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Status of the very high temperature reactor system

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ABSTRACT

The purpose of this paper is to provide an update on the international effort in the development of the Very High Temperature Reactor system pursued through international collaboration in the Generation IV International Forum (GIF) and an outlook for further activities.

The initial motivations to develop this reactor type are recalled, a historical overview is given about technology developments and test reactors since 1945 and several of the targeted non-electric applications of VHTR power are addressed.

Cooperation in the frame of GIF is clearly beneficial for all project partners. Initially, a wealth of historical experience was collected and shared in the form of documents, dedicated workshops or fuel and material samples. This exchange included properties data, fabrication, irradiation and post-irradiation testing methods, quality assurance, design and analysis tools and methods, as well as the experience in building and operating related equipment. In the further course of the project execution, time, effort and scarce facilities (such as irradiation space or hot cell equipment) are shared, they accelerate progress and create synergies.

Recent highlights from currently active GIF VHTR R&D projects (Materials, Fuel and Fuel Cycle, Hydrogen Production) are then provided and placed into the context of the GIF VHTR signatories' national programs. The majority of these currently focus on licensing requirements for demonstrators of near term process steam production scenarios while more aggressive, longer term and higher temperature applications are mainly pursued to enable thermochemical production of bulk hydrogen.

Based on the VHTR's high technology readiness level, orientations for future R&D are outlined which would contribute to enhancing the system's market readiness level. These include work on System Integration and Assessment, Safety Analysis and Demonstration, Waste Minimization and Cost Reductions.

The inherent safety characteristics of the VHTR are a precious asset for it to become a strong response to today's concerns of nuclear safety, energy security and climate change.

1. Introduction

Fast population growth globally, industrialization of emerging countries and political instabilities have confronted the world already for several decades with ever increasing energy challenges. Despite tremendous efforts to cut back on the use of fossil fuel, most of the growing energy demand is still being satisfied with fossil hydrocarbons. Even in countries which are politically committed to stringent climate change mitigation and energy security policies, new smokestacks are growing as fast into the sky as

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wind turbines. The onset of large-scale shale gas exploitation in the US has caused coal prices to drop significantly thus making electricity generation from coal the economically most attractive option for many utilities in many countries. Today, the global long-term trend towards increasing fossil fuel consumption appears almost unstoppable.

Obviously, coal combustion causes harmful emissions, not only the greenhouse gas CO_2, but also dust, heavy metals, NO_x etc. and is at the origin of large numbers of life cycle fatalities. As yet, Carbon Capture and Storage (CCS) is neither an economically established nor a publicly accepted technology and, for cost and efficiency reasons, it is likely not to be deployed where it would be needed the most. The alternative to CCS, Carbon Capture and Utilization, which is increasingly under discussion in several countries, requires large amounts of hydrogen to synthesize useful products (syngas, synfuel, plastics, construction materials etc.) from smokestack or atmospheric CO_2. Of course, this hydrogen has first to be produced by some form of low-carbon primary energy.

In addition, the sense of urgency to solve energy issues has weakened as a consequence of economic priorities dictated by the widespread financial crisis since 2008. Strategic long term decisions in the area of energy infrastructure are considered less acute now than economic and political short-term benefits.

Nonetheless, security of affordable primary energy supply is and will remain for the decades to come one of the most severe technical, economic and political issues and is possibly even key to a lasting economic upturn and a halt to de-industrialization of countries with stringent emission limits. Current energy policies direct most efforts towards “de-fossilization” of the growing electricity sector, although electricity generation represents typically only 30% of a country’s primary energy consumption. Therefore, changes in the other two big sectors (industry and transport) become increasingly pressing. Many countries consider it mandatory to domestically maintain strategically important industrial manufacturing capabilities of, for instance, fertilizers, chemical products, steel and, in several cases, a nuclear vendor industry along with the related jobs and tax income. Almost unnoticed by the public and political decision makers, these sectors consume very large amounts of fossil primary energy and are often enough incompatible with the low power density and variability of renewables.

While nuclear energy together with energy savings and development of renewables can be part of the answer to the described energy challenges, the Fukushima Daiichi accident has also emphasized the need for particularly safe reactor designs.

