Technical Note

https://doi.org/10.7733/jnfcwt.2023.037

Assessing the Potential of Small Modular Reactors (SMRs) in Spent Nuclear Fuel Management: A Review of the Generation IV Reactor Progress

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(Received July 19, 2023 / Revised August 7, 2023 / Approved September 20, 2023)

The initial development plans for the six reactor designs, soon after the release of Generation IV International Forum (GIF) TRM in 2002, were characterized by high ambition [1]. Specifically, the sodium-cooled fast reactor (SFR) and very-high temperature reactor (VHTR) gained significant attention and were expected to reach the validation stage by the 2020s, with commercial viability projected for the 2030s. However, these projections have been unrealized because of various factors. The development of reactor designs by the GIF was supposed to be influenced by events such as the 2008 global financial crisis, 2011 Fukushima accident [2, 3], discovery of extensive shale oil reserves in the United States, and overly ambitious technological targets. Consequently, the momentum for VHTR development reduced significantly. In this context, the aims of this study were to compare and analyze the development progress of the six Gen IV reactor designs over the past 20 years, based on the GIF roadmaps published in 2002 and 2014. The primary focus was to examine the prospects for the reactor designs in relation to spent nuclear fuel burning in conjunction with small modular reactor (SMR), including molten salt reactor (MSR), which is expected to have spent nuclear fuel management potential.

Keywords: GIF (Generation IV international forum), Generation IV reactor, SMR (Small modular reactor), MSR (Molten salt reactor), GIF technical roadmap

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1. Introduction

The signing and implementation of the Framework Agreement for the GIF took place in 2005. This was followed by the VHTR System Arrangement in 2006 and the SFR System Arrangement in 2007 [4]. These arrangement marked the initiation of international collaborative research on six nuclear reactor technologies: VHTR, SFR, MSR, SCWR (Supercritical Water-cooled Reactor), LFR (Lead-cooled Fast Reactor), and GFR (Gas-cooled Fast Reactor). Table 1 provides a summary of the attributes, key contents, and current status of GIF's three-stage collaborative system.

When analyzing the participation of countries in the GIF, a distinction can be made between inactive member

Table 1. GIF 3-Stage agreement structure and key contents

Agreement	Attributes	Key contents	Current status
Framework agreement	GIF membership agreement, signed by the governments of member countries	Principles of collaborative research, designation of implementing organizations	Currently 12 countries signed
System arrangement	System-specific research and development collaboration	Participation methods in research and development, principles of intellectual property rights	Arrangement enactment for the four systems (SFR, VHTR, SCWR, GFR)
Project arrangement	Contractual collaboration arrangement for the execution of subunit projects within each system	Scope, cost, schedule, and management approaches for collaborative research and development, utilization of production information, intellectual property rights, dispute resolution, etc.	Enactment of nine project arrangement (4 for SFR, 3 for VHTR, 1 for SCWR, 1 for GFR)

