-temperature electrolysis or hybrid processes.

## Nomenclature

AGR – Advanced Gas Reactor  
ASME – American Society of Mechanical Engineers  
ASTM – American Society for Testing and Materials  
AVR – Arbeitsgemeinschaft Versuch Reaktor  
bbls/d – barrels (42 gallons)/day  
BISO – Buffered isotropic pyrolytic carbon fuel particle  
BTU – British Thermal Unit  
C-C – Carbon-Carbon  
CEGB – Central Electricity Generating Board  
CTL– Coal To Liquids  
EdF – Electricite de France  
FSV – Fort Saint Vrain  
FT – Fischer-Tropsch process  
GA – General Atomics company  
GIF – Generation IV International Forum  
GWe – Gigawatt (electric)  
HTE – High Temperature Electrolysis  
HTR – High Temperature Reactor  
HTR 10 – High Temperature Reactor – 10 MWe  
HTR PM – High Temperature Reactor – Prototype Modular  
HTTR – High Temperature Test Reactor  
M – Thousand (common terminology in petroleum industry)  
MM – Million (common terminology in petroleum industry)  
MTs/y – Metric Tonnes per year  
MWe – Megawatt (electric)  
MWt – Megawatt (thermal)  
NGCC – Natural Gas fired Combined Cycle  
NGNP – Next Generation Nuclear Project  
OECD – Organization for Economic Co-operation and Development  
PBMR – Pebble Bed Modular Reactor  
QUAD – Quadrillion BTU  
RCCS – Reactor Cavity Cooling System  
RPV – Reactor Pressure Vessel  
SiC-SiC – Silicon Carbide-Silicon Carbide  
SMR – Steam Methane Reforming  
TCF – Trillion Cubic Feet  
THTR – The Thorium High Temperature Reactor  
TRISO – Tri-structural-isotropic fuel  
UKAEA – United Kingdom Atomic Energy Agency  
USAEC – United States Atomic Energy Commission  
VHTR – Very High Temperature Reactor

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