In this context, the attractive passive safety features of the medium-size (<600 MWth) Very High Temperature Gas-cooled Reactor VHTR stand out as a particular advantage. The VHTR was selected in 2002 among more than 100 proposals as one of six reactor concepts which had the potential to fulfill the performance criteria of the Generation IV International Forum (GIF). These include advances in sustainability (e.g. stretch fuel resources, minimize waste), economics (e.g. minimize CAPEX, OPEX, and LCOE), safety and reliability (e.g. robust safety architecture, no need for off-site measures) and proliferation-resistance & physical protection (e.g. absence of separated plutonium which could be illicitly diverged).

The VHTR is currently based on an open uranium fuel cycle, which at this time is not considered a sustainability issue given the long term availability of affordable uranium and the perspective to extract further uranium from seawater at defendable cost (Uranium 2011, 2012). While a VHTR is unsuitable for Pu breeding (indeed, it is better suited for Pu incineration), it could, once required, achieve long-term fuel sustainability based on the thorium-uranium fuel cycle. Reprocessing of VHTR fuel and integration of its fuel cycle into existing LWR or fast breeder reactor fuel cycles is no longer considered a challenge as suitable head-end processes could be demonstrated in the meantime. Another VHTR specific issue, the generation of graphite waste, is also being tackled by a European project proposing methods for decontamination and recycling of irradiated graphite.

Designed from the start to enable deployment in proximity of industrial sites and agglomerations, the VHTR capability to deliver heat above 600 °C to the end user makes them uniquely suited for cogeneration of process heat and electricity. This feature enables them for instance to efficiently produce hydrogen through steam electrolysis or thermochemical processes, to supply both hydrogen and high temperature heat for producing synthetic fuels from coal, biomass or captured CO_2, or to deliver high temperature heat and hydrogen or syngas as chemical reactants to a variety of industrial plants including petro-chemistry, fertilizer production and steelmaking. According to market studies performed in several countries, the potential market for this process heat is approximately as large as the electricity market and currently almost exclusively provided by fossil fuels with the concomitant CO_2 emissions.

The VHTR system can rely on operating experience acquired between the 1960s and now from experimental reactors and prototypes in the US (Peach Bottom, Fort St. Vrain), Germany (AVR, THTR), Japan (HTTR) and China (HTR-10), the latter two being operational.

Recognizing the potential benefit of the VHTR, the following countries gathered in the frame of the GIF and participate in R&D activities related to the VHTR: US, China, Japan, South Korea, France, Switzerland and the European Union. In addition, Canada contributes to the project on hydrogen production. South Africa, initially participating, has pulled out due to cancellation of their national development program while France will request observer status due to their national program focus on the sodium fast reactor system. The cooperation on VHTR under the GIF umbrella complements national projects and encompasses both, R&D in support of licensing near-term demonstrators (700–950 °C reactor outlet temperature) and the long term vision towards more demanding applications of this reactor type requiring even higher temperatures (950–1000 °C).

This paper first recalls the historical background of HTR technology and gives an overview of existing reactors and technologies. The motivations and priority applications of each participating country are explained. A section of this paper describes how VHTR system R&D is structured in GIF and quotes recent examples for the most salient results and future R&D priorities before addressing the current status of international demonstration projects.

Based on the past experience acquired since the 1960s on experimental high temperature reactors and prototypes, the attractive safety features of medium size HTRs, together with several development and demonstration projects worldwide confirm the VHTR as a system with a large market and CO_2 savings potential showing very active R&D cooperation with a high degree of achievement in the frame of the GIF.

2. Historical experience with demonstration and prototype reactor projects

Gas-cooled reactors were deployed originally for their simplicity and in quest for high power conversion efficiencies. The first commercial nuclear power plant was a CO_2-cooled Magnox reactor (Calder Hall, 1956). In total 26 Magnox reactors were built (270–1760 MWth) with one still in operation (Wylfa-1, 1971–2014) reaching the end of its service life in 2014. Later, 14 Advanced Gas-Cooled Reactors were built on 7 sites (~1200 MWe/site) in the UK with all AGR still in operation with high availability. From this initial