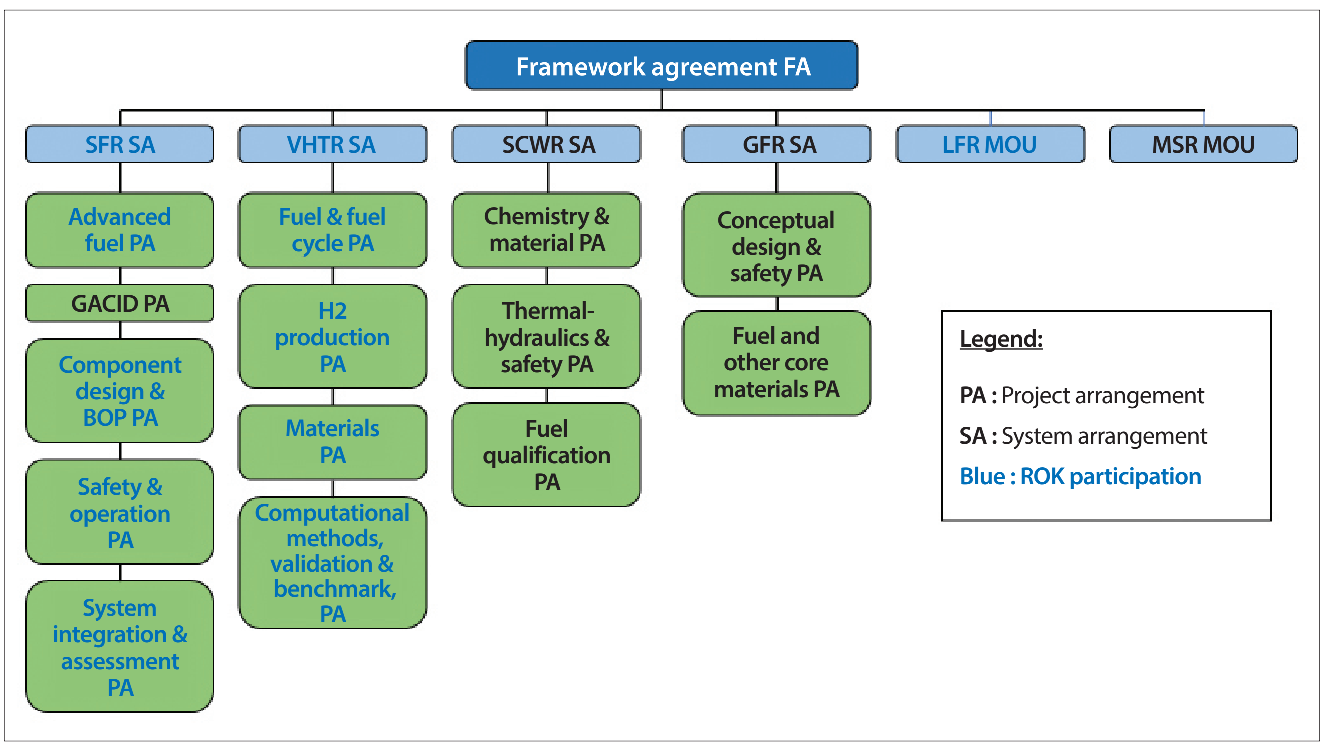

Fig. 1. System configuration and South Korea's participation status.

countries, such as the Argentina and Brazil. These countries have only signed the GIF Charter but have not yet entered into the Framework Agreement. On the other hand, active member countries have joined the Framework Agreement and are actively engaged in collaborative research. Furthermore, with the exception of the LFR and MSR systems, which are still stayed as Memorandum of Understanding (MOU), each system within the GIF has associated projects. The SFR system encompasses five projects, while the VHTR system comprises four projects. Fig. 1 illustrates the project configuration for each system, in which South Korea's involvement in the SFR, VHTR, and LFR systems is indicated by blue color letters in the box.

2. Four Goals of GIF and Technical Roadmap Update

Within the GIF, which encompasses safety, economics, proliferation resistance/physical protection, and sustainability as its four goals, sustainability is paramount importance and requires significant attention. GIF's sustainability efforts can be summarized into two key aspects: resource recycling within spent nuclear fuel and the substitution of fossil fuels by low-carbon emitting sources of energy. Out of the numerous candidate designs proposed or developed worldwide in the early 2000s, GIF selected six Gen-IV designs based on these goals. Notably, except for VHTR and SCWR, four of these designs are fast reactors, highlighting the significance placed on addressing spent nuclear fuel disposal and recycling, regardless of whether they are burners or breeders. Additionally, the emphasis on fossil fuel replacement was underscored by the Nuclear Hydrogen Initiative (NHI) announced by the Bush administration, which emphasized utilizing nuclear energy for industrial hydrogen and process heat production.

To assess the technological development and maturity of the Gen-IV designs, it is necessary to compare the roadmap published in 2002 with its 2013 update.

In 2002, GIF released the Technology Roadmap (TRM) as an initial step in establishing a collaborative framework for developing the six Generation IV (Gen-IV) systems. The progress was assessed by the OECD/NEA, providing support for the GIF Technical Secretariat, based on a decade of achievements. In early 2014, GIF published an updated version of the roadmap known as the Technology Roadmap Update (TRU) [5]. The TRU took into account the research and development achievements, prospects for overcoming future technical challenges, and the participating countries' Gen-IV system development plans. Fig. 2 presents GIF's Technical Road Map in 2002 and the updated TRU in 2014. This figure delineates the progress of technology development for each system design across three phases: Viability, performance, and demonstration. By comparing the 2002 TRM with the 2014 TRU, one can assess the relative level of technological development, research achievements for the six Gen-IV systems, and observe changes in trends among participating GIF countries. Such analysis provides valuable insights into future prospects as well.

