The High Temperature Gas-Cooled Reactor

Michael A Fütterer[a], **Gerhard Strydom**[b], **Hiroyuki Sato**[c], **Fu Li**[d], **Eric Abonneau**[e], **Tim Abram**[f], **Mike W Davies**[g], **Minwhan Kim**[h], **Lyndon Edwards**[i], **Ondrej Muransky**[i], **Manuel A Pouchon**[j], **and Metin Yetisir**[k], [a]European Commission, Joint Research Centre, Petten, The Netherlands; [b]Idaho National Laboratory, Idaho Falls, ID, United States; [c]Japan Atomic Energy Agency, Ibaraki, Japan; [d]INET, Tsinghua University, Beijing, China; [e]Commissariat à l'Energie Atomique et aux Energies Alternatives, Paris, France; [f]Manchester University, Manchester, United Kingdom; [g]Jacobs Clean Energy Limited, Knutsford, Cheshire, United Kingdom; [h]Korea Atomic Energy Research Institute, Daejeon, South Korea; [i]Australian Nuclear Science and Technology Organisation, Lucas Heights, Australia; [j]Paul Scherrer Institut, Villigen, Switzerland; [k]Canadian Nuclear Laboratories, Chalk River, ON, Canada

Glossary

AGR Advanced Gas-cooled Reactor
AVR Arbeitsgemeinschaft Versuchsreaktor
BISO Bi-Structural Isotropic Fuel
GCR Gas-Cooled Reactor
GIF Generation IV International Forum
GT-MHR Gas Turbine Modular Helium-cooled Reactor
HTGR High Temperature Gas-Cooled Reactor
HTR High Temperature Gas-Cooled Reactor
HTR-10 10 MW High Temperature Reactor
HTR-PM High Temperature Reactor – Pebble-bed Module
HTTR High Temperature engineering Test Reactor
HWR Heavy Water Reactor
INET Institute of Nuclear and New Energy Technology (Tsinghua University, Beijing)
JAEA Japan Atomic Energy Agency
LANL Los Alamos National Laboratory
LWR Light Water Reactor
MWe Megawatt electric
MWth Megawatt thermal
NGNP Next Generation Nuclear Plant
ORNL Oak Ridge National Laboratory
PBMR Pebble Bed Modular Reactor
R&D Research and Development
S-I Sulfur-Iodine thermochemical process for hydrogen production
SFBR Sodium-cooled Fast Breeder Reactor
THTR Thorium High Temperature Reactor
TRISO Tri-Structural Isotropic Fuel
VHTR Very High Temperature Reactor

What is a high temperature gas-cooled reactor?

High Temperature Gas-cooled Reactors (HTR or HTGR) are helium-cooled graphite-moderated nuclear fission reactors utilizing fully ceramic fuel. They are characterized by inherent safety features, excellent fission product retention in the fuel, and high temperature operation suitable for the delivery of industrial process heat, in particular hydrogen production. Typical coolant outlet temperatures range between 750 °C and 850 °C, thus enabling power conversion efficiencies up to 48%.

The Very High Temperature Reactor (VHTR) is a longer term evolution of the HTR targeting even higher efficiency and more versatile use by further increasing the helium outlet temperature to 950 °C or even higher (Gougar, 2011).

From groundbreaking technology. . .

The HTR has evolved from the early gas-cooled reactors (GCRs) that gained widespread popularity for their simplicity and high power conversion efficiencies (Beech and May, 1999). The first commercial nuclear power plant was a CO_2-cooled graphite-moderated Magnox reactor (Calder Hall in 1956). In total, 26 Magnox reactors were built (270–1760 MWth), with the last one (Wylfa-1, 1971–2015) shut down at the end of 2015. As a second generation, 14 Advanced Gas-Cooled Reactors (AGRs) were deployed in seven nuclear power plants at six sites in the UK with a total capacity of approx. 8 GWe. All these AGRs are expected to remain in operation until 2023–30, although their life extension required clearance of graphite cracking issues and two power plants have to run at lower power because of the observation of cracks in boilers. This multi-decade effort in the development and operation of gas-cooled reactors allowed for collection of a considerable technical background and operational experience, which then served as the basis for the development of current HTRs. GCRs have an extremely clean primary cooling circuit (few radiological and chemical contaminants) and use a conventional steam cycle ($\sim$ 540 °C, same as for coal fired power plants) resulting in high thermal efficiencies ($>$ 40%). However, GCRs had to observe a temperature limitation due to the dissociation of CO_2 and the resulting carburization of structural materials and oxidation of graphite at elevated temperatures. Modern HTR are characterized by increased operating temperature and thermal efficiency, which could be achieved by two major changes: the designs adopted helium as the cooling gas along with fully ceramic fuel, which is discussed in more detail in Section "TRISO fuel: Key to performance and safety."

The first HTR was proposed in a 1945 design study in the US, but was never realized. It featured a primary circuit (helium at 1.55 MPa, 438–732 °C) coupled to a secondary Brayton power conversion cycle (air at 2.9 MPa, 677–22 °C) leading to an expected power rating of 5 MWe.

In 1962–63, a 3.3 MWth Mobile Low-Power Reactor (ML-1) with 140 (330 nominal) kWe was built in the US with a closed-cycle nitrogen turbine. The project was not pursued because it could not fulfill the power output expectations.

In 1964, the Experimental Gas-Cooled Reactor (EGCR) was built at ORNL in the US, but not completed. This was basically a helium-cooled AGR-type reactor using stainless steel fuel rod clusters. EGCR was expected to produce 85 MWth/25 MWe with helium at 566 °C.

Ensuing developments led to conceptual changes in the existing gas-cooled reactors involving, as mentioned, in particular the use of helium instead of CO_2, and the substitution of metallic fuel clads by fully ceramic fuel, both in view of a further increase of reactor outlet temperature and improved safety performance.

The first tangible step in this direction was made in the UK with the DRAGON reactor (see also Section "Which HTR versions were developed?"). With a power of 21.5 MWth, it was an OECD project and operated from 1964 to 1975 primarily as a test bed for HTR fuel development. It used already early versions of fully ceramic coated particles as its own fuel.

In the US, the Ultra-High-Temperature Reactor Experiment (UHTREX) operated at LANL from 1966 to 1970. Its rated power was 3 MWth using helium at 3.4 MPa (870–1300 °C). It used extruded fuel with TRISO coated particles in an annular rotatable core for on-line refueling.

