GEN IV International Forum

Expertise | Collaboration | Excellence

ANNUAL REPORT 2024

www.gen-4.org

Foreword from the Chair

The year 2024 has been productive for GIF, with significant technical progress made on the six GIF systems, as well as many accomplishments in the form of publications, webinars and outreach. GIF was pleased to roll out its refreshed public-facing website to better showcase the value GIF offers to the advanced nuclear technology community, an accomplishment which owes much appreciation to the hard work of the Nuclear Energy Agency (NEA) as the GIF Technical Secretariat. We are also grateful to Euratom for hosting the May meeting in Brussels and the United Kingdom for hosting the October meeting in London. These meetings fostered collaboration and allowed us to celebrate our work.

To extend the impact of Gen IV technology, GIF collaborations continued to explore the potential for diversified energy products ranging from electricity to numerous heat applications. The Non-Electric Applications of Nuclear Heat Task Force was approved to transition to a working group, renamed Non-Electric and Cogeneration Applications (NECA), in October 2024. The overall objective of the NECA Working Group is to advance knowledge and access to energy system design, analysis and optimization tools to allow decision makers to find optimal energy system solutions.

The development of a new framework agreement to continue the work of GIF among mutually willing parties began in 2023 and went into effect on 1 March 2025. This new framework agreement allows GIF to continue to provide global leadership and support to ensure that safe, secure, resilient and sustainable nuclear energy is available for the future.

The 2025-2027 leadership team aims to keep the organization at the forefront of technological innovation by pursuing international collaborations to accelerate the deployment of Gen IV systems. The project for the next three years is based on two main pillars: 1) the capitalization of acquired expertise; and 2) expansion into new actors, applications and markets beyond electricity production.

An essential goal is to foster collaboration with start-ups specializing in advanced reactors and integrate new participants. To achieve this, we will promote an integrated vision of reactors and fuel cycles to maximize the efficiency of technologies and provide decarbonization solutions for various sectors, such as heat, hydrogen and desalination. We will also strengthen our ties with international organizations and industry, while enhancing GIF's communication to increase its visibility and attract new talent.

With best wishes,

Stéphane Sarrade
2025-2027
GIF Policy Group Chair

Alice Caponiti
2022-2024
GIF Policy Group Chair

Table of contents

List of figures

List of tables

1 GIF membership and organization highlights

The Generation IV International Forum (GIF) brings together 13 countries, as well as Euratom (representing the 27 European Union members), to coordinate research and development on advanced nuclear energy systems. In 2024, the structure and organization of GIF remained the same.

Figure 1-1: GIF membership

This chapter will focus only on major changes that occurred in 2024. More detailed information on the GIF membership and organization can be found on the GIF website.[1]

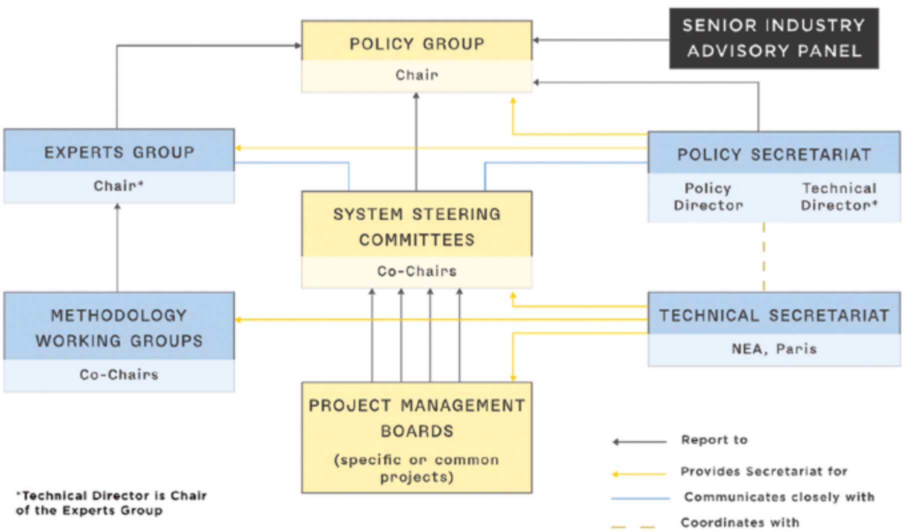
GIF organization

The global governance of GIF and its main bodies are summarized in Figure 1-2. The GIF Chair in 2024 was Alice Caponiti (United States), who will be succeeded by Stéphane Sarrade (France) in 2025. The Policy Director was Fiona Rayment (United Kingdom), who will be succeeded by Daniel Brady (Canada). The Technical Director was Robert Hill (United States), who will be succeeded by Michael Fütterer (European Union).

The chairs of each System Steering Committee (SSC) are indicated in Chapter 3, and the chairs of each Working Group (WG) are indicated in Chapter 4. To ensure continuity of operational requirements within the GIF Technical Secretariat, several staff changes occurred at the Nuclear Energy Agency (NEA) in 2024; the resulting structure as of October 2024 is shown in Figure 1-3.

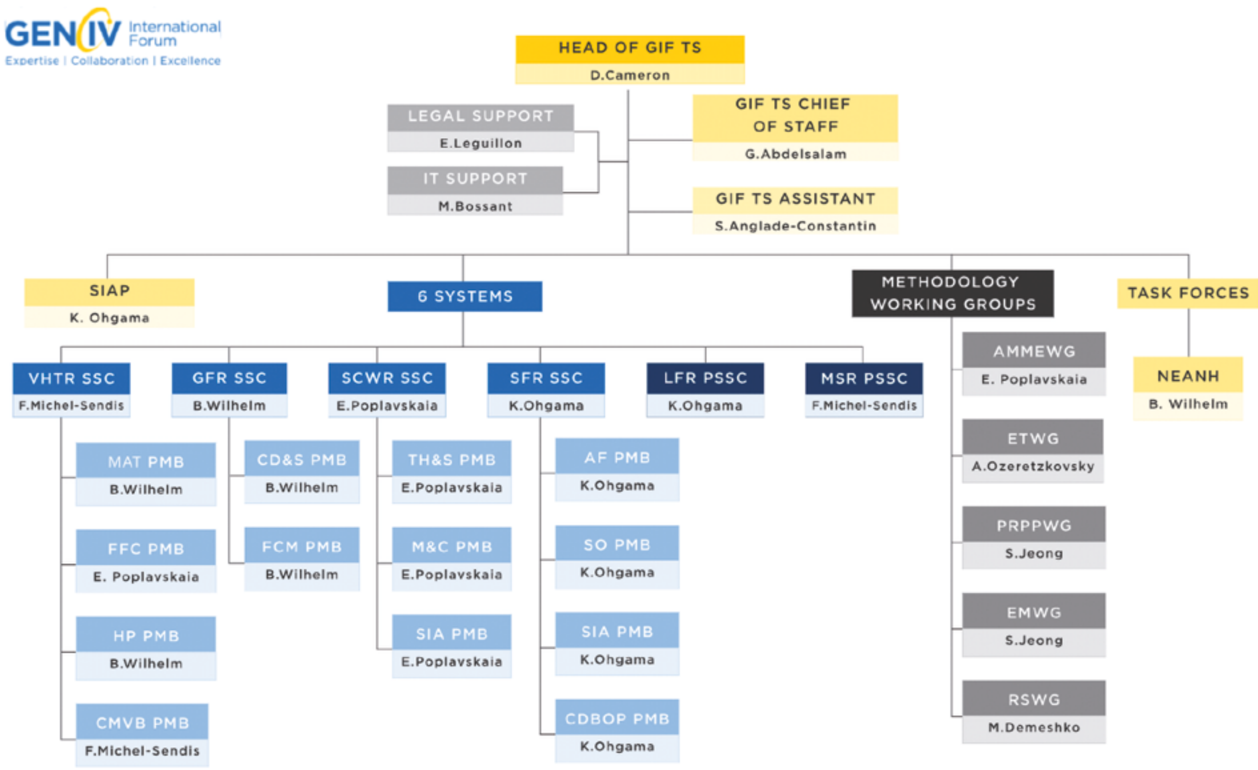
Throughout 2024, GIF members made substantial progress in their work and increased engagement with industry. The NEA continued to provide support to the GIF technical bodies in charge of developing the different systems, to the methodology working