The comparison between the 2002 TRM and the 2013 TRU for each system shows that the development progress for the six GIF Generation IV Systems has experienced significant delays. In 2013, it was predicted that the MSR and GFR systems will face difficulties in reaching the demonstration phase by 2030. The LFR system showed relatively better technological development progress compared to other designs [6]. It was due to the fact the system entered the Performance Phase in the mid-2010s and was expected to achieve the demonstration phase in the early 2020s. The VHTR system, on the other hand, experienced slower technological development progress than anticipated in 2002. The performance phase was prolonged. In 2013, it was expected that the VHTR system would reach the demonstration phase around 2025, approximately 10 years after the initial projections. Similarly, the SFR system experienced a

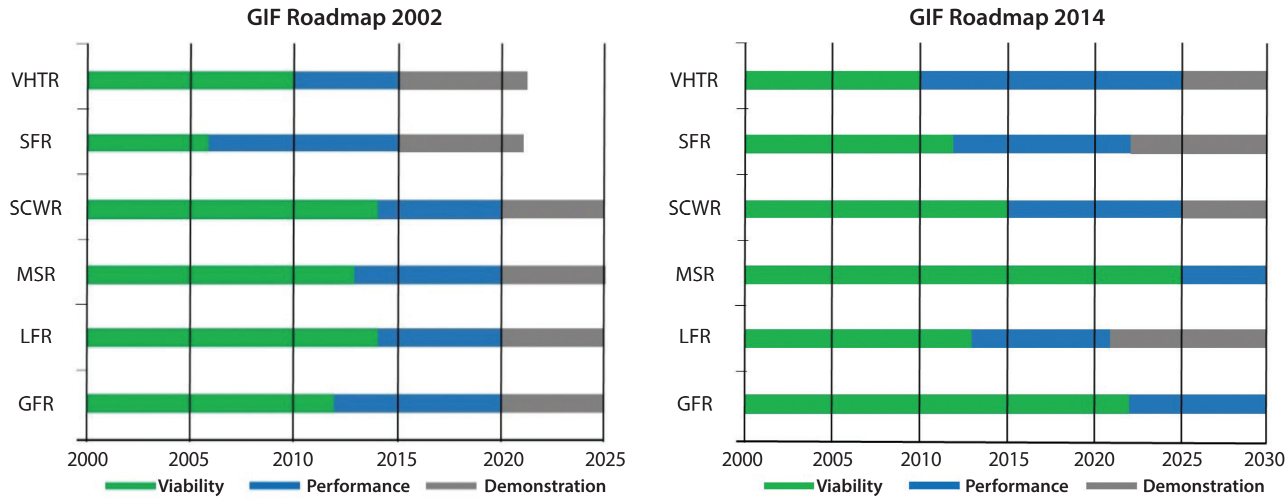

Fig. 2. GIF technology roadmap in 2002 and GIF technology roadmap update in 2014.

delay of about 7 years in reaching the demonstration phase, while the MSR system faced delays of over 10 years.

Considering these delays, it was clear by 2013 that the demonstration and commercialization timelines for the GIF 6 systems would be postponed. At the current point, which is 10 years after the last TRU publication, it is necessary to reevaluate the achieved progress and the future prospects outlined in the TRU.

3. Small Modular Reactors (SMRs) Applicable to Generation IV Reactors

Following the Fukushima accident, global efforts have been underway to achieve enhanced safety, reduced investment burdens, and diversified utilization of nuclear energy. Recently, IAEA presented with more than 70 SMR designs under development in 17 countries, and SMRs are expected to play an increasingly important role in helping the global energy transition to net zero [7]. Within the framework of the Generation IV International Forum (GIF), the development of Small Modular Reactors (SMRs) has emerged as a significant point, alongside the advancement of the existing six reactor designs. Former U.S. Secretary of Energy, Ernest Jeffrey Moniz, emphasized the importance of SMR development in his August 2014 speech, envisioning SMRs as a game-changer in the global nuclear industry. He described them as safe, reliable, and innovative low-carbon technologies, foreseeing active involvement by the United States in the emerging SMR market [8].