More details on the development of HTR technology can be found in a recent authoritative summary (Kugeler and Zhang, 2019; Tsvetkov, 2020).

. . . to modern characteristics

The following developments led to basic technical characteristics and design features shared by all modern HTR.

- can be built with passive safety features up to 625 MWth/core (prismatic block type core) and 250 MWth/core (pebble bed core); this is the power range of Small Modular Rectors (SMR);
- long grace time after an accident (large heat capacity, low power density);
- self-stabilization of power transients (negative temperature coefficient);
- low source terms (outstanding fission product retention in robust TRISO coated fuel particles and structures);
- fully ceramic core (fuel and moderator/reflector);
- high-purity graphite as moderator/reflector, high thermal inertia;
- chemically and neutronically inert helium as primary coolant;
- high operating temperatures for high efficiency, capability for nuclear cogeneration of heat and power, including for bulk hydrogen production;
- high burn-up capability;
- high fuel utilization (good neutron economy and possible use of thorium).

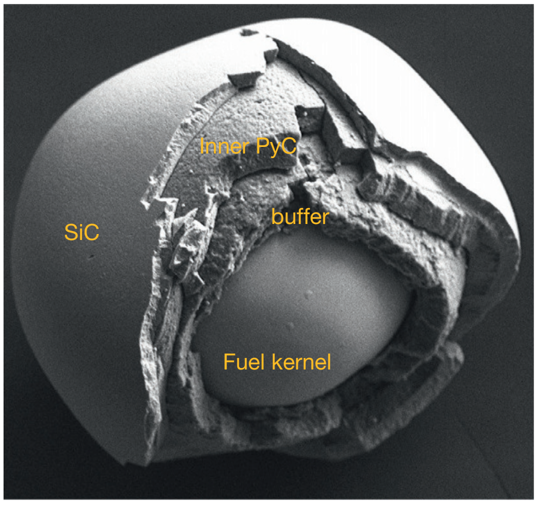

Fig. 1 SEM picture of a modern TRISO coated particle broken up to visualize the coatings; the top outer PyC layer is still missing on this particle.

There are two competing HTR designs based on the TRISO coated fuel particle (Fig. 1): the prismatic block core and the pebble bed core (Fig. 2).

- Invented by Peter Fortescue and his team at General Dynamics in the US, the prismatic block core is built from hexagonal graphite blocks containing vertical holes. Some of these holes are used for helium cooling, while others receive the fuel in the form of "compacts", which are little cylinders (typically ∅12.3 × 25 mm) pressed from graphite and coated fuel particles (Fortescue, 1975).
- The pebble bed HTR was conceived in 1942 by Farrington Daniels in the US (Daniels, 1944). This early vision was later developed to a power plant design by Rudolf Schulten in Germany, which employed ∅60 mm fuel spheres made of graphite and coated fuel particles (Schulten et al., 1959). These pebbles are filled into the reactor pressure vessel, which is internally lined with graphite blocks. The resulting pebble bed constitutes the reactor core. The pebble bed can flow and allows discharge and (re-)injection of pebbles during operation, enabling online refueling.

TRISO fuel: Key to performance and safety

One of the major challenges and key to achieving a fully ceramic reactor core was fuel development (IAEA, 2010). The initially used UO_2 or UC fuel was placed in ceramic clads which showed poor fission product retention. Coated particle fuel was invented

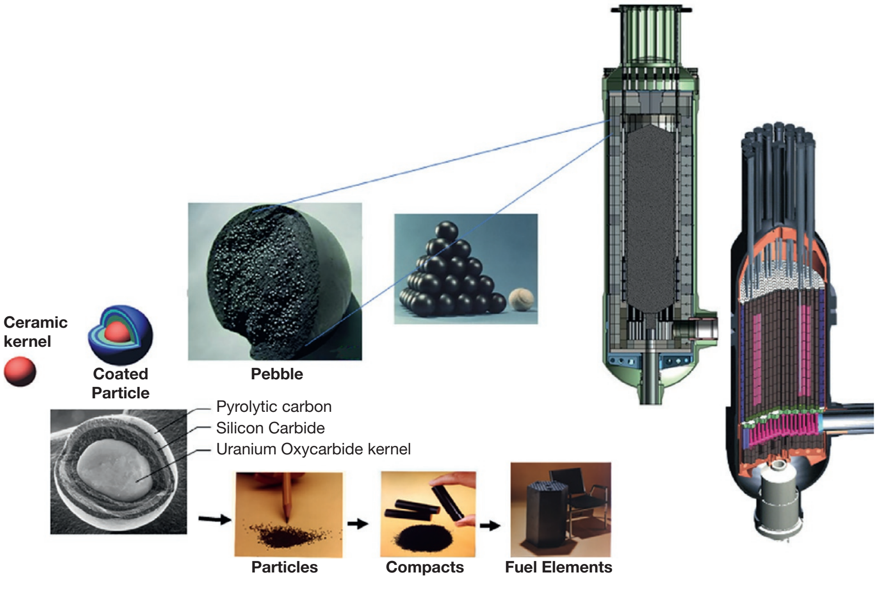

Fig. 2 TRISO coated particle fuel as the basis for hexagonal block and pebble bed core designs (Gougar et al., 2020).

between 1957 and 1961 by the United Kingdom Atomic Energy Authority (UKAEA) and Battelle, but no patent was granted at that time. The UO_2 fuel kernels were made by external gelation of uranyl nitrate in ammonia and, after a heat treatment, coatings were deposited on top of these kernels via pyrolysis of hydrocarbons in a fluidized bed. The next development step was the early BISO (bi-structural isotropic) particle fuel comprising a buffer layer directly deposited on the kernels and an additional pyrolytic carbon (PyC) layer on top. Finally, modern TRISO (tri-structural isotropic) particles were given an additional SiC diffusion barrier leading to confirmed fission product retention up to 1600 °C or even higher (Gougar et al., 2020). These TRISO coated particles, typically in the order of 1 mm in diameter, are the basis for all modern HTR fuel designs (Gerczak, 2020; Helmreich, 2020). As shown in Fig. 1, they feature (from inside out) the kernel, a porous PyC buffer to accommodate fuel swelling and fission gases, a dense PyC buffer and a dense SiC layer as diffusion barriers against fission product escape, and a final PyC layer (missing in Fig. 1) for better bonding with the matrix graphite into which they will be integrated.