Figure 1-2: GIF governance



1. For further details, please visit the GIF website at: www.gen-4.org/about-gif/gif-organisation-and-governance.

Figure 1-3: **Structure of the GIF Technical Secretariat as of October 2024**



groups, and to the Senior Industry Advisory Panel and task forces. The NEA also coordinated efforts to revamp the GIF public website to improve performance and usability, and to increase awareness and transparency with industry and the broader private sector. The newly revamped website was launched in October 2024.

GIF Framework Agreement

The GIF Framework Agreement (FA) is the international agreement that establishes the framework for international collaboration to foster and facilitate the achievement of the purpose and vision of the GIF. In 2023, following concerns expressed by several members regarding extending the present FA with the current membership, the GIF Chair was mandated to develop options other than extension to continue GIF collaborations upon expiration of the existing FA.

As a major accomplishment in 2024, the GIF Policy Group and their legal counsels successfully concluded negotiations to develop a new FA to ensure full continuity of the GIF from 2025 onwards, with legal and administrative support from the NEA. The new GIF FA opened for signature in October 2024 and is intended to enable continuity of all GIF projects from the prior FA, which expired on 28 February 2025.

The first two signatories to the 2025 GIF FA were the United States and the United Kingdom (Figure 1-4), which signed at the UN Climate Change Conference (COP29) in Baku, Azerbaijan, on 18 November 2024. On 29 January 2025, Canada, France, Japan and Switzerland signed at the Organisation for Economic Co-operation and Development (OECD) in Paris (Figure 1-5). The 2025 GIF FA came into force on 1 March 2025, superseding all previous agreements. Additional Parties are expected to sign the new FA in 2025.

During 2024, the GIF Policy Director also chaired the dialogue on the GIF budget formula and the 2025 budget to enable a new Policy Group established under the 2025 FA to reach early agreement. A revised policy statement on governance, aligned with the new FA, was also created to facilitate transition.

GIF-International Atomic Energy Agency (IAEA) engagement

The GIF and the IAEA have recently enhanced their method of collaboration. This important interaction, which has been ongoing since the first annual interface meeting in 2003, allows the two organizations to exchange information, progress, status and future plans with respect to Generation IV (Gen IV) technologies. At the 18th GIF-IAEA interface meeting in 2024, collaboration updates on ten topic areas covering the six reactor technologies and several crosscutting or enabling topics were reviewed.

The two organizations also engage in regular updates to the collaboration matrix document and focused discussions ("deep dives") held on specific topics. In 2024, a deep dive meeting was held on economics alongside the 58th Policy Group and 52nd Experts Group meetings in London, United Kingdom.

Figure 1-4: **SUK Energy Secretary Ed Miliband and US Deputy Secretary of Energy David Turk signing FA (left)**

Figure 1-5: **FA signing ceremony with representatives from Canada, France, Japan and Switzerland (right)**

Strategic priorities, perspectives and objectives

In 2024, the GIF Technical Secretariat pursued its efforts to improve GIF communications and outreach to industry, researchers, policy makers, government stakeholders and the general public so as to reinforce the GIF position as a leading collaborative organization at the international level, with technical expertise focused entirely on fourth-generation nuclear energy systems. It was agreed by the Policy Group to create the new GIF leadership role of Director of Communications, a role that would focus on using new and different platforms to communicate GIF's activities and accomplishments.

In April 2024, the GIF Task Force on Non-Electric Applications of Nuclear Heat (NEANH) organised a workshop on Non-Electric and Hybrid Applications of Nuclear Energy in Busan, Korea, in collaboration with the Korea Atomic Energy Research Institute (KAERI). At the workshop, international organisations worked together to explore the opportunity for NEANH, energy end users in hard-to-abate industrial sectors, regulators, and nuclear technology developers targeting non-electric applications. During the 52nd Experts Group and 58th Policy Group meetings in London, the Policy Group approved the creation of a GIF Working Group on Non-Electric and Cogeneration Applications of Nuclear Energy (NECA) to pursue the activities initiated by this task force.

In October 2024, the GIF Senior Industry Advisory Panel participated in the NEA workshop, Digital Innovation in Nuclear, in Ottawa, Canada, to discuss the potential of artificial intelligence (AI) for nuclear knowledge management challenges.

Monthly webinars on GIF reactor systems and cross-cutting subjects continue to be held by the GIF Education and Training Working Group (ETWG), with support from the Technical Secretariat, reaching a growing audience worldwide. In 2024, GIF initiated a series of "GIF talks with industry" in the form of webinars featuring advanced reactor developers discussing how they articulate their efforts to move to the stage of deployment. The first webinar set focused on lead-cooled fast reactor (LFR) technologies.

The perspectives and objectives for 2025 are to continue to assume and improve GIF Technical Secretariat services by:

- Providing assistance in reviewing or renewing GIF contracts and agreements such as the GIF System and Project Arrangements, and Memoranda of Understanding.
- Continuing to develop GIF communications (technical, external and internal) to increase GIF's engagement with industry while enhancing support to GIF members and bodies.
- Pursuing efforts to improve the GIF website to enhance its performance and usability, improve collaboration between members, and enhance GIF's brand awareness.
- Maintaining coordination and cooperation with other international organizations active in the field of Gen IV nuclear reactors, such as the NEA, the IAEA, the International Energy Agency (IEA) and the World Nuclear Association (WNA).

Diane Cameron
Head of the GIF Technical Secretariat

Fiona Rayment
GIF Policy Director

2 GIF outlook and current initiatives

The year 2024 marked the conclusion of the US presidency of GIF, which has achieved a great deal over the past three years. Although the many accomplishments cannot be fully detailed in this Annual Report, we would like to take this opportunity to highlight a few key achievements and to propose objectives for the coming three years under the new French-led team.

During Alice Caponiti's leadership, GIF has successfully established a significant partnership with the private sector, as exemplified by the successful Industry Forum in 2022 and the adoption of a new policy statement on industry engagement[1]. The new leadership team is committed to pursuing this effort. Globally, small (advanced) modular reactors (SMRs) are considered promising, with many based on the technologies of the six GIF concepts. Many of the industrial companies in the SMR supply chain have a need for data generated by GIF for design and licensing purposes, and it is GIF's intention that they will be able to use it in a legally clean, fair and equitable manner. As noted in Chapter 1, the GIF Framework Agreement was renewed and took effect on 1 March 2025, and the GIF website was thoroughly upgraded with a fresh look and more easily accessible content.

