High Temperature Reactors (VHTR & GFR)

F. Carré[(1)], T.J. O'Connor[(2)] and P. Anzieu[(3)]

(1) Frank Carré – Commissariat à l'énergie atomique (*franck.carre@cea.fr*)
(2) Thomas J. O'Connor – U.S. Department of Energy – (*tom.oconnor@nuclear.energy.gov*)
(3) Pascal Anzieu – Commissariat à l'énergie atomique (*pascal.anzieu@cea.fr*)

I. INTRODUCTION

Assets of high temperature reactors include both potentialities of producing electricity with high conversion efficiency and supplying process heat above 600°C which put them in a position to supplement light water reactors for displacing fossil fuels in a wide range of applications. They may indeed cogenerate steam, hydrogen and heat for varied industrial sectors such as oil industry (refinery, synthetic transportation fuels…), chemistry and steelmaking. Owing to growing concerns about climate change high temperature reactors (HTRs) that led to prototype reactors from the 1960s through the 1980s currently experience a revival of interest in the form of new projects of reactors by 2015-25 and cooperative R&D for a *Very High Temperature Reactor (VHTR)* that materializes a long term vision of this reactor type in the Generation IV International Forum. New builds are planned in China, South-Africa and the United-States with the aim of testing modern technologies for high temperature reactors and demonstrating non conventional nuclear applications at pre-industrial stage. Multinational cooperation in the Forum complements national R&D efforts for these projects of reactor at 700-850°C and also develops technology break-throughs for the VHTR aiming at 900-1 000°C. All active members of the Forum currently contribute to the development of VHTR technologies. The renewed interest in the *Gas-cooled Fast Reactor (GFR)* stems from its dual assets of being both an alternative type of fast neutron reactor avoiding critical issues associated with liquid metals, and a vision of highly sustainable high temperature reactor enabling a durable production of varied energy products. Both types of gas-cooled reactors complement each others as the VHTR is a stepping stone towards the GFR which in turn opens up more durable prospects for VHTR specific missions. GFR specific R&D that is currently conducted by five members of the Forum focuses on ceramic clad carbide fuels, design studies and safety analyzes, and results obtained so far have established confidence in the feasibility and potential performances of this type of reactor.

Both types of gas-cooled reactors call for synergistic R&D on heat resisting materials, helium systems' technology and power conversion systems which are addressed in the Forum as cross-cutting R&D projects. Pre-conceptual studies of an experimental GFR supplement current R&D work to prepare a possible decision of build in the next decade. Among the six Generation IV systems the VHTR and the GFR constitute a consistent and versatile set of reactors with high potential which arouses a growing interest as the Forum expands.

II. PAST EXPERIENCE ON HTRs AND GFRs

Five experimental and prototype high temperature reactors were built and operated from the 1960s through the 1980s in the United-States and Europe with block-type and pebble bed core designs respectively: *DRAGON (20 MW_{th})* in the UK, *Peach Bottom (40 MW_e) and Fort-Saint-Vrain (330 MW_{th})* in the US, *and AVR*

(15 MW_e) and THTR (300 MW_e) in Germany. They demonstrated the technical viability of this reactor type but could not prove their economic competitiveness with light water reactors for electricity production. No further developments were to occur until the late 1990s when the interest in HTRs was revived by needs of low carbon high temperature heat supply for varied industrial processes.

Projects of gas cooled fast reactors also existed from the 1960s through the 1980s as an alternative to sodium cooled fast reactors that would avoid complex liquid metal coolant technology but no prototype was ever built as the slow development of nuclear energy postponed the need for fast neutron reactors and the safety of these early gas fast reactors was challenged by the use of conventional steel clad fuel and the desire for high power density for short doubling times. The Gas-Cooled Fast breeder Reactor program (GCFR) led by General Atomics in the United States has probably been the most active initiative in this direction. These developments came to an end in the late 1980s and were revived in 2001 with a new vision of Gas-cooled Fast Reactors (GFR) within the framework of the Generation IV International Forum.

III. TODAY'S CONTEXT

III-A – Current Experimental High Temperature Reactors

First, the Japan Atomic Energy Agency (JAEA) built a research reactor in Oarai, the High Temperature engineering Test Reactor (HTTR) that was put in service in 1998 and reached its full design power of 30 MW_{th} in 1999 with an outlet helium temperature of 850°C. Subsequent tests have demonstrated the safe behavior of the reactor in various accidental sequences and the successful operation at the design temperature of 950°C. The HTTR restarted in 2009 after 18 months at shutdown. It will proceed with a continuous operation at 950°C for 60 days. In parallel with tests on the HTTR, JAEA is developing the sulfur-iodine thermo-chemical process to produce hydrogen. A first demonstration of this process was achieved in 2003 when a continuous production of 30 litres of hydrogen per hour was obtained for a few days. The next steps are tests of a pilot plant of 400 kW (30 m^3/hr) around 2012 and tests of nuclear production coupled to the HTTR at pre-industrial scale (10 MW and 1 000 m^3/hr) around 2015-2020.