Baked into matrix graphite, the TRISO coated particles can now be given a macroscopic shape (Fig. 2), usually in the form of thumb-thick cylinders ("compacts") either solid or annular, or in the form of spherical fuel elements ("pebbles"). The compacts are inserted into hexagonal blocks made of graphite, which are then assembled to constitute the reactor core contained in a pressure vessel.

Typical pebble and compact design characteristics are given in Table 1:

Which HTR versions were developed?

Based on these characteristics, in the 1960s two different types of reactors were designed and built, primarily to produce electricity. Experimental HTRs with a prismatic block core and TRISO coated particle fuel were developed in the UK (DRAGON reactor, operated 1964–1975, 21.5 MWth, an OECD project (Price, 2012) and in the US (Peach Bottom, operated 1966–1974, 115 MWth/40 MWe Beck and Pincock, 2011). They were followed by the prototype of the Fort St. Vrain Generating Station (operated 1976–1989, 842 MWth/330 MWe, Beck and Pincock, 2011). This reactor established the technical feasibility of HTRs although it experienced problems (Rempe, 2020) of power fluctuations, jamming of a control rod and leakage of moisture into the core, which finally caused its decommissioning for economic reasons.

Over the same period, Germany developed and built an experimental pebble bed reactor (AVR, 46 MWth/15 MWe, Pohl, 2008) at the Jülich Research Centre that successfully operated from 1967 to 1988 and produced valuable feedback on different types of pebble fuels and overall reactor operation. In particular, it was used for several demonstrations of passive safety performance. After a water ingress accident provoked by a steam generator leak it could be repaired, dried and returned to service. Following this experience, a 300 MWe prototype power reactor that aimed at using thorium fuel was built and operated: the Thorium High Temperature Reactor (THTR-300, 750 MWth/300 MWe, Baumer and Kalinowski, 1991; Dietrich et al., 2019). This prototype, however, met a number of technical difficulties. Examples of design issues are the direct insertion of the control rods in the pebble

Table 1 Typical examples for nominal characteristic data of German AVR GLE-4 particles and pebbles and US NGNP particles and compacts.

Coated particle	*AVR pebble*	*NGNP compact*
Kernel composition	UO_2	UCO
Kernel diameter [μm]	502	425
Enrichment [U-235 wt%]	16.76	14
Thickness of coatings [μm]:	92	100
buffer	40	40
inner PyC	35	35
SiC	40	40
outer PyC		
Particle diameter [μm]	916	855
Fuel element (FE)	*Pebble*	*Compact*
Dimensions [mm]	∅60 (spherical)	∅12.3 × 25 (cylindrical)
Heavy metal loading [g/FE]	6.0	1.27
U-235 content [g/FE]	1.00	0.18
Number of coated particles per FE	9560	3175
Volume packing fraction [%]	6.2	35
Fraction of factory defective SiC coatings	7.8×10^{-6}	$< 1.2 \times 10^{-5}$
Matrix density [kg/m^3]	1750	1600
Temperature at final heat treatment [°C]	1900	1850

bed (causing pebble damage) and the pebble discharge system, which allowed for jamming. The THTR was closed in 1989 in the aftermath of the Chernobyl accident after only 3 years of operation.

In the same period, the Power Nuclear Project (PNP-500, 500 MWth, Neef and Weisbrodt, 1979) started in Germany aiming at using nuclear heat to produce hydrogen by steam methane reforming. This project led to development and testing of large modules of heat exchangers and a steam reformer. It was brought to a halt in 1989 after the Chernobyl accident, which caused a temporary stop of HTR development worldwide.

In the 1980s, Interatom/Siemens in Germany developed the 200 MWth HTR-Modul as the first modular pebble bed design consisting of a metallic reactor pressure vessel connected to an adjacent steam generator through a hot gas duct (Siemens, 1988). The concept features a simplified design with a size and power rating chosen to enable passive decay-heat removal after a loss-of-coolant-accident solely by conduction and radiation. No natural or forced convection is necessary (Reutler and Lohnert, 1984; Kugeler et al., 2017). Although it was never built, the HTR-Modul has served as the basis for the PBMR in South Africa and for the HTR-10 and HTR-PM reactors in China.

The Gas Turbine Modular Helium Reactor (GT-MHR, LaBar, 2002) is a 600 MWth design developed by a group of Russian and US enterprises, Framatome in France and Fuji Electric in Japan. It was based on the earlier MHTGR-350 design by General Atomics. It employs an annular prismatic core and utilizes a direct helium Brayton cycle for electricity generation with an efficiency of up to 48% based on a reactor outlet temperature of 850 °C. Extensive analysis has shown that this reactor, and more generally most HTR designs, are particularly suitable for the incineration of excess plutonium which became an issue in the US and in the former USSR for the implementation of the START I disarmament treaty in 1991. Hydrogen production with the Sulfur-Iodine (S-I) process was also envisaged. The Preliminary Design of the reactor plant and GT-MHR prototype power plant was completed in 2001. The GT-MHR regulatory process started in 2002 but was not completed. More recently, the GT-MHR design was proposed by General Atomics as one of the options for the US NGNP project until the NGNP Alliance expressed in 2012 a preference for the ANTARES concept (625 MWth) developed by AREVA (Lommers et al., 2012), based on the GT-MHR but with an indirect steam cycle. A smaller version (SC-HTGR, 350 MWth) equally with indirect steam cycle was proposed by AREVA/Framatome as well (AREVA, 2014). The GT-MHR was also the basis for the Japanese GT-HTR300 designed by JAEA (Kunitomi et al., 2004).

A review summary on the 7 built reactors (Dragon, Peach Bottom, Fort St. Vrain, AVR, THTR, HTTR and HTR-10) can be found in (Beck and Pincock, 2011). The experience of past experimental and prototype HTRs demonstrated their technical viability, however, they were not given the time to prove their economic competitiveness with LWR for electricity production. No further developments were to occur until the late 1990s when the interest in HTRs revived owing to the needs of low carbon high temperature heat supply for a variety of industrial processes.