Among the many impactful achievements, several 2024 highlights deserve a special mention:

- Engagement with the GIF Senior Industry Advisory Panel (SIAP) to promote the relevance of GIF research and development (R&D) accomplishments. As described in Chapter 5, detailed strategic guidance was provided by SIAP on local new build approaches and international safety standards.
- Owing to the considerable member interest and support for a non-electric applications task force, a new and sustained Non-Electric and Cogeneration Applications (NECA) Working Group was created (see Chapter 4). Here again, interaction with private industry is pivotal, with GIF industry meetings held on three continents to capture geographical differences. Cooperation and communication with industry experts beyond the nuclear supply chain (e.g. investors, energy customers, decision makers) is also important for extending nuclear beyond electricity.
- Opportunities were pursued to engage private industry in GIF collaborations, as discussed in Chapter 3. For the database developed in the very high-temperature reactor materials project, a contents summary was publicly posted, and specific procedures were refined for sharing with industry. Also, a new sodium-cooled fast reactor project on thermal-hydraulic validation and testing was created with private industry included as full, contributing project members.

Building upon these achievements, the new leadership team for 2025-2027 is committed to advancing the deployment of GIF systems and strengthening links with other international initiatives. A dedicated Communications Director is part of the new team and will improve internal and external communication on research, achievements, perspectives and collaboration. This will require events, regular website updates and social media presence to showcase GIF activities and even career opportunities in the sector. Reaching beyond classical education and training efforts, GIF will continue to engage particularly with more recent graduates, because nuclear research and industry have to compete increasingly with other sectors for a highly skilled workforce.

A new GIF Industry Forum will be planned over the next three years. The new leadership team is carefully considering all options, including the possibility of one or more smaller-scale events that could place greater emphasis on SMR start-ups, investors, decision makers and energy customers.

GIF consistently delivers high-quality scientific outcomes from various projects, task forces, working groups, as well as the generally seamless coordination and administration of R&D, including within the six system steering committees and the Technical Secretariat, as outlined in subsequent sections of this Annual Report. However, it is important to acknowledge the effort invested by the individuals in these groups who, for more than 20 years, have contributed to the success of GIF as a collaborative platform with their visions, scientific and management skills, and personal energy and dedication.

1. www.gen-4.org/sites/default/files/2024-04/2022_10%20F%20Rayment_gif_industry_forum_industry_engagement_final.pdf.

In member countries, GIF activities must compete, annually, for visibility, manpower, budget and other resources in a variable political and economic environment. This competition is healthy and constructive. As a leadership team, we will strive to make available all the good arguments needed by our colleagues to maintain robust support to GIF.

What was learnt from the past 23 years of GIF research is that not all six GIF concepts can achieve the GIF goals (safety, security, sustainability, economy) equally well. Additionally, the value proposition of nuclear reactors as part of a comprehensive long-term infrastructure investment for the customer and its socio-economic impact is contingent on the utilization of this energy (electricity, heat, hydrogen, etc.). In light of these considerations, it may be beneficial for GIF systems to consider conducting a more thorough analysis of the future role of specific reactors within mixed energy ecosystems, potentially complemented by a related life-cycle analysis.

As several GIF concepts approach their licensing and demonstration stage, there will be an increased need for member countries to shift from scientific R&D towards engineering qualification, for instance of fuel or components. The existing international R&D infrastructure is vital to support the timely availability of required skills, labor and infrastructure.

GIF, with the resources from member countries and taxpayers, is generating a wealth of knowledge, data and documents. One of the challenges ahead is making these more easily accessible, searchable and compatible with modern analytical tools, including AI. Recognizing the shared aspiration of many organizations to achieve this goal, this subject will be explicitly included in GIF collaborations.

GIF is far more than an administrative framework for international R&D collaboration on a subject that in several member countries is considered controversial. GIF delivers the results that are necessary to realize members' vision for the sustainable long-term use of nuclear energy. Please take the individual contributed sections of this Annual Report as a concise testament to this commitment.

Michael Fütterer
2025-2027 GIF Technical Director

Robert Hill
2022-2024 GIF Technical Director

3 System summaries

This chapter summarizes the 2024 accomplishments of GIF collaborations for the six reactor technologies identified in the GIF roadmap[1]: gas-cooled fast reactor, lead-cooled fast reactor, molten salt reactor, supercritical water-cooled reactor, sodium-cooled fast reactor and very high-temperature reactor.

Gas-cooled fast reactor

Signatories of the System Arrangement for collaboration on gas-cooled fast reactor (GFR) R&D are the following GIF members: Euratom, France and Japan. Two technical projects have been established for GIF collaborations:

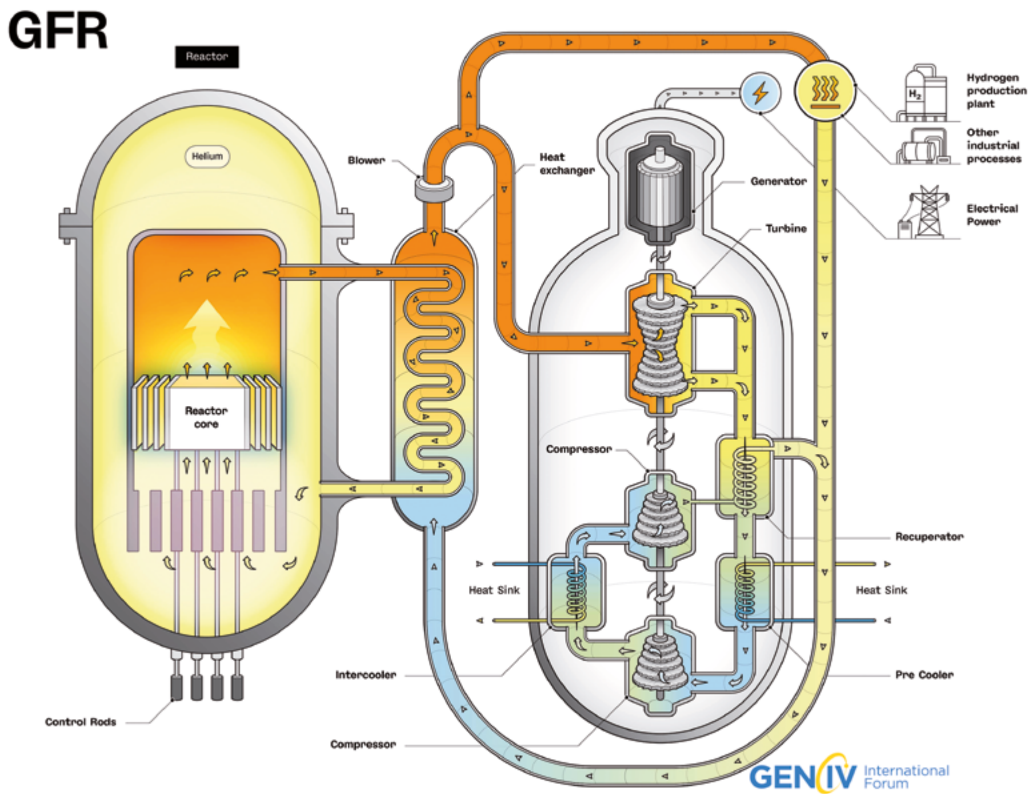
- GFR conceptual design and safety, with the EU Joint Research Centre (JRC) and French Alternative Energies and Atomic Energy Commission (CEA) as members;
- GFR fuel, core materials and fuel cycle, with the JRC, CEA and Japan Kyoto University as members.

R&D collaboration activities pursued in the two GFR technical projects focus on the ALLEGRO gas-cooled fast reactor demonstration concept. The GIF projects have scope for conceptual design, safety analysis, testing of start-up fuel and core materials, and fuel performance modeling.