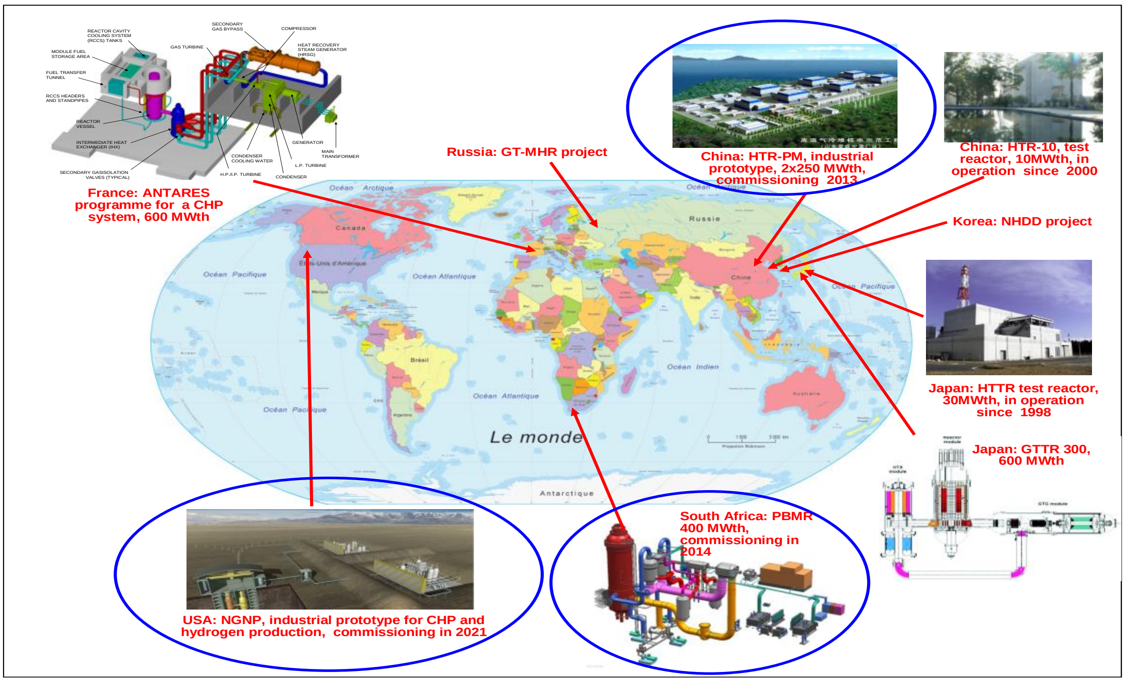

Figure 1: Status of HTR development in the world

Then, Institute of Nuclear and New Energy Technology (INET) of Tsinghua University in China built the experimental reactor HTR-10 (10 MW_{th}) that was put in operation in 2000. The successful operation of this reactor demonstrated an updated pebble bed core HTR technology and paved the way for scaling up this technology into the HTR-PM[1] project in China.

Currently, the revival of interest in high temperature process heat applications fostered R&D and projects of new builds of HTRs in the world for the period 2015-2025 (Figure 1) thus preparing the advent of a new generation of this reactor type (*the Very High Temperature Reactor (VHTR)*) and its varied applications: electricity first and process heat in a second stage, or dedication to hydrogen production

III-B – Ongoing High Temperature Reactors International Projects

The interest and support of end user industries is sought to create private/public partnerships to build and operate such prototypes and proceed with demonstrations relevant to their industrial needs. Industrial sectors concerned include the oil industry (extraction & treatment of oil sands, production of synthetic fuels from coal & biomass), as well as chemical and steel industries.

In 2005, **China** announced its intention to scale up the HTR-10 technology and to realise a national project of 200 MW_e commercial plant with independent intellectual property rights. This project consists in two High Temperature Reactor-Pebble Bed Modules (HTR-PM) [1] of 250 MW_{th} with a helium core outlet temperature of 750°C that drive together a steam turbine of 200 MW_e. The construction has begun in 2009 on the site of the Shidaowan plant in the Province of Shandong with a commissioning planned in 2013. The reactor is designed to ultimately achieve a core outlet temperature of 950°C with current core design and fuel element technologies. Besides, the modular nature of the HTR-PM makes it possible to replace the steam turbine of the power conversion system by a helium turbine or a super critical steam turbine, as well as by a hydrogen production plant in a second stage.