One of these new projects was the Pebble Bed Modular Reactor (PBMR, Matzner, 2004) in the Republic of South Africa. PBMR Pty. Ltd. is a public-private partnership established in 1999 in response to threats of nation-wide power outages in South Africa and to initiate the development of a modular pebble-bed reactor with a rated capacity of 165 MWe. This design featured a thermal power of 400 MWth and a direct power conversion with a gas turbine operating with a helium outlet temperature of 900 °C. In June 2003 the South African government approved a prototype of 110 MWe for the utility Eskom on the site of Koeberg. This prototype was intended to be put in service in 2014 and expected to precede a fleet of 24 PBMRs so as to make up 4000 MWe out of the 12,000 MWe additional nuclear capacity planned by 2030. Large facilities dedicated to PBMR specific technologies testing were built in 2007: a "Heat Transfer Test Facility", a "Helium Test Facility", a "Pebble Bed Micro Model" and an "Electro-magnetic blower." A fuel laboratory developed manufacturing processes and quality assurance testing techniques in collaboration with NECSA and successfully manufactured coated fuel particles with enriched uranium in December 2008.

In 2009 the PBMR project, like other projects of nuclear equipment in South Africa, faced funding difficulties and had its business plan re-oriented towards the supply of industrial process heat, a difficult endeavor in a country with large coal reserves and no CO_2 emission limits. The new focus of the PBMR was on onsite power, cogeneration, seawater desalination and direct process heat delivery. Target process heat applications included coal-to-liquid or gaseous fuels, petrochemicals, ammonia/fertilizer, refineries, steam for oil sand recovery, bulk hydrogen for future transportation and water desalination. Thus, PBMR Ltd. started developing options for commercial fleets with Sasol (the South African coal liquefaction company), with the utility Eskom for electricity, as well as with US and Canadian cogeneration end users including oil sand producers. The PBMR project was accordingly revisited to develop one standard design that meets all requirements for these applications, thus leading to a cogeneration steam plant with a power of 200 MWth, a helium temperature of 750 °C at the core outlet and a steam generator directly placed in the primary loop. A conventional subcritical steam turbine was selected for first generation plants whereas super-critical cycles were envisaged for next generation plants.

Due to funding issues and problems in the interaction between PBMR and the South African regulator the project was stopped in 2010. This development was analyzed critically in (Thomas, 2011). Another investigation with negative conclusions from operational performance of HTR in the past with a pessimistic outlook is summarized in (Ramana, 2016).

Since then, the aforementioned technological problems encountered with test reactors (e.g. moisture leakages into the core) have been solved to a large extent, so that most recent HTR designs could be deliberately geared towards short-term realization with minimum R&D efforts and development risks. In addition, with a much longer-term view, a number of research organizations cooperate internationally on the Very High Temperature Reactor, which is usually understood to produce heat above 950 °C to maximize power conversion efficiency and to enable ambitious process heat applications such as thermochemical hydrogen production with the S-I cycle. The VHTR is thus a long-term concept requiring new materials and design codes along with fuel qualification for the higher temperatures. The very significant progress of this cooperation is summarized in (Fütterer et al., 2014).

Recent results from test reactors

In the 1990s, the Japan Atomic Energy Agency (JAEA) built a research reactor in Oarai, the High Temperature Test Reactor (HTTR, (Kunitomi, 2013), Fig. 3). It is a prismatic block type reactor with annular compacts. It was put in service in 1998 and reached its full design power of 30 MWth in 2001 with a helium outlet temperature of 850 °C. Subsequent tests until 2010 have demonstrated the safe behavior of the reactor. This included reactivity insertion as well as partial and complete loss of forced cooling, but not yet at full power. The HTTR was successfully operated at the design temperature of 950 °C first in 2004, then for 50 continuous days in 2010. In parallel with tests on the HTTR, JAEA is developing the S-I thermo-chemical process to produce hydrogen (Fig. 4). A first demonstration of this process was achieved in 2003 when a continuous production of 30 l/h of hydrogen was maintained for several days. During the March 2011 earthquake, which triggered the Fukushima accident, the HTTR was only slightly damaged. After extensive inspection, some repair and after the review by the regulator, a restart is planned for 2021, pending a positive

Fig. 3 External view of the HTTR building in Japan.

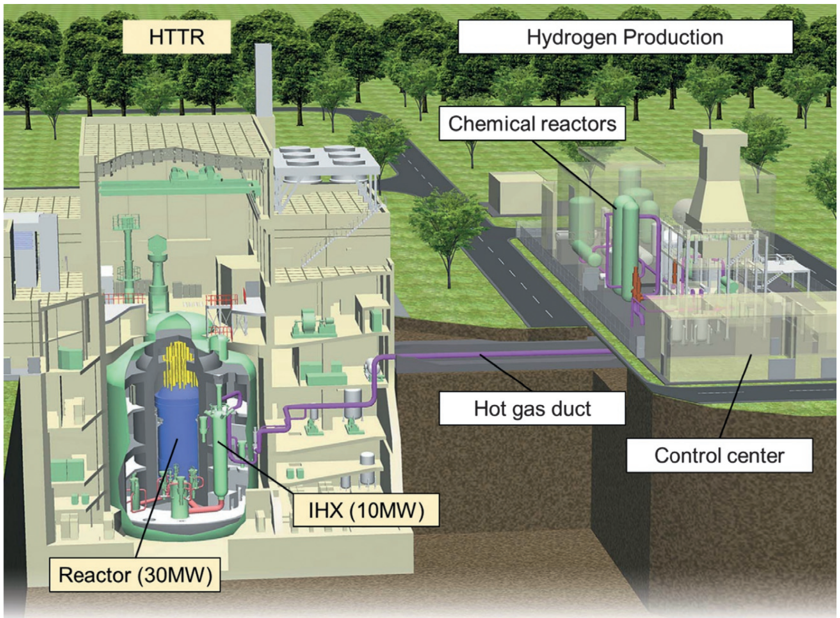

Fig. 4 Schematic of HTTR and future heat use facilities.