Main characteristics of the system

The GFR system is designed to operate with a fast neutron spectrum and high-temperature helium coolant (Figure GFR-1). It aims to achieve high ther-

Figure GFR-1: GIF gas-cooled fast reactor



1. The 2002 GIF roadmap can be found here: www.gen-4.org/gif/upload/docs/application/pdf/2013-09/genivroadmap2002.pdf.

mal efficiency and is intended to support a closed fuel cycle. Its advanced design incorporates helium as the primary coolant due to its inert and single-phase properties, enabling higher outlet temperatures up to 850°C. This temperature range facilitates industrial applications such as hydrogen production and enables electricity generation with an efficiency of approximately 48% through combined gas-steam cycles.

The reference concept for the 2 400 MWt (megawatt thermal) GFR reactor is available on the GIF website.[2] The core design includes ceramic-clad, mixed carbide fuel pins housed within silicon carbide (SiC) composite hextubes, ensuring durability under extreme temperatures and irradiation conditions. A guard containment system enhances safety, housing the primary circuit and three intermediate heat exchangers to transfer heat to a secondary helium-nitrogen gas cycle and steam turbine. The GFR's modular scalability, ranging from 200 MWe (megawatt electric) to 1 500 MWe, aligns with Gen IV objectives for construction time, cost-effectiveness and sustainability.

The GFR system prioritizes high burnup fuel with actinide recycling, minimizing feedstock usage and ensuring spent fuel isotopic composition is unattractive for proliferation. The ALLEGRO demonstrator project will be critical to validate GFR technologies, focusing on fuel and materials testing, decay heat removal systems, and high-temperature process heat applications.

ALLEGRO demonstration project overview

The ALLEGRO project, coordinated by the V4G4 Centre of Excellence (EU), continues to progress as the primary demonstrator for GFR technology. The reactor, designed for a nominal power of 75 MWt, features two distinct core configurations. The initial core uses proven mixed oxide (MOX) and enriched uranium oxide (UO_2) fuel with stainless steel cladding to support the testing of experimental fuel assemblies with advanced ceramic fuel. Subsequent phases will implement an all-ceramic core to achieve higher operating temperatures, power densities and fast neutron fluences.

Key features of the ALLEGRO reactor include:

- **Thermal power**: A nominal output of 75 MW, allowing for controlled experimental conditions and scalable insights for future commercial reactors.
- **Core configurations**: The initial core employs MOX and UO_2 fuels with stainless steel cladding, transitioning to advanced ceramic cores in later phases.
- **Safety systems**: Passive decay heat removal mechanisms form a cornerstone of its design, reducing reliance on active safety systems during off-normal events.
- **Materials testing**: ALLEGRO serves as a platform for qualifying SiC composites and other high-temperature materials, ensuring resilience under fast-spectrum, high fluence and high-temperature conditions.
- **Fuel cycle development**: Experiments conducted in ALLEGRO aim to optimize the fuel cycle, focusing on sustainability, waste minimization and non-proliferation objectives.

The ALLEGRO project is closely integrated with international R&D initiatives, including the SafeG project and collaborations with Euratom, Japan and other global stakeholders. Research conducted within ALLEGRO not only advances GFR technology, but also contributes to the broader Gen IV reactor development goals, emphasizing safety, sustainability and efficiency.

Development towards a commercial GFR system is also being advanced through the HeFASTo concept, which is being designed by Ustav Jaderneho Vyzkumu (UJV) Group and follows a long-term program in Gen IV development and GFR R&D, including the ALLEGRO project. The HeFASTo design (Figure GFR-2) intends to have a thermal power capacity of 200 MW and a core outlet temperature reaching 900°C. HeFASTo offers a versatile solution for energy production including for electricity, high-potential heat supply for chemical industries, and efficient hydrogen production.

Figure GFR-2: HeFASTo reactor system concept

Source: UJZ (2025).

2. www.gen-4.org/generation-iv-criteria-and-technologies/gas-cooled-fast-reactor-gfr.

R&D objectives and technology innovations

The GFR community is focused on several priority areas to advance the technology and its applications in support of commercial deployment of this Gen IV system:

- **Fuel cycle optimization**: Efforts are being directed at enhancing the efficiency and sustainability of fuel utilization, including reprocessing strategies for MOX fuel derived from light water reactors (LWRs).
- **Safety enhancements**: Developing robust decay heat removal systems and refining accident mitigation strategies remain critical. This includes validating computational tools and conducting targeted experiments.
- **Industrial applications**: Exploring the potential of GFR systems for cogeneration and hydrogen production to support industrial decarbonization initiatives.
- **Material development**: Advancing SiC-based materials and other high-temperature resistant components to ensure reliability under extreme operating conditions.
- **Regulatory engagement**: Strengthening collaboration with regulatory bodies to address licensing challenges and align safety standards with innovative GFR technologies.
- **Education and outreach**: Engaging the next generation of nuclear professionals through training programs, summer schools and collaborative research opportunities.

Collaborative research under the SafeG project (www.safeg.eu) focused on the GFR system funded by Euratom's Horizon 2020 program, which advanced development of passive decay heat removal systems and the qualification of SiC-based materials for primary and safety-related systems. Euratom's work through the SafeG project concentrated on enhancing safety concepts for the GFR. Activities included core optimization for neutron physics and thermo-mechanical performance, along with the design of advanced materials to withstand extreme conditions. Notable results from 2024 include advancements in computational safety analyses and experimental data collection under prototypical conditions.

In October 2024, the GIF Education and Training Working Group held a webinar focused on the prospects and challenges of GFR technology (GIF, 2024). This webinar explored the current approaches to addressing challenges with the GFR technology and the efforts underway to maximise its potential. It included a historical overview of GFR development and an examination of modern GFR concepts, including the HeFASTo concept for a commercial GFR.

2024 also marked the beginning of the European TREASURE project (Towards Reliable and Safe GFR), which represents a significant collaborative effort aimed at advancing the maturity of GFR technology. Coordinated by the Nuclear Power Plan Research Institute (VUJE) in the Slovak Republic, this project involves 18 partner organizations from nine countries. The project builds upon prior achievements to enhance the safety, reliability and operational flexibility of GFR systems, with a specific focus on the ALLEGRO demonstrator. The research activities carried out in the GIF GFR system and in the TREASURE project will be aligned to leverage efforts to develop GFR technologies and scale them appropriately.

Key objectives of the TREASURE project include optimizing GFR fuel cycles, developing innovative materials and advancing decay heat removal technologies. Research also addresses integration with industrial applications, such as high-efficiency hydrogen production, and includes experimental validation using scaled-down prototypes such as the S-ALLEGRO facility. The project prioritizes education and knowledge dissemination, fostering engagement with students, regulators and international stakeholders.

A unique feature of the project is the direct involvement of the Czech regulatory body as a project partner, leading a task focused on the assessment of regulators and transmission system operators of the GFR technology and the ALLEGRO concept, with a focus on areas that might be challenging in the current regulatory environment in Europe.

Petr Vacha
Chair of the GFR System Steering Committee, with contributions from GFR members

References

GIF (2024), "Education and Training Series #94: Prospects and challenges of the GFR technology", Generation IV International Forum, Paris, www.gen-4.org/resources/webinars/education-and-training-series-94-prospects-and-challenges-gfr-technology.

UJZ (2025), "HeFASTo – Concept of Advanced Modular Reactor for the Future", www.ujv.cz/en/products-and-services-1/research-development/hefasto (accessed 21 March 2025).

Lead-cooled fast reactor

The following GIF members are participating in the GIF memorandum of understanding for collaboration on lead-cooled fast reactor (LFR) R&D: the People's Republic of China (hereafter "China"), Euratom, Japan, Korea, the Russian Federation (hereafter "Russia") and the United States. This section highlights the main collaborative achievements of the GIF LFR provisional System Steering Committee (pSSC) to date. It also summarizes the highlights for the development of LFRs in GIF member countries and entities, as shared within the GIF collaboration.