In the **Republic of South Africa**, the Pebble Bed Modular Reactor Pty. Ltd (PBMR) [2] is a public-private partnership that was established in 1999 to initiate the development of a modular pebble-bed reactor with a rated capacity of 165 MW_e. In 2009 the PBMR project had its business re-oriented towards the supply of industrial process heat. Thus, PBMR Ltd started developing options for commercial fleets with Sasol for producing synthetic fuels from coal, with Eskom for electricity, as well as with US and Canadian cogeneration end users including oil sand producers. The PBMR project was accordingly revisited as a cogeneration steam plant with a thermal power of 200 MW_{th}, a helium temperature of 750°C at core outlet and a steam generator directly placed in the primary loop.

In the **United States**, the *Next Generation Nuclear Plant* (*NGNP*) [3] project was mandated by the US Energy Policy Act of August 8, 2005 as a high-temperature gas-cooled reactor intended for high-efficiency electricity production, high-temperature process heat generation, and nuclear-assisted hydrogen production at the Idaho National Laboratory (INL). It would be co-located with an industrial plant that would use process heat from the reactor and could operate in 2021. Pre-conceptual and conceptual design studies concluded that there are no discriminating technical factors that favor pebble bed or prismatic design over another and that the initial gas outlet temperature will be in the 750-800°C range to meet most users' needs. The NGNP project took another step in August 2008 when the US-DOE and the NRC submitted a joint licensing plan leading to a license application filed in 2013. DOE is currently developing a final strategy for partnering with the industry (nuclear vendors and potential users of process heat in sectors such as oil-, chemistry or steelmaking) to drive the development of the NGNP project.

In **Japan**, the Japan Atomic Energy Agency (JAEA) is currently conducting research and development for the project of "*Gas Turbine High Temperature Reactor 300 – Cogeneration*" (*GTHTR300C*) [4] that is dedicated to CO_2 emission free cogeneration of electricity and hydrogen by sulfur-iodine thermo-chemical water splitting process. With a thermal power of 600 MW and a block-type core with an exit temperature of 950°C, the GTHTR300C is believed to be highly efficient and economically competitive for cogenerated hydrogen and electricity.

In the **Republic of Korea**, the context of wilful development of hydrogen technologies to prepare the hydrogen economy led the Korean Atomic Energy Commission to approve in Dec.'08 a national program on key technologies development for nuclear hydrogen and a project of Nuclear Hydrogen Development and Demonstration (NHDD) [5] This project aims at designing and constructing a nuclear hydrogen production system, as well as demonstrating its safe and reliable operation. The project is expected to be launched in 2010 with target dates of 2022 for the completion of construction and 2026 for prototypical demonstrations.

In **Europe**, a partnership of European nuclear industrial and research organisations for developing HTR technologies has been established with the creation in 2000 of the (European) "HTR Technology Network" (HTR-TN). HTR-TN has played since then a prominent role in defining a strategy for European R&D on HTRs and implementing this strategy in Euratom Framework Programmes (FP) since 2000 (5^{th} FP). This led to revive in the 6^{th} FP (2002-06) the past experience in Europe on HTR design tools and technologies (fuel, materials, helium systems' technology, coupling technologies…) in a program called RAPHAEL. This set the stage for Euratom to bring consistent contributions to VHTR R&D Projects in the Generation IV International Forum and for approaching industrial sectors potentially interested in low-carbon process heat. However, marketing prospects of high temperature nuclear heat are still too uncertain for stakeholders of the nuclear industry and potential users of HTR energy products to envision yet building a prototype of next generation HTR in Europe.

In parallel the 6^{th} FP also established a cooperative framework in Europe on Gas-cooled Fast Reactors through the action GCFR and its successor GoFastR in the 7^{th} FP. This created a community that supports a project of experimental prototype of *Gas Fast Reactor* as an option to be documented for decision by 2012 to advance alternative fast reactor types in parallel to a prototype of new generation sodium fast reactor planned for 2020 within a European Technology Platform on "Sustainable Nuclear Energy" (SNE-TP) [6] launched in 2007.