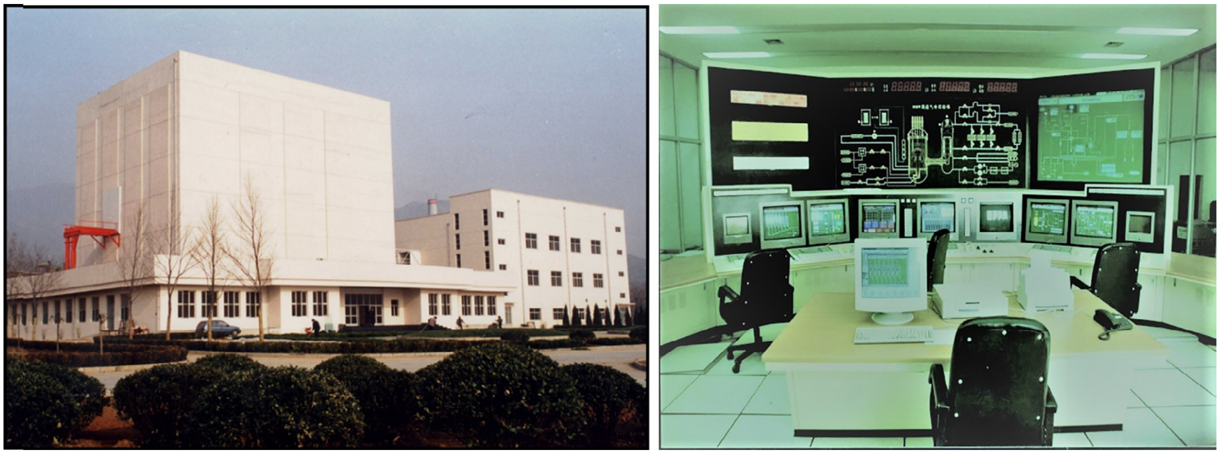

Fig. 5 External view of HTR-10 building in China and Control Room.

outcome of the public hearing. JAEA intends to conduct further safety tests in the frame of an OECD-NEA Loss of Forced Cooling Project.

The Institute of Nuclear and New Energy Technology (INET) of the Tsinghua University in China has built the experimental reactor HTR-10 (10 MWth) (Dong, 2012; Wu et al., 2002; Fig. 5) that was put into service in 2000. The successful operation of this reactor demonstrated an updated pebble bed core HTR technology. In particular, it served as a test bed for fuel, components and for code validation. The HTR-10 was also employed for district heating of the INET campus in the vicinity of the reactor. With several successful demonstrations of its benign safety performance for the public and the licensing authority it paved the way for scaling up this technology to the High Temperature Reactor – Pebble bed Module (HTR-PM, 210 MWe) project (Zhang et al., 2016) .

Together with their predecessors, HTTR and HTR-10 have significantly contributed to the establishment of the rather high technology readiness level both for block type and pebble bed HTR designs.

The case for new next generation HTRs

Why have past HTRs not been successful economically and why do we think that this is changing?

GCRs were developed worldwide, but only the AGRs in the UK remain in commercial operation. After reasonable experiences with the first HTR plants in the UK (Dragon), the US (Peach Bottom Unit 1) and Germany (AVR), national HTR programs ended with no commercial deployments for various reasons. In the UK, the Thatcher government decided to build PWRs essentially because of absence of confirmed economic data for other designs, higher perceived financial risk of HTR designs compared to the mainstream PWR, and because of the then unsolved difficulty to integrate the HTR into a long-term sustainable closed fuel cycle that included Fast Breeder Reactors and reprocessing. In Germany, AVR was shut down in 1988 due to public opposition to nuclear energy, shortly after the Chernobyl accident. In the US, poor capacity factors of the Fort St. Vrain demonstration plant led to its premature shutdown in 1989. This has coincided with the time period of three decades without new nuclear orders in the US starting with the Three Mile Island accident in 1979.

In general, most HTR operational issues were associated, as already mentioned, with leakages, e.g. moisture ingress that resulted in corrosion of components, core temperature oscillations caused by coolant flow bypass and in-core behavior of graphite (cracking, dimensional changes, movement of blocks and distortions, dust formation) (Beck and Pincock, 2011). Most of these were first-of-a-kind operational issues and took a long time to resolve without the benefit of the broader industry experience that is dominated by water-cooled reactors. As a result, it led to poor performance in some HTR reactors, most notably the Fort St. Vrain reactor in the US.

On the positive side, however, the operational experiences with HTRs showed excellent fuel performance and demonstrated the concept's inherent safety features. Many lessons learned through past HTR experiences led to improvements in modern HTR concepts, such as the use of magnetic bearings in the helium circulator, or the use of a steel pressure vessel for improved reliability instead of a pre-stressed concrete vessel. Passive cooling systems, requiring no pumps or monitoring systems to initiate them, have been adopted. The excellent performance of TRISO fuel is further improved by recent extensive research programs (Electric Power Research Institute, 2019), which benefitted both fuel types, compact and pebble. These developments eliminate major known issues experienced by early HTRs and further corroborate HTR safety characteristics.

Ongoing HTR development

The last decade has seen significantly growing interest worldwide in Small Modular Reactors, which the IAEA defines as units producing less than 300 MWe. A snapshot of the very dynamic SMR landscape is given in (IAEA, 2018). These reactors are being

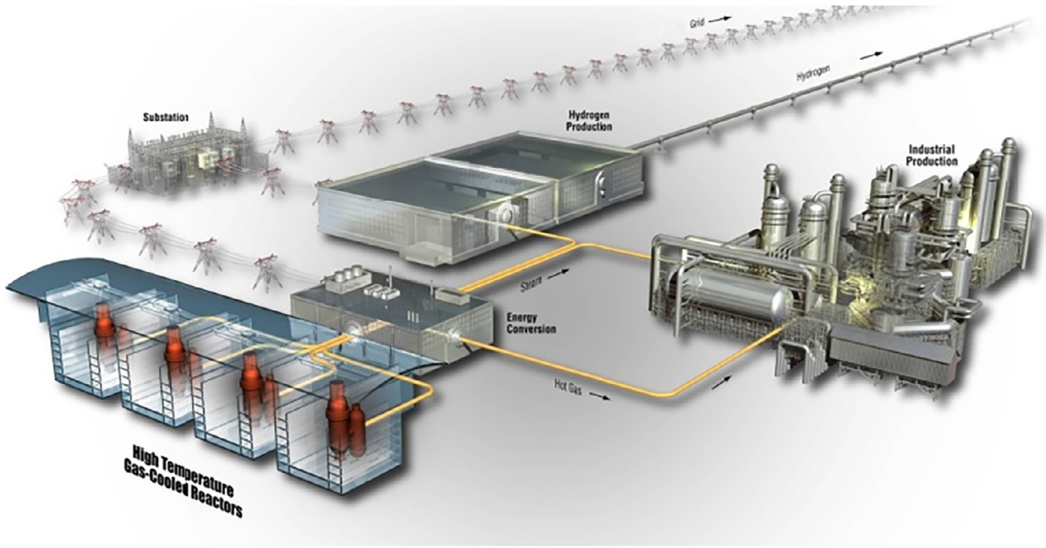

Fig. 6 Artist's view of a 4-pack modular HTR for process heat, hydrogen production and electricity generation (INL).

designed by several classical vendor companies and start-ups for flexibility, affordability, for a wide range of users and applications, and to replace fossil generation plants including in off-grid areas. These advanced reactors are deployable either as single or multi-module nuclear power plants, and are designed to be built in factory workshops and shipped to utilities for installation as demand evolves. Fig. 6 shows how a multi-module pack could be configured to polygenerate heat, hydrogen and electricity.