Main characteristics of the system

GIF has identified the LFR as a technology with great potential to meet the needs of both remote sites and central power stations, fulfilling the four main goal areas of the GIF: 1) sustainability; 2) economics; 3) safety and reliability; and 4) proliferation resistance and physical protection.[1] In the technology evaluations of the 2002 GIF roadmap, and its update in 2014, the LFR system was ranked at the top in terms of sustainability (i.e. a closed fuel cycle can be easily achieved), and in proliferation resistance and physical protection (GIF, 2002; 2014). It was also assessed as good in relation to safety and economics. Safety was considered enhanced by the choice of a relatively inert coolant.

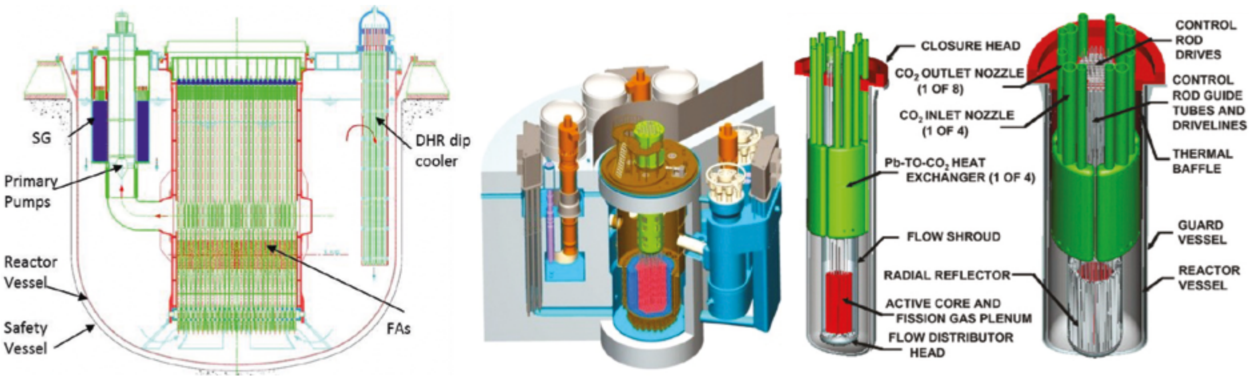
Gen IV LFR concepts include three reference systems: 1) a large system rated at 600 MWe – the European Lead Fast Reactor (ELFR), intended for central station power generation; 2) a 300 MWe system of intermediate size – the Russian BREST-OD-300; and 3) a small, transportable system of 10-100 MWe size – the US small secure transportable autonomous reactor (SSTAR), which features a very long core life (Figure LFR-1). GIF LFR systems thus cover the full range of power levels, from small and intermediate to large sizes. The expected secondary cycle efficiency of each LFR system is at or above 42%. There are important synergies among the different reference systems, with one of the key elements of LFR development being the coordination of efforts carried out among participating countries.

The LFR System Research Plan developed within the GIF is based on the use of molten lead as the reference coolant and lead-bismuth eutectic as the back-up. Given R&D needs for fuel, materials and corrosion-erosion control, the LFR system is expected to require two-step industrial deployment. In the first step, reactors operating at relatively modest primary coolant temperatures and power densities would be deployed by 2030, with higher performance reactors deployed by 2040 as the second step.

Technical highlights – Provisional System Steering Committee activities

Two meetings of the GIF LFR pSSC took place in 2024. The first meeting was hosted by the International Academy of Neutron Science in Qingdao, China, on 22-24 April. LFR developers in China were invited to the meeting, including State Power Investment Corporation Limited and Shanghai Nuclear Engineering Research and Design Institute (SPIC-SNERDI); China General Nuclear Power Corporation and China Nuclear Power Technology Research Institute; China National Nuclear Corporation and China Institute of Atomic Energy (CIAE); Xi'an Jiaotong University; Lanzhou University; and Shanghai Jiao Tong University. The LFR pSSC and

Figure LFR-1: GIF lead-cooled fast reactor reference systems



Note: The European Lead Fast Reactor (left), the BREST-OD-300 reactor (middle) and the SSTAR reactor (right).
Source: Alemberti, A. et al. (2018).

1. www.gen-4.org/generation-iv-criteria-and-technologies/lead-fast-reactors-lfr.

Figure LFR-3: **Construction of the BREST-OD-300 power unit as part of the Pilot Demonstration Energy Complex**

Source: Rosatom.

Chinese LFR developers exchanged information on the status of LFR development. The second meeting was held at Brasimone, Italy, on 3 October. These meetings featured presentations on the status of member activities with descriptions of their respective national LFR programs, information sharing with participants from the industry, and discussions of the LFR system design criteria.

In 2024, the LFR pSSC organized the Global Symposium on Lead and Lead Alloy based Nuclear Energy Science and Technology (GLANST) (Figure LFR-2), held in Brasimone, Italy, on 30 September to 2 October and hosted by the Italian National Agency for New Technology (ENEA). GLANST covered four technical fields: 1) modelling and simulation; 2) coolant, materials and fuel; 3) experiments and code validation; and 4) design of systems and components. Around 45 people, including experts and graduate students, participated, and there were 28 contributions, including eight invited talks from several industry players.

Figure LFR-2: **GLANST in Basimone, Italy, October 2024**

The LFR pSSC launched a new "GIF talks with industry" webinar series. Three webinars were organized: 1) newcleo's R&D Programme in support of Small Modular Lead-cooled Fast Reactor Technology Development and Deployment, by Dr. Fabio Moretti from newcleo[2]; 2) Status of Blykalla's commercial LFR development in Sweden, by Prof. Janne Wallenius from Blykalla[3]; and 3) Ansaldo Nucleare leading a joint European roadmap towards a competitive LFR, by Dr. Michele Frignani from Ansaldo Nucleare.[4] These webinars were a great opportunity to learn the current status of LFR development and to discuss industry needs, challenges and expectations for GIF activities.

National LFR demonstration and development highlights

In Russia, the BREST-OD-300 innovative LFR is being developed as a pilot demonstration prototype for commercial reactor facilities of the future nuclear power industry with closed nuclear fuel cycle. The results of R&D, the developed design documentation and the license issued in February 2021 made it possible to start the construction of the power plant with the BREST-OD-300 reactor on 8 June 2021. Construction was ongoing continuously in 2021 2024, while the main equipment and reactor components are being manufactured, and the production of fuel components has been launched. Installation of the BREST-OD-300 reactor on site began in December 2023. Some of the first operations included the installation of a 165-ton steel support plate and tiers of the reactor enclosing structure (Figure LFR-3). In 2024, the first stage of reactor vessel installation was completed.

2. www.gen-4.org/resources/webinars/gif-talks-industry-series-1-lfr-developers-newcleo.
3. www.gen-4.org/resources/webinars/gif-talks-industry-series-2-lfr-developers-blykalla.
4. www.gen-4.org/resources/webinars/gif-talks-industry-series-3-lfr-developers-ansaldo-nucleare.