Among the system designs within GIF, excluding GFR (Gas-cooled Fast Reactor) and SCWR (Super-Critical Water Reactor), the potential for SMR development is assessed. While numerous SMR designs are being developed outside the GIF framework, such as NuScale and mPower, within GIF, the proposed SMRs for each design have an output scale of less than 100 MWe and can be summarized in Table 2.

For many SMR candidates proposed within Gen IV Systems, there are technological hurdles to be overcome. Significant R&D activities need to be performed, for example, for nuclear data measurement, nuclear fuel development with irradiation test and high temperature material development. Furthermore, to meet the four GIF goals, industrial demonstration efforts are also required

Table 2. Examples of Small Modular Reactors (SMRs) Proposed by GIF

Reactor type	System	Key contents	Countries
SFR	SMFR	MA burning and electricity generation	US
VHTR	HTR-PM	Modular type gas reactor (250 MWt), electricity generation	China
LFR	SSTAR	30 years or more of autonomous operation	US
MSR	MSR	MA recycling and reduction of HLW	US, China

including the operation of a demonstration plant (e.g. LFR) or a prototype (e.g. SFR which are currently only at a preconceptual design phase) [9]. For the near term SMRs (e.g. Gen 3 or Gen 3.5 reactors), the first commercial fleet of SMRs is expected to be in operation in the time frame of 2025–2035 if deployment challenges and issues are well resolved [10]. These issues include assessing human factor for multi-module SMR plants, defining the source term for multi-module SMR plants with regards to determining the emergency planning zone and developing new codes and standards.

In recent times, there has been an increasing enthusiasm surrounding the development of Molten Salt Reactors (MSRs) among these reactor designs. The concept of MSRs aims to achieve the ambitious objective of encompassing both the front-end and back-end fuel cycle within a reactor [11]. Actinides burning is improved thanks to the fast neutron spectrum and MSRs open the possibility of reprocessing the fuel without shutting down the reactor. This becomes particularly significant in order for the global spent nuclear fuel issue to be addressed well. The EU Green Taxonomy, which outlines clear operational plans for disposal facilities until the 2050s, further emphasizes the significance of "accident tolerant fuel" for safety and outlines the importance of Generation IV reactors with closed fuel cycle or fuel self-breeding "in light of their potential contribution to the objective of decarbonization and minimization of radioactive waste" [12]. However, within the GIF framework, the development of MSRs is still in the Memorandum of Understanding (MOU) stage, signifying that substantial time and technological obstacles must be overcome before practical implementation can be realized. This entails considerations of technological maturity and plans for real-world demonstrations.

4. Conclusion

The 55th Policy Group (PG) and the 49th Expert Group (EG) meetings took place consecutively in Lyon, France, from April 17th to April 23rd, 2023. The Policy Group meeting covered a range of topics, including discussions on the country-specific matters related to the extension of the Generation IV International Forum (GIF) Agreement, which had previously been extended until 2025 [13].

Assessing the development of the GIF system, it is observed that technological progress has been slower than initially envisioned in the early 2000s, mainly due to the constraints of international collaborative research and several reasons mentioned before. In future endeavors, whether through potential extensions or restructuring of the GIF framework, it is crucial to learn lessons from the International Thermonuclear Experimental Reactor (ITER) and take steps to determine specific reactor types, host countries, and solidify demonstration projects including the SMR type. By taking this approach, although Generation IV reactors have experienced delays compared to their initial milestones, they are expected to progress towards commercialization by further solidifying their demonstration. The Gen IV nuclear reactor systems, in accordance with the EU Green Taxonomy, are expected to play a pivotal role in minimizing carbon emissions [14], providing safer and more cost-effective solution, and addressing the challenges associated with spent nuclear fuel.

Conflict of Interest

No potential conflict of interest relevant to this article was reported.

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