Several designs ensure enhanced safety performance through inherent and passive safety features as well as suitability for cogeneration and non-electric applications thus opening opportunities for hybrid energy system architectures combining nuclear, fossil and renewable energy carriers. They have reached different stages of development and target near-term deployment with several vendor companies participating in feasibility and licensing studies.

About 16 of these SMR designs are HTRs with one currently under construction and commissioning in China (HTR-PM). Several of these reactors are derivatives or evolutions of earlier parent concepts, e.g. the HTR Modul for the pebble bed designs and the MHTGR-350 (designed by General Atomics) for several prismatic block designs. For the HTR concepts in Table 2, publicly available design information can be found in (IAEA, 2018).

R&D efforts as well as cooperation between all stakeholders (vendors, suppliers, regulators, utilities/end-users, investors, politicians, public etc.) are ongoing and organized at different national and international levels including GIF, IAEA, OECD-NEA, and are including economic analyses, as well as novel investment options and licensing approaches, e.g. (Gougar et al., 2020; Kalilainen et al., 2019). While the nuclear accident in Fukushima in 2011 has dealt a blow to nuclear energy development for several years, the ongoing debate about climate change mitigation has created new interest in low-carbon technologies in several countries and specifically awareness of the need to address the massive energy requirements of the process heat market in industrialized

Table 2 Summary of HTR-type small modular reactor concepts.

Concept	*Developer*
Pebble Bed	
HTR-PM	Tsinghua University, China
Xe-100	X-energy, USA
HTMR-100	Steenkampskraal Thorium Ltd., South Africa
PBMR-400	Pebble Bed Modular Reactor SOC Ltd., South Africa
AHTR-100	Eskom Holdings SOC Ltd., South Africa
Hexagonal Block	
GTHTR300	Japan Atomic Energy Agency, Japan
MHTGR-350	General Atomics, USA
GT-MHR	OKBM Afrikantov, Russian Federation
MHR-T Reactor/Hydrogen Production Complex	OKBM Afrikantov, Russian Federation
MHR-100	OKBM Afrikantov, Russian Federation
SC-HTGR	Framatome Inc., USA
MMR-5, MMR-10	UltraSafe Nuclear Corporation, USA
StarCore HTGR	StarCore Nuclear, Canada
U Battery	U Battery, UK

countries. As shown in Table 2, interest in the inherently safe, highly efficient and versatile HTR technology is steadily growing, and new demonstration projects, in particular for the coupling of the nuclear reactor with a process heat end-user installation, are being implemented to help de-risk (and possibly shorten the time to) industrial deployment.

Beyond electricity: Emission-free process heat and cogeneration

Because HTRs are particularly fit for process heat applications and cogeneration of heat and power, this section is dedicated to non-power utilization aspects of nuclear energy, which has very significant potential impacts since it reduces fossil fuel consumption in areas beyond the electric power market, and thus enhances energy security, further increases the reduction of noxious emissions, and helps mitigating climate change. Already with earlier reactor types, nuclear cogeneration was performed in many countries and with several types of reactors including Light Water Reactors (LWR), Heavy Water Reactors (HWR), and Sodium Cooled Fast Breeder Reactors (SFBR). District heating (80–150 °C) is probably the most widely found application of nuclear heat: 46 reactors in 12 countries, including for instance Slovakia, Switzerland, Russia and China were and are used for this purpose.

Examples for low temperature applications of nuclear heat include seawater desalination (Japan, Kazakhstan), paper and cardboard industry (Norway, Switzerland), heavy water distillation (Canada), or salt refining (Germany).

The technology options for nuclear process heat utilization with HTRs were already documented quite early (Schulten, 1976). A survey of two decades of activities in Germany is given in (Verfondern, 2007a), and further potential is outlined in (Verfondern, 2007b).

The HTR produces heat at a much higher temperature level (exergy) than the LWR. This opens the possibility to replace a large number of existing industrial cogeneration plants delivering process steam in the 500–600 °C temperature range. Very significant amounts of such process steam are consumed in the chemical and petrochemical sector as well as in the fertilizer industry, where today this steam is mostly produced by gas or coal firing.

For several stakeholders, in particular in those countries where natural gas is expensive, the prospect of hydrogen production continues to be the main driver for development and potential deployment of the HTR and VHTR. Process heat from an HTR can be used for several more or less advanced methods of hydrogen production. The most near-term option is steam methane reforming of natural gas with steam at 700 °C, 5.5 MPa. Owing to the external heat supply, more than a third of natural gas is saved. In the 1980s, the necessary components, e.g. heat exchangers or reformers, were developed and tested under nuclear conditions in Germany and in Japan (Harth et al., 1990).

Processes and components for allothermal and steam coal gasification processes were also tested in Germany. They require typically steam in the range of 750–900 °C at 0.1–4 MPa. Although external heat supply makes coal upgrading more efficient, these processes release large amounts of unwanted CO_2.

These activities were brought to a temporary halt in an anti-nuclear climate after the Chernobyl accident, with inexpensive oil and gas and in absence of CO_2 emission restrictions.

As steam methane reforming to produce hydrogen consumes natural gas and generates CO_2 emissions in the process, direct water splitting methods are under investigation in several countries as a clean alternative. HTRs can provide steam for a rather low temperature process, the copper-chlorine (Cu-Cl) cycle, requiring steam at just over 500 °C (Rosen et al., 2012). Other prominent hydrogen production methods are (i) High Temperature Steam Electrolysis (750–950 °C) where a part of the required water dissociation energy is delivered in the form of heat, and (ii) thermo-chemical cycles such as the Sulfur-Iodine Cycle where one of the three process steps (SO_3 decomposition) requires heat input at 850 °C (Yan and Hino, 2011). This process is particularly suitable for VHTR operating at 900–1000°. The market for bulk hydrogen is currently very large and growing fast, with distribution networks already in place in several countries. To justify large-scale production of hydrogen, the development of a specific "hydrogen economy" is not required. Hydrogen uses include upgrading of increasingly heavy oils to lighter fractions, hydrogenation processes, hydro coal gasification, metal refining, ammonia production for fertilizers, the synthesis of methanol or synfuel, or the use of hydrogen in combination with fuel cells as a transport fuel. For some Asian countries, the replacement of coke by hydrogen for direct iron ore reduction is of particular interest to cut back emissions from steel making. Finally, hydrogen can also play a role in carbon capture and utilization processes, which would use CO_2 together with hydrogen as a feedstock for the fabrication of a wide array of possible products ranging from plastics or synfuel for aviation to construction materials. A summary of such processes and products is provided in (Styring et al., 2011).