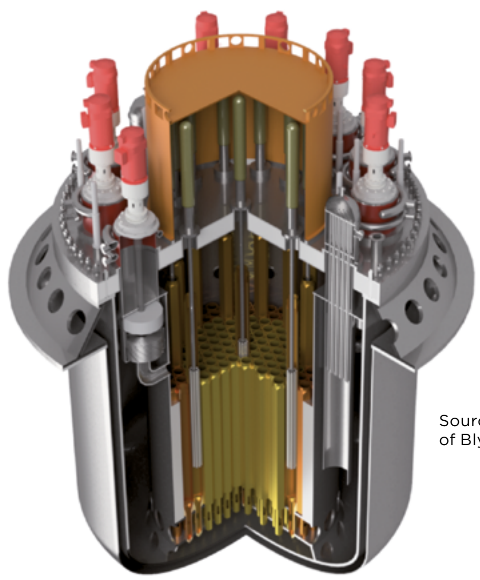
As part of fulfilling the conditions of the license, work continued on the in-depth justification of the BREST-OD-300 reactor and equipment testing. Full-scale modeling of the BREST-OD-300 core has been completed at the large critical BFS-2 test facility. Experiments on the BFS-88 assembly showed good agreement with the results of calculating the effective multiplication factor and reactivity effects for the BREST reactor. A wide range of experimental data was obtained on spatial distributions, worth of control rods, reactivity effects and local characteristics, and measurements at a significant distance from the center of the core. Experiments have been completed at the Impulse Graphite Reactor to test the mixed nitride U-Pu (MNUP) fuel under conditions of increased power up to the destruction of the fuel element. The operability of fuel elements during design basis reactivity accidents has been confirmed, and one of the design limits for the fuel element cladding temperature has been substantiated: 1 000°C for no more than 100 seconds. The maximum radial mean enthalpy of MNUP fuel is substantiated to be 700 J/g (joules per gram).

At the big lead acceptance test stand, comprehensive tests of the prototype of the main circulation pump were carried out, which generally confirmed the main design parameters. In 2024, comprehensive testing of the fuel fabrication equipment on depleted uranium was completed, and the commissioning of the main process equipment was finalized. Further, there are plans to transfer the world's first production of MNUP fuel to pilot industrial operation. The production of MNUP fuel involves the use of reprocessing products from spent nuclear fuel from thermal reactors.

In Europe, activities related to LFR mainly focused on the following projects:

1. The development of a SMR LFR. The Belgium Nuclear Research Centre (SCK CEN), ANSALDO NUCLEARE and ENEA (Italy), and the Romania Institute for Nuclear Research (RATEN-ICN) are discussing a framework agreement to speed up the industrial deployment of SMR LFR technology.
2. R&D activities for the construction of an LFR demonstrator in Romania, the Advanced Lead Fast Reactor European Demonstrator project (ALFRED), supported by the FALCON Consortium (ANSALDO NUCLEARE, ENEA and RATEN-ICN as tier-1 members). The largest worldwide pool-type facility, ATHENA, aimed at developing LFR technologies in the frame of ALFRED has been realized and commissioned in Mioveni (Romania), supported by the FALCON Consortium.
3. R&D activities continued for the construction of an LFR demonstrator in Sweden (Oskarshamn), the Swedish Advanced Lead Reactor (SEALER), which is designed for commercial power production in a highly compact format (Figure LFR-4).

Figure LFR-4: **SEALER-55 Reactor Concept**



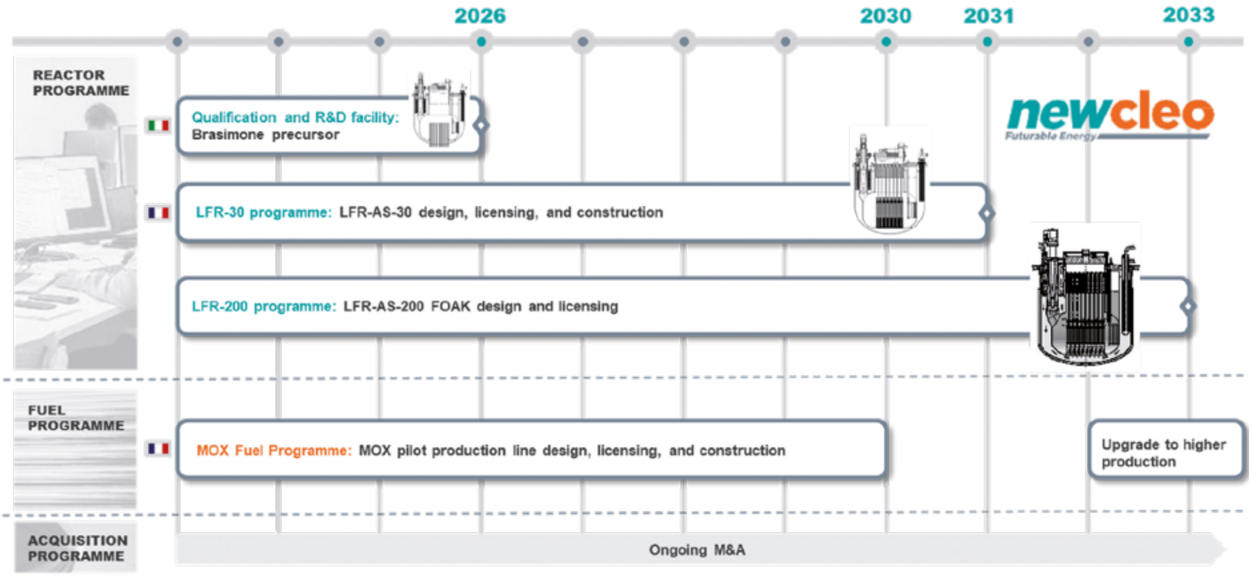
Source: Courtesy of Blykalla.

4. R&D activities were carried out by newcleo, mainly in Italy and France, in collaboration with several EU organizations for the development of the LFR-AS-30 and LFR-AS-200. newcleo is investing up to EUR 50 million to build large-scale research infrastructure in collaboration with the ENEA Brasimone Research Centre (Italy). newcleo is also working to set up a MOX fuel factory in France, fully funded by private investments, to complement its commercial LFR program. The newcleo roadmap is reported in Figure LFR-5.

In parallel, several ongoing European collaborative projects (Euratom co-funded initiatives such as LESTO, CONNECT-NM, ANSELMUS, PASCAL, PATRICIA) are dedicated to heavy liquid metal technology, the development and validation of numerical tools and safety assessments, and material and fuel development and qualification.[5] These Euratom R&D projects are complemented by the R&D work conducted by European Universities (Del Moro et al., 2024; Cioli Puviani et al., 2024). JRC has designed and operates the Liquid Lead Laboratory (LILLA) facility for the investigation of environmentally induced effects on the mechanical properties of materials exposed to oxygen-containing stagnant liquid lead (350 kg) at high purity, with controlled very low oxygen content and up to 650°C. LILLA accommodates four different bellows-based, pneumatically operated test sections simultaneously, two for slow strain rate tensile (SSRT) tests and two for small punch tensile (SPT) tests. LILLA is available for open access.[6] The high shutdown temperatures of LFRs (380-400°C), the opaque coolant, and the in-vessel components of the LFR being completely

5. www.gen-4.org/resources/webinars/gif-talks-industry-series-3-lfr-developers-ansaldo-nucleare.
6. https://joint-research-centre.ec.europa.eu/laboratories-z/liquid-lead-laboratory_en.

Figure LFR-5: Roadmap for newcleo LFR



Source: Courtesy of newcleo.

submerged in liquid lead, and thus not easily accessible, pose significant challenges for in-service inspections. These are addressed in the Euratom project ANSELMUS, which is working to provide an outline of an inspection strategy and age monitoring program, mainly for in-vessel components and practical trials for LFR vessel inspection. As an LFR-relevant harmonization activity in Europe, the CEN Workshop 64 project is supporting the further evolution of the AFCEN codes (the design and construction rules for French pressurized water reactors – PWRs – and advanced reactors) specifically for mechanical components of high-temperature reactors, research reactors and fusion reactors. Every year, several proposals for code evolution and supporting qualification needs are issued.