IV. CURRENT GIF ACTIVITIES ON VERY HIGH TEMPERATURE REACTORS (VHTRs)

The potential of a VHTR at 900-1 000°C to match temperature requirements for advanced hydrogen production processes based on electro- or thermo-chemical water splitting processes was the initial driver for selecting this reactor type in 2002 among the six Generation IV Systems. Missions of the VHTR have expanded since then to cogeneration of electricity and process heat for varied industrial applications. [7] This system experiences a sustained interest from all active members of the GIF since its beginning. The VHTR System Arrangement was signed in December 2006 by Canada, Euratom, France, Japan, the Republic of Korea, Switzerland and the United-States. The People's Republic of China signed this Arrangement in October 2008. Multinational cooperation in the GIF complements national R&D efforts for current projects of reactor at 700-850°C and also develops technology breakthroughs for the VHTR aiming at 900-1 000°C. R&D Projects on "Fuel and fuel cycle" and "Hydrogen production" became effective in January and March 2008 and a project on "Materials" has become effective in the fall of 2009. A project on "Computational methods, validation and benchmarking" will be ready for signature in early 2010.

Specific Agreements will be worked out to frame exchanges between cooperative R&D in the GIF and VHTR related projects so as to assure a fair treatment of R&D results generated by GIF members and their privileged access to operating parameters of prototype reactors in fair conditions.

IV-A – Fuel Fabrication and Qualification

Cooperative work on TRISO fuel includes sharing irradiation experiments, characterization methods and facilities as well as constituent materials properties. Besides, research is also conducted on advanced fuel particles such as UCO fuel and ZrC coated particles. GIF contributes to sharing the effort to reacquire the mastery of standard TRISO coated fuel particles fabrication and qualification. Figure 2 shows the laboratory-scale line CAPRI that was put in operation in 2005 on the CEA site of Cadarache as part of the effort to revive HTR technologies in France.

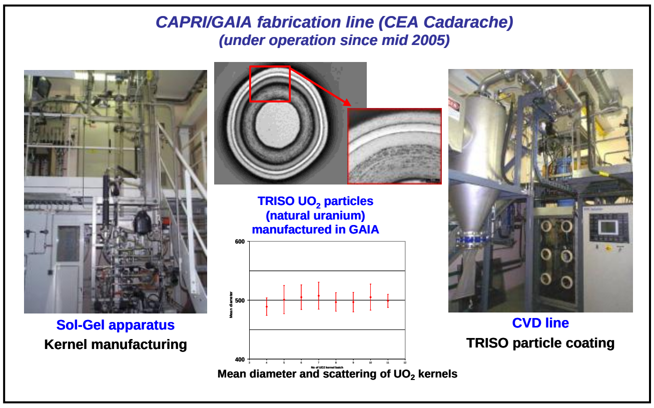

Figure 2: CAPRI/GAÏA fabrication line of fuel particles (CEA-Cadarache)

The cooperation within the GIF takes an especially active part in sharing irradiation services for TRISO fuel. Within this framework, an invitation was extended by the United States to France and the Republic of South Africa to join with their own samples the American TRISO particles test program AGR2 in the Advanced Test Reactor (ATR) that will begin in early 2010. The cooperation is also active on characterization methods to check and improve the fabrication quality of TRISO particles first at laboratory-scale and then at industrial scale.

The management of spent TRISO fuel particles and that of used graphite are also parts of the cooperative work within the GIF. Acoustic waves and pulsed currents de-structuring methods are tested on dummy coated particles to retrieve nuclear materials from the kernel for recycling and package coatings as ultimate waste. The same de-structuring methods are also tested on graphite as a first step for processing used graphite and partitioning ^{14}C for disposal. These issues are also addressed at the European level in the 7th Framework Program in a research program (CARBOWASTE) dedicated to best practices for retrieval, treatment and disposal of used graphite and other carbonaceous forms.

IV-B – Materials and Components

Cooperative development of materials covers graphite, advanced super-alloys (nickel-based and 9Cr ferritic steels) and composite ceramics. It aims at screening and qualifying structural materials for key components of VHTRs and particularly high temperature heat exchangers. The experimental work is defined in common and shared among participating GIF members. Mechanical and corrosion tests are conducted to screen candidate materials and to acquire data needed for extending current design codification rules in VHTR service conditions and for licensing prototype reactors of this type. Results are compiled in a common data base operated by the Oak Ridge National Laboratory.

The 9Cr1Mo alloy is currently characterized as promising candidate for a hot reactor pressure vessel operating at 400-450°C (*i.e.* beyond limits of the SA 508 steel commonly used in PWRs). Besides, two conventional nickel-base alloys (617 and 230) are currently characterized at temperatures ranging from 700°C to 1 000°C in terms of mechanical properties and corrosion resistance for use as structural material, especially for the intermediate heat exchanger.

An example of shared experimental work that consisted in coordinating irradiation tests of various grades of graphite at different temperatures is shown on Figure 3. It contributed to significantly accelerate the characterization of candidate grades of graphite in relevant service conditions for use in block-type or pebble-type HTR cores.

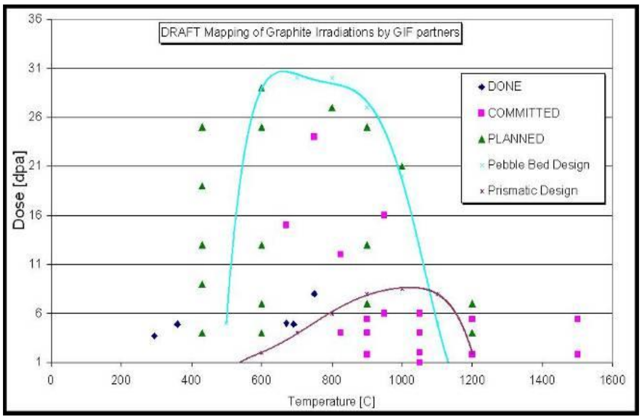

Figure 3: Test matrix (dose, temperature) of graphite samples for use in block-type or pebble type HTR cores

Components such as compact heat exchangers, as well as associated manufacturing technologies and tests of mock-ups on helium loops are currently conducted on a national basis and have not given rise to cooperative work so far.

IV-C – Hydrogen Production

Cooperation on hydrogen production processes includes:

- Sharing basic R&D to establish optimized flow-sheets and update assessments of technical/economic performances
- Sharing laboratory scale experiments to demonstrate key features for the feasibility and performance of water splitting processes (high temperature steam electrolysis, sulfur-iodine thermochemical cycle, and hybrid sulfur cycle)
- Investigating and developing technologies to couple the reactor and the hydrogen production process
- Establishing common plans for next step experiments in the range of 0.5 – 1 MW as well as for pre-industrial demonstrations with the HTTR (~2015) and near term HTR projects in the 2020s.

GIF cooperative framework contributed to share the realization and results of laboratory scale experiments on the sulfur-iodine and high temperature electrolysis, to advance the development of catalysts and to share results of technical and economic assessments of varied candidate water splitting processes. An example of shared experimental work consisted in an Integrated Laboratory Scale experiment of the sulphur-iodine thermochemical process that was jointly constructed and operated by CEA, Sandia National Laboratories and General Atomics in 2007-2008 on the site of the latter in San Diego. This experiment, that was designed for a production rate of 100 l/hour confirmed the difficulty to manage iodine in chemical processes, even at laboratory scale, and contributed together with economic analyses to orient priority research of some GIF members towards high temperature steam electrolysis.

IV-D – Computer Code for Design Studies

Cooperative work on computational methods, validation and benchmarks includes:

- Sharing analyses of key aspects of VHTR designs that call for priority improvements in modelling and simulation methods (PIRT analysis)
- Comparing computational methods for predicting VHTR key design and operating parameters
- Sharing experimental results to qualify computational methods in use for national VHTR-related projects.

V. CURRENT GIF ACTIVITIES ON GAS FAST REACTORS (GFRs)

The renewed interest in gas-cooled fast reactors stems from their potential for being both:

- A real alternative to sodium cooled systems as an attractive fast reactor concept featuring a good breeding capability and high plant efficiency owing to the low neutron absorption and high temperature capability of helium as a coolant, and

- A sustainable high temperature reactor for a durable cogeneration of non-electricity energy products.

Gas as coolant implies a poor thermal inertia and a reduced heat transfer capability, which both call for heat resisting fuel forms (ceramic clad) and redundant/diversified systems to safely manage cooling accidents. In return, helium exhibits definite advantages such as single phase cooling in all situations, chemical inertness, transparency to neutrons (hence a reactivity effect of coolant void <1$), optical transparency likely to facilitate in service inspection, maintenance and repair…

GFR studies that were launched in 2001 within the framework of the Generation IV International Forum led to defining in 2005 a ~1 100 MW_e reference concept with a core outlet temperature of 850°C as a result of active international cooperation with major inputs from both JAEA and USDOE-ANL. As planned in the GIF roadmap of the GFR, results of conceptual studies and operating transient analyzes were compiled in a pre-feasibility report [8] at the end of 2007 and presented in an international seminar hosted on February 5-6, 2008 in Paris. These results globally established confidence in the feasibility and safety of the considered GFR baseline concept. Furthermore they identified priority R&D to support further feasibility demonstrations and update the baseline concept by 2012 with innovative design features such as pin-type fuel and a pre-stressed concrete pressure vessel for improved performance. This milestone is essential as it coincides with the end of the GFR viability phase, with the issue of a final viability report, and with decisions about detailed studies for construction of a 50-100 MW_{th} experimental GFR (project "Allegro").

V-A– Fuel and Core Design

Heat resisting fuel forms constitute the key feasibility issue of GFR's feasibility and performance. Requirements that were considered at first to assure a safe management of most severe cooling accidents include keeping sufficient cladding integrity to contain fission products up to 1 600°C, and preserving the geometry of the fuel element up to 2 000°C. Plate or pin shaped carbide fuels with SiC-SiC_{fibers} composite cladding have been the subject of modelling and laboratory-scale R&D since 2001. The main focus was first put on plate fuel (Figure 4) that was selected as reference for the GFR baseline concept documented in 2007. Current plans include testing plate fuel to advance feasibility demonstrations of the base line concept, and shifting the main focus of R&D to pin fuel with multilayer composite cladding and compliant thermal joints between fuel pellet and cladding.

Carbide fuel (U, Pu)C or (U, Pu, MA)C with minor actinides is taken as reference fuel for its high heavy atom content and good thermal conductivity that feature excellent neutronic properties *(core critical size, breeding)* and moderate normal operating temperature (~1 100°C at 100 MW/m^3 average core power density *vs* a melting temperature above 2 350°C). Zirconium silicide (Zr_3Si_2) is identified as promising material for the neutron reflector.

The collaboration within the GIF is essential to share developmental work on advanced composite forms considered as fuel cladding and other core structural materials for the GFR. This work benefits from synergies with the development of ceramics for fusion reactors' first wall and blanket.

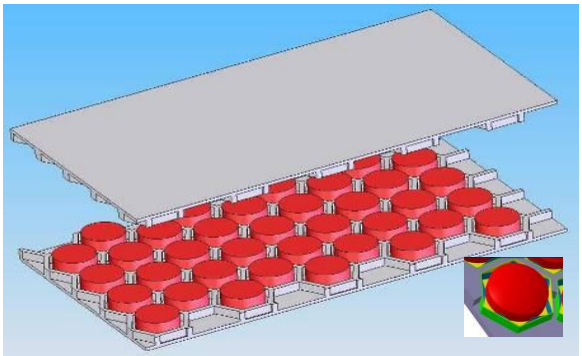

Figure 4: GFR plate fuel design, cell details (fuel pellet in red, clad in grey, leak-tight barrier in yellow/green)

Fuel plates are fitted in hexagonal wrapper tubes (as in sodium-cooled fast reactors) that constitute robust fuel subassemblies and thus assure core stability and mechanical equilibrium (Figure 5). A first design of the fuel subassembly was performed with available thermal-mechanical models so as to minimize the volume fraction of structural materials and keep acceptable stress levels.

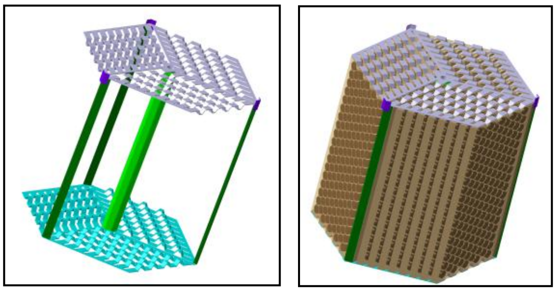

Figure 5: Basket, basket filled with plates.

A first demonstration of fuel viability will be achieved by the end of 2012 though a variety of irradiation tests including FUTURIX-MI (inert materials) and FUTURIX-CONCEPTS (fuel concepts) in PHENIX and IRRDEMO (plate and pin prototype fuel elements) in BR2 (SCK-Mol).

V-B– Core and System Design

The current core design features a plutonium hold-up of ~10 t/GW$_e$ that is comparable with the performance of sodium cooled reactors and fairly acceptable for an industrial deployment in a fleet of reactors. At equilibrium, the core achieves breeding without blankets, the fraction of minor actinides in the core reaches 1.1% and reactivity coefficients are quite satisfactory to provide sound reactivity feed-back effects for safety: the effect of helium depressurization is less than the delayed neutron fraction (<1$), the Doppler coefficient is larger than in SFRs – owing to a softer spectrum in GFRs – thus resulting in a markedly stabilizing effect.

The reference version of the Gas-cooled Fast Reactor that was selected in 2007 by GIF participants in the GFR system features a 2 400 MW$_{th}$ (~1 100 MW$_e$) reactor with three primary cooling loops (800 MW$_{th}$ each) indirectly coupled to a power conversion system using a combined cycle composed of three gas turbines and one steam turbine. In a first approach, the same reactor pressure vessel as that considered for the GT-MHR (Gas-Turbine Modular Helium-cooled reactor) was taken for the GFR assuming that associated manufacturing and other issues had been investigated and resolved (forging, welding, transport…). The primary system is illustrated on Figure 6.

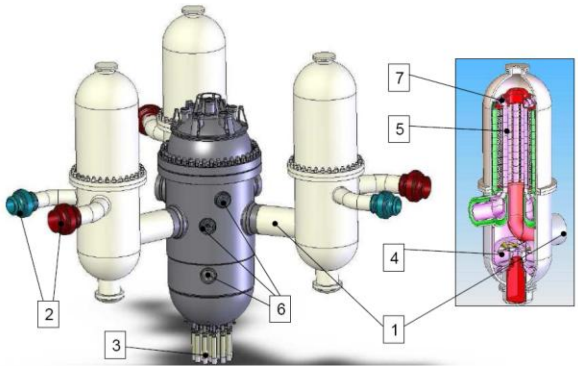

Figure 6: GFR reactor pressure vessel and IHX vessels (and exploded view of one IHX – blower unit)

Key

1. *Primary cross-duct*
2. *Secondary pipes with isolating valves*
3. *Control Rod Drive Mechanisms*
4. *Primary blower and associated motor*
5. *Compact Heat Exchanger modules*
6. *Pipe connections for Decay Heat Removal systems*
7. *Primary isolation valve*

Each of the three cooling loops is fitted with a 800 MW$_{th}$ IHX-blower unit enclosed in a single vessel (indirect cycle). Intermediate heat exchangers are mounted above the core to ease natural circulation of flow across the core. GFR cooling systems design studies strive to take maximum benefit from relevant technology developments that are currently performed for the VHTR, especially for advanced gas/gas intermediate heat exchangers. The secondary side of the IHX that is connected to the power conversion system uses a mixture of helium and nitrogen at 6.5 MPa as working fluid (Figure 7).

Electrical power is generated by the three gas turbines (3 x 130 MW$_e$) and the unique steam turbine (730 MW_e) thus achieving an efficiency close to 45% with an inlet core temperature of 400°C. This performance can be further improved while optimizing component efficiencies and pressure drops.

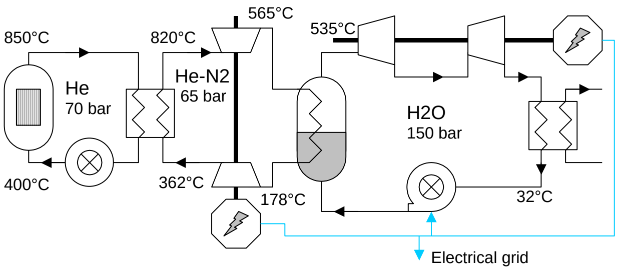

Figure 7: Indirect combined cycle – Arrangement of power conversion system

V-C– Decay Heat Removal Strategy and Safety Systems

Owing to the low thermal inertia of the GFR core, an efficient and reliable Decay Heat Removal (DHR) strategy is of utmost importance to assure a robust management of cooling accidents, including fast reactor blow-down. The cooling strategy assumed in GFR's reference-2007 design relies on assuring a gas flow across the core by forced convection in the short term and by natural convection at a back-up pressure of 0.4 – 1 MPa typically one day after the accident (and before in most accidental situations). [9, 10] The back-up pressure is maintained by a guard containment that encloses the primary system. Gas injection from pressurized nitrogen tanks complement a diversified set of cooling loops designed to operate over the whole pressure range from nominal to back-up. Figure 8 shows the lay-out of the various DHR systems (normal and back-up) as well as their integration in the guard containment vessel and the containment building.

A preliminary safety analysis of the current GFR with DHR systems design shows that decay power can be removed reliably with moderate pumping power and/or natural convection in any postulated accident including large breaks with multiple additional failures (with the addition of nitrogen injection for some of the most severe loss of coolant accidents). Typical pumping power needs (a few 100s KW_e) may be supplied by batteries.

Figure 8: Schematics of varied DHR systems (normal and backup) and their integration in the guard containment vessel and containment building.

Current GFR design studies are supplemented by pre-conceptual studies of a 50-100 MW_{th} experimental facility that could demonstrate in the 2020s GFR key technologies and operating principles, and provide multipurpose fast spectrum irradiation services (project "Allegro").

VI. FUTURE PROSPECTS

As evidenced by large national projects of prototype gas-cooled reactors such as HTR-PM in China, PBMR in the Republic of South Africa and the NGNP in the United States, today's concerns of energy security and climate change open up renewed perspectives for high temperature gas-cooled reactors and for demonstrations of nuclear cogeneration of non-electricity energy products. This, together with the fact that all active GIF members contribute to R&D on VHTRs, acknowledges the potential of this reactor type to displace fossil fuels in varied applications such as producing electricity, non-conventional hydrocarbon fuels from coal or biomass, and process heat for energy intensive industries (oil refining, oil-sand recovery, petro-chemistry, chemistry, steelmaking…). Current prospects of carbon taxes and rising oil prices favour potential applications of high temperature reactors.

Besides, the support brought by a subset of GIF members to a renewed vision of the Gas-cooled Fast Reactor with very high temperature resisting fuel forms acknowledge the potential of this reactor type to be a real alternative to sodium cooled fast reactors with good performances and safety features in spite of a less efficient coolant than liquid metal. It also acknowledges the potential of this reactor type to more sustainably achieve VHTRs' high temperature applications owing to the better utilization of uranium afforded by fast neutrons.

Among the six Generation IV systems the VHTR and the GFR constitute a consistent and versatile set of reactors with high potential which arouses a growing interest as the GIF expands. The VHTR acts as a stepping stone towards the GFR (by supporting the development of cooling and conversion system technologies for both reactors), and the GFR opens up more durable prospects for VHTR specific missions.

Cooperative research projects in the Generation IV International Forum and the European Sustainable Nuclear Energy Platform supplement national programs to develop both types of gas-cooled reactors. They speed-up the development of key technologies (very high temperature technologies, refractory fuels, advanced conversion systems…), they spur the interest of process heat using industries in high temperature reactors, and they favour the creation of consortiums with the industry interested in building prototypes as public/private endeavours.

Gas-cooled reactors currently encounter less support in Europe than they do in other parts of the world and various initiatives within the European Technology Platform SNE-TP aim at strengthening research on these reactor types and fostering decisions on a VHTR prototype for demonstrations of cogeneration, as well as promoting a 50-100 MW_{th} experimental facility supporting GFR's demonstration needs and multipurpose fast spectrum irradiation services (project "Allegro").

Beyond being essential for sharing costs of R&D and prototypes, the development of strong frameworks of multilateral cooperation will also be essential to support the development of harmonized international standards that would apply to future nuclear systems in terms of safety, design rules, physical protection and non-proliferation.

Acknowledgements

Authors acknowledge the inputs from members of both GIF's VHTR and GFR Steering Committees to this review paper of international R&D on High Temperature Reactors.

Nomenclature

AEC – Atomic Energy Commission
AVR – Arbeitsgemeinschaft Versuch Reaktor
CEA – Commissariat à l'énergie atomique
FP6, FP7 – 6th, 7th European R&D Framework Programme
GIF – Generation IV International Forum
GT-MHR – Gas Turbine Modular Helium-cooled Reactor
HTR – High Temperature Reactor
HTR-10 – High Temperature Test Reactor (10 MW_e)
HTR-PM – High Temperature Reactor – Prototype Modular
HTR-TN – High Temperature Reactor Technology Network
HTTR – High Temperature Test engineering Reactor
IHX – Intermediate Heat eXchanger
INET – Institute of Nuclear and New Energy Technology
INL – Idaho National Laboratory
JAEA – Japan Atomic Energy Agency
KAERI – Korea Atomic Energy Research Institute
MHTGR – Modular High Temperature Gas-cooled Reactor
MW_e – Megawatt (electric)
MW_{th} – Megawatt (thermal)
NGNP – Next Generation Nuclear Project
NHDD – Nuclear Hydrogen Development and Demonstration
NRC – Nuclear Regulatory Commission
PBMR – Pebble Bed Modular Reactor
PIRT – Phenomena Identification and Ranking Table
R&D – Research and Development
SNE-TP – European Sustainable Nuclear Energy Technology Platform
THTR – Thorium High Temperature Reactor
TRISO – Tri-Structural Isotropic Fuel
US-DOE – Department Of Energy of the United-States
VHTR – Very High Temperature Reactor

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