In the context of energy system integration efforts with growing fractions of variable renewable electricity in many countries, it is of particular interest that the cogeneration capability of HTRs would allow it to contribute to grid stabilization ("peak shaving"), e.g. by modulating the production of (storable) hydrogen depending on the electricity demand in the grid, similar to what is currently envisaged for wind energy ("power to gas").

To further corroborate the incentive for process heat and hydrogen production with nuclear energy, several market research, economic analyses, trade studies, and business plans were recently prepared in several countries, some of which are publicly available (e.g. Angulo et al., 2012; Bredimas, 2012; INL, 2012; Konefal and Rackiewicz, 2008; Shropshire, 2013).

Outlook

The unique capability of the HTR to produce process heat above 600 °C makes it an efficient reactor type to displace fossil fuels in various applications such as producing electricity, non-conventional hydrocarbon fuels from coal or biomass, and process heat for energy-intensive industries (oil refining, petro-chemistry, oil sand recovery, chemistry, steelmaking, etc.). Several market studies confirmed the potential for the HTR system to be used in such applications while the economic boundary conditions (e.g. price of natural gas, CO_2 tax) for market deployment have become clearer. The inherent safety characteristics of the HTR are a precious asset in contributing convincing answers to today's concerns in terms of nuclear safety, energy security, and climate change.

Current research performed within frameworks supported by GIF, IAEA and OECD-NEA, as well as specific national programs address primarily issues related to R&D, licensing, demonstration, and deployment. In particular, the multinational cooperation within GIF (GIF, 2018) allows sharing efforts to advance the technologies and to accelerate development in view of licensing and deployment. Currently, cooperation on the VHTR within GIF focuses on development and qualification of (i) fuel, (ii) structural and functional materials, (iii) hydrogen production processes and (iv) computer tools. GIF has also produced guidance for (V)HTR designers, e.g. in the areas of sustainability, economy, reactor safety, non-proliferation questions or energy system integration. The cooperation is clearly geared towards producing licensing-relevant information across the signatory countries and has recently opened to closer interaction with competing designer and vendor companies. Furthermore, the experimental reactors in Japan (HTTR) and in China (HTR-10) offer unique opportunities to qualify technologies and design codes. The next hurdle towards deployment is being taken by China with the ongoing commissioning of the HTR-PM demonstrator (Fig. 7). Japan will perform further safety demonstrations on the HTTR.

Since 2002, the bi-annual International Topical Meeting on High Temperature Reactor Technology is the sole international conference with focus on HTR and process heat applications (https://htr2020.org/).

Although very substantial results were produced, in particular by the signatories of the GIF VHTR System Arrangement, funding opportunities for a demonstrator coupled with an end-user process will have to be found soon to capitalize on previous investments. Several such international initiatives are on the way. Their success will depend on how much and where nuclear will be allowed to contribute to climate change mitigation, be it for political and public acceptance reasons or for economic boundary conditions (cheap natural gas, CO_2 tax, financial risk).

Fig. 7 Installation of RPV into HTR-PM reactor building in 2016.

References

Angulo C, et al. (2012) EUROPAIRS: The European project on coupling of high temperature reactors with industrial processes. *Nuclear Engineering and Design* 251(2012): 30–37.

AREVA (2014) *HTGR Information Kit*. . March 2014.

Baumer R and Kalinowski I (1991) THTR commissioning and operating experience. *Energy* 16(1991): 59–70.

Beck JM and Pincock LF (2011) *High Temperature Gas-Cooled Reactors—Lessons Learned Applicable to the Next Generation Nuclear Plant*. INL Report INL/EXT-10-19329 Revision 1, April 2011.

Beech DJ and May R (1999) Gas reactor and associated nuclear experience in the UK relevant to high temperature reactor engineering. In: *The First Information Exchange Meeting on Survey on Basic Studies in the Field of High Temperature Engineering*. OECD NEA, Paris, France, 27–29 September 1999.

Bredimas A (2012) Results of a European industrial heat market analysis as a pre-requisite to evaluating the HTR market in Europe and elsewhere. In: *Proc. HTR 2012*. Tokyo, Japan, 28 October–1 November 2012 .

Daniels F (1944) *Suggestions for a High-Temperature Pebble Pile*. MUC-FD-8; N-1668b Chicago, Illinois: Chicago University Metallurgical Laboratory.

Dietrich G, Michels J, Cleve U (2019) Personal communication 2015–2020.

Dong Y (2012) China's activities in HTGRs HTR-10 and HTR-PM. In: *IAEA Course on High Temperature Gas Cooled Reactor Technology*. Beijing, China, 22–26 October 2012.

Electric Power Research Institute (2019) *Uranium Oxycarbide (UCO) Tristructural Isotropic (TRISO) Coated Particle Fuel Performance*. Topical Report EPRI-AR-1, May 2019.

Fortescue P (1975) Advanced HTGR systems. *Annals of Nuclear Energy* 2(11–12).

Fütterer MA, Fu L, Sink C, de Groot S, Pouchon M, Kim YW, Carré F, and Tachibana Y (2014) Status of the very high temperature reactor system. *Progress in Nuclear Energy* 77(2014): 266–281.

Gerczak TJ (2020) Irradiation Performance: High-Temperature Gas Reactor Fuels, this encyclopedia, ch. 00520.

GIF (2018) *R&D Outlook for Generation IV Nuclear Energy Systems: 2018*. Update, available at https://www.gen-4.org/gif/jcms/c_108744/gif-r-d-outlook-for-generation-iv-nuclear-energy-systems-2018-update.

Gougar H (2011) *The Very High Temperature Reactor, Nuclear Energy Encyclopedia: Science, Technology, and Applications*. Steven Krivit, Editor-in-Chief John Wiley and Sons. ISBN: 978-0-470-89439-2.