In Japan, research on innovative small fast reactors using lead or lead-bismuth as coolant continues at the Tokyo Institute of Technology. This reactor is called the rotational fuel-shuffling breed-and-burn fast reactor (RFBB), which uses only natural uranium or depleted uranium as fuel and achieves high burnup without reprocessing. The analysis of this reactor from the start-up core to the equilibrium burnup state through the transient phase was conducted in 2024, using nitride fuel. Compared to RFBB, which uses sodium as coolant, it is clear that lead or lead-bismuth has an advantage, especially in small cores, because of the smaller neutron leakage.

In Korea, the MicroURANUS conceptual design is being advanced towards a standard design edition (Hwang et al., 2024). It has a 20-30 MWe power rating, lead-bismuth eutectic coolant and a minimum 40-year full power service life. Passive safety shows merit for practically eliminating severe accidents. Assessments have explored the risk of steam explosions, considering scenarios such as steam generator tube ruptures and nuclear ships sinking into deep, high-pressure water. LFR designs showed freedom from steam explosion risks in contrast to other proposed maritime reactor designs. Advanced materials, as well as innovative component development and testing, maintain sufficient design margins, accounting for corrosion and void swelling.

In the United States, recent projects directly related to LFR technology include: an effort led by the Massachusetts Institute of Technology in the area of corrosion/irradiation testing in lead and lead-bismuth eutectic; a project at the University of Pittsburgh to develop a versatile liquid lead testing facility and test material corrosion behavior and ultrasound imaging technology in liquid lead (Lee, 2024); and a project at the Rensselaer Polytechnic Institute to address critical issues with the compatibility and chemical interactions of uranium nitride fuel, alumina-forming austenitic alloys, and lead coolants and sublayers. The US Department of Energy (DOE) also funded two Technology Commercialization Fund projects, which are supporting the adaptation of the fast reactor analysis software developed at national laboratories for industry needs: SAS4A/SASSYS-1 Improvements for Lead Fast Reactors (Lee et al., 2024; O'Grady et al., 2024a; O'Grady et al., 2024b; Thomas et al., 2024) and Enhancement of PyARC for Westinghouse LFR Design and Modeling (Stauff et al., 2024). These projects are both between Argonne National Laboratory and Westinghouse, an industry partner.

The Chinese government has provided continuous national support to develop lead-based reactor technology since 1986 through the Ministry of Science and Technology, the National Science Foundation, and China's 13th and 14th Five-Year Plans. The China Lead-based Reactor (CLEAR) was selected as the reference reactor for the accelerator-driven system (ADS) project, as well as for the technology development of the Gen IV LFR. A 10 MWt grade CLEAR-M10 project aimed at the construction of a small modular energy supply system has been launched. In August

2021, an electrically heated pool-type lead-bismuth eutectic cooled integration facility, CLEAR-M0, with more than 5 MWt power completed construction at the International Academy of Neutron Science. A series of verification experiments for thermal-hydraulic characteristics and prototype components are being performed in CLEAR-M0 (Li et al., 2024).

For the ADS system, several concepts and related technologies are under assessment. For example, the detailed conceptual design of CLEAR for minor actinide transmutation and traveling-wave reactor for energy production has been completed. The China initiative ADS project, led by the Chinese Academy of Sciences in collaboration with the CIAE and other industrial organizations, aims to build a 10 MWt sub-critical experimental lead-bismuth eutectic cooled reactor coupled with an accelerator. The Ministry of Ecology and Environment approved the environmental impact assessment report of the first phase of the project, and civil construction began in 2022.

In recent years, other Chinese organizations have started paying more attention to LFR development. SPIC-SNERDI are researching a long-life fully natural circulation small lead-bismuth eutectic-cooled reactor, and Lanzhou University is developing an offshore stationary LFR. Xi'an Jiaotong University is developing the SARAX code for advanced reactor design and analysis, and Shanghai Jiao Tong University is carrying out thermal-hydraulic experimental and numerical research and multi-scale and multiphysics coupled analysis. Other Chinese industry and several universities have also been carrying out LFR-related R&D.

Andrei Moiseev
Chair of the LFR provisional System Steering Committee, with contributions from LFR members

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Molten salt reactor

The following GIF members participate in the memorandum of understanding for collaboration on molten salt reactor (MSR) R&D: Australia, Canada, Euratom, France, Russia, Switzerland and the United States. In addition, there are three observers: China, Japan and Korea. The mission of the MSR provisional System Steering Committee (pSSC) is to support international collaboration on the development of future nuclear energy concepts. Gen IV concepts are designed to use fuel more efficiently, reduce waste production, be economically competitive, and meet stringent standards of safety and proliferation resistance.

In 2024, the pSSC meeting was held once online (36th meeting) and once in person (37th meeting) in Orsay, France. Based on a decision from the 52nd Policy Group meeting, the GIF MSR group will continue as a pSSC and will evaluate its technical situation every two years. In 2024, cooperation continued around three main axes: 1) salt behavior; 2) materials properties; and 3) system integration. The overview and history of the GIF MSR project is summarized in Bourg (2024).

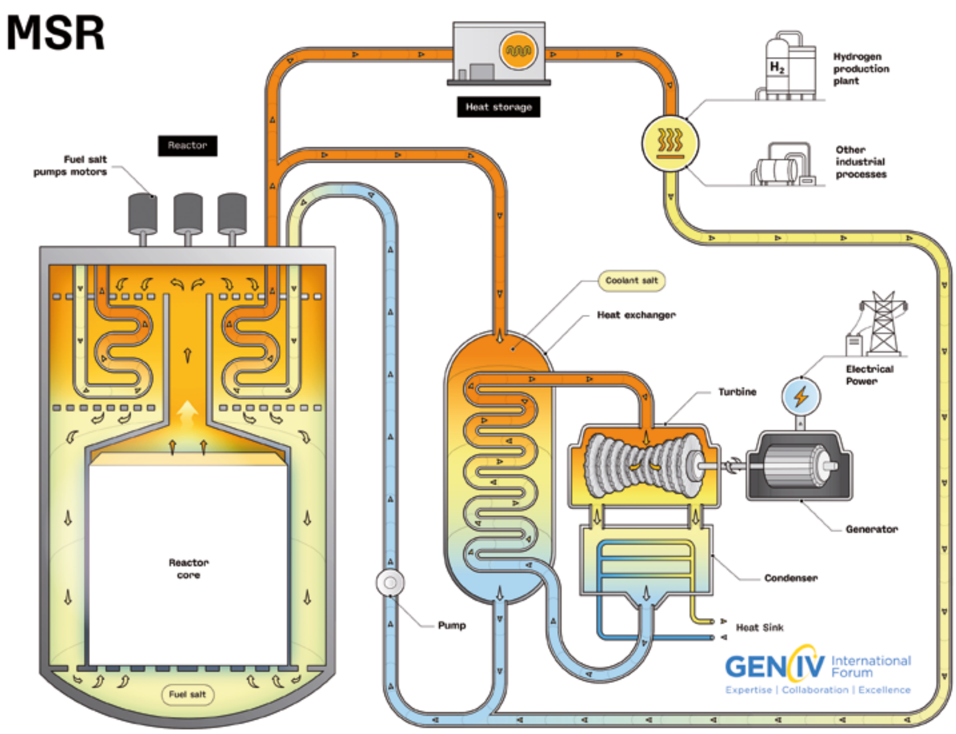
Main characteristics of the system

An MSR is any reactor where a molten salt has a prominent role in the reactor core (i.e. fuel, coolant and/or moderator) (Figure MSR-1).[1] Liquid-fuel MSRs are a type of nuclear fission reactor in which a halide salt serves as the nuclear fuel and may also serve as the coolant. In solid-fuel MSRs, the halide salt serves as the coolant for solid phase nuclear fuel. MSRs were originally conceived in the 1940s.

Both liquid- and solid-fuelled MSRs have seen a resurgence in interest over the past two decades. Proposed designs, with molten salt fluoride and chloride salt mixtures, include thermal and fast-spectrum systems, as well as designs with time and spatially varying spectra. Nearly every form of fertile and fissile material is being considered for its potential in an MSR fuel cycle. MSRs can be grouped into three classes and six families according to their technical characteristics (IAEA, 2023), as shown in Figure MSR-2, which also highlights some prominent MSR developers.

MSRs have a number of advantageous characteristics, ranging from high-temperature operation, which leads to increased thermodynamic efficiency, to low-pressure operation, which reduces the driving force for radionuclide dispersal in the event of an accident. MSRs also tend to have strong negative reactivity feedback characteristics and effective passive decay heat rejection.

Figure MSR-1: GIF molten salt reactor



1. www.gen-4.org/generation-iv-criteria-and-technologies/super-critical-water-reactors-scwr.

However, challenges include the fact that the distribution of radionuclides by liquid fuels can necessitate fully remote maintenance. Furthermore, to prevent pressurization, the gaseous and volatile fission products need to be managed on site, unlike a solid-fuel reactor where fission products are trapped in claddings. Molten salt can also become highly corrosive if exposed to oxidative impurities. Overall, MSRs have substantial technology differences from both existing LWRs and other advanced reactor concepts, necessitating different approaches to safety assessment, safeguards and operations.

R&D objectives

While MSRs may be demonstrated in the next few years, their performance could be improved through the development of improved technologies and techniques. Potentially useful collaborative projects include:

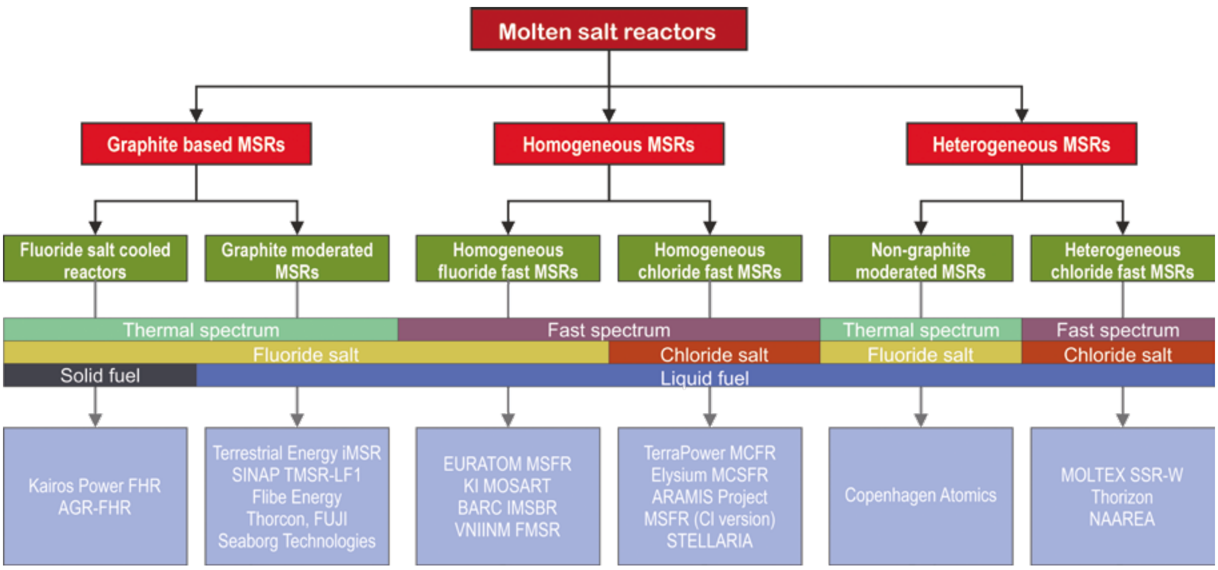
- salt fabrication and measurement of thermochemical and thermophysical properties;
- performance of integral and separate effects tests to validate safety performance;
- development of improved neutronic and thermal-hydraulic models and tools;
- study of materials issues of MSRs (e.g. erosion, corrosion, radiation damage, creep fatigue);
- management of volatile fission products and waste;
- demonstration of tritium management technologies;
- salt redox control technologies to master corrosion in the primary fuel circuit and other components;
- demonstration of surveillance and maintenance technologies for high radiation areas;
- development of a safety and licensing approach dedicated to liquid-fuelled reactors.

National MSR demonstration and development highlights

The Australian Nuclear Science and Technology Organisation (ANSTO) is actively conducting research to support the development of materials for MSR systems, focusing on four key areas: 1) graphite and carbon-carbon (C/C) composites; 2) structural materials and coatings; 3) waste form development; and 4) advanced manufacturing technologies. Progress achieved in 2024 includes:

- **Fracture properties of graphite**: In collaboration with the Idaho National Laboratory (INL), ANSTO is evaluating the fracture properties of graphite, leveraging its exceptional thermal and chemical stability in the extreme environments of MSRs. This work aims to ensure graphite's reliability under high-temperature, corrosive and irradiation conditions.
- **Corrosion behavior of structural alloys**: ANSTO is investigating the corrosion performance of structural materials in molten salt environments. The research includes applying high-nickel alloy coatings to cost-effective structural steels, evaluating the long-term performance of nickel-based alloys, and assessing the combined effects of radiation damage and high-temperature creep on material degradation.
- **Waste form development for fluoride salts**: Synroc-based materials are being tested for their potential to immobilize fluoride salt waste. This work contributes to the development of safe, durable and efficient waste forms, addressing a critical need for the long-term management of radioactive waste generated by MSRs.

Figure MSR-2: Classification of MSR types with some key developer concepts



- **Advanced manufacturing for nuclear applications**: Progress has been made in arc-based directed energy deposition, which is an additive manufacturing technique that enables the rapid production of complex geometries essential for nuclear components. This approach supports the fabrication of high-performance materials and structures tailored to the unique demands of MSR systems.

MSR research in the EU is driven by its member states but strongly supported through research programs at the JRC and the Euratom Research and Training Programme, particularly through the Horizon Europe framework programme. In 2024, most of the studies are aligned with the technical needs identified by EU commercial entities developing MSRs as part of a future carbon-free energy source. Several EU MSR enterprises are members of the recently established European Industrial Alliance on Small Modular Reactors, which aims to facilitate and accelerate the development, demonstration and deployment of SMRs in Europe by the early 2030s.

At JRC, R&D efforts in 2024 included the development of methods to synthesize high-purity plutonium(III) chloride ($PuCl_3$) and uranium(III) chloride (UCl_3). The resulting material was used to conduct a series of experiments to measure the thermophysical properties of the most important salt compositions for the chlorine-based fast-spectrum MSR being investigated in Europe, as well as to attract attention from overseas partners. The focus was on salt mixtures of $PuCl_3$ with sodium chloride (NaCl), and on selected iodide systems as representatives of fission products. JRC also expanded to safeguards and material testing in 2024. One of the highlights was the organization of the Putting Science into Standards workshop on MSR technology (Jenet, 2024), which attracted many partners worldwide, with over 100 attendees.