Gougar H, et al. (2020) The US Department of Energy's high temperature reactor research and development program—Progress as of 2019. *Nuclear Engineering and Design* 358(2020): 110397.

Harth R, Jansing W, and Teubner H (1990) Experience gained from the EVA II and KVK operation. *Nuclear Engineering and Design* 121(1990): 173–182.

Helmreich G (2020) *Fuel Design and Fabrication: TRISO Particle Fuel*. this encyclopedia, ch. 00513.

IAEA (2010) *High Temperature Gas Cooled Reactor— Fuels and Materials*. IAEA TECDOC 1645, 2010.

IAEA (2018) *Advances in Small Modular Reactor Technology Developments*—2018 Edition, https://aris.iaea.org/Publications/SMR-Book_2018.pdf.

INL (2012) *Energy Development Opportunities for Wyoming*. INL Report, INL/EXT-12-26732, November 2012.

Kalilainen J, et al. (2019) High Temperature Gas-cooled Reactors in a European Electricity Supply Environment; Main Outcomes of a Project in PSI. In: *Nuclear Science and Technology Symposium - SYP2019*. Helsinki, Finland, 30–31 October 2019.

Konefal J and Rackiewicz D (2008) *Survey of HTGR Process Energy Applications*. MPR Associates report MPR-3181, May 2008.

Kugeler K and Zhang Z (2019) *Modular High-Temperature Gas-Cooled Reactor Power Plant*, 1st edn. Springer. ISBN: 978-3-662-57710-3.

Kugeler K, Nabielek H, Buckthorpe D, Scheuermann W, Haneklaus N, and Fütterer MA (2017) *The High Temperature Gas-cooled Reactor: Safety considerations of the (V)HTR-Modul*. JRC Technical Report JRC107642, EUR 28712 EN . ISBN: 978-92-79-71312-5, https://doi.org/10.2760/970340.

Kunitomi K (2013) Status of HTTR Project in JAEA. In: *TWGGCR Meeting at IAEA*. 5 March 2013.

Kunitomi K, Katanishi S, Takada S, Takizuka T, and Yan X (2004) Japan's future HTR—The GTHTR300. *Nuclear Engineering and Design* 233(2004): 309–327.

LaBar MP (2002) The gas turbine-modular helium reator: A promising option for near-term deployment. In: *General Atomics*. GA-A23952, 2002.

Lommers LJ, Shahrokhi F, Mayer JA III, and Southworth FH (2012) AREVA HTR concept for near-term deployment. *Nuclear Engineering and Design* 251(2012): 292–296.

Matzner D (2004) In: Letcher TM (ed.) *Chapter 14: The Pebble Bed Modular Reactor*, p. 2008. Oxford: Elsevier.

Neef J and Weisbrodt I (1979) Coal gasification with heat from high temperature reactors: Objectives and status of the project "Prototype Plant for Nuclear Process Heat (PNP)" *Nuclear Engineering and Design* 54(1979): 157–174.

Pohl P (2008) *IRPhE/AVR, High Temperature Reactor Experience, Archival Documentation*, OECD/NEA, NEA-1739/02, https://www.oecd-nea.org/tools/abstract/detail/nea-1739.

Price MST (2012) The Dragon project: Origins, achievements and legacies. *Nuclear Engineering and Design* 251(2012): 60–68.

Ramana MV (2016) The checkered operational history of high temperature gas-cooled reactors, Bulletin of the Atomic Scientists, 72:3, 171–179, https://doi.org/10.1080/00963402.2016.1170395, 2016

Rempe JL (2020) *U.S. Nuclear Reactor Regulation of Two non-LWRs*. this encyclopedia, ch. 00416.

Reutler H and Lohnert GH (1984) Advantages of going modular in HTRs. *Nuclear Engineering and Design* 78(1984): 129–136.

Rosen M, Naterer G, Sadhankar R, and Suppiah S (2012) Nuclear-based hydrogen production with a thermochemical copper-chlorine cycle and supercritical water reactor. *International Journal of Energy Research* 36(4): 456–465.. March 2012.

Schulten R (1976) Nukleare Prozeßwärme. *Chemie Ingenieur Technik* 48(1976): 375–380.

Schulten R, Bellermann W, Braun H, Schmidt HW (1959) *Der Hochtemperaturreaktor von BBC/Krupp (in German)*, Die Atomwirtschaft.

Shropshire D (2013) Integration challenges for nuclear cogeneration coupled to renewable energy systems. In: *Proc. Joint NEA/IAEA Expert Workshop on the Technical and Economic Assessment of Non-Electric Applications of Nuclear Energy (NUCOGEN)*. OECD Paris, France, 4–5 April 2013.

Siemens (1988) *Hochtemperaturreaktor-Modul-Kraftwerksanlage, Kurzbeschreibung*, Siemens/Interatom, Germany, November 1988

Styring P, Jansen D, de Coninck H, Reith H, and Armstrong K (2011) *Carbon Capture and Utilisation in the Green Economy, Using CO_2 to Manufacture Fuel, Chemicals and Materials*. The Centre for Low Carbon Futures. July 2011.

Thomas S (2011) The pebble bed modular reactor: An obituary. *Energy Policy* 39(5): 2431–2440.

Tsvetkov P (2020) *Gas Cooled Reactors*. this encyclopedia, ch. 00207.

Verfondern K (2007a) Survey on 20 years of R&D on nuclear process heat applications in germany. In: *IAEA Proceedings IAEA-CN-152-16, Intl. Conf. on Non-Electric Applications of Nuclear Power: Seawater Desalination, Hydrogen Production and other Industrial Applications*. Oarai, Japan, 16–19 April 2007.

Verfondern K (2007b) Potential for nuclear process heat application. In: *IAEA Proceedings IAEA-CN-152-59, Intl. Conf. on Non-Electric Applications of Nuclear Power: Seawater Desalination, Hydrogen Production and other Industrial Applications*. Oarai, Japan, 16–19 April 2007.

Wu Z, Lin D, and Zhong D (2002) The design features of the HTR-10. *Nuclear Engineering and Design* 218(2002): 25–32.

Yan XL and Hino R (2011) *Nuclear Hydrogen Production Handbook*. CRC Press. ISBN: 978-1-4398-1083-5.

Zhang Z, et al. (2016) The Shandong Shidao Bay 200 MWe high-temperature gas-cooled reactor pebble-bed module (HTR-PM) demonstration power plant: An engineering and technological innovation. *Engineering* 2(2016): 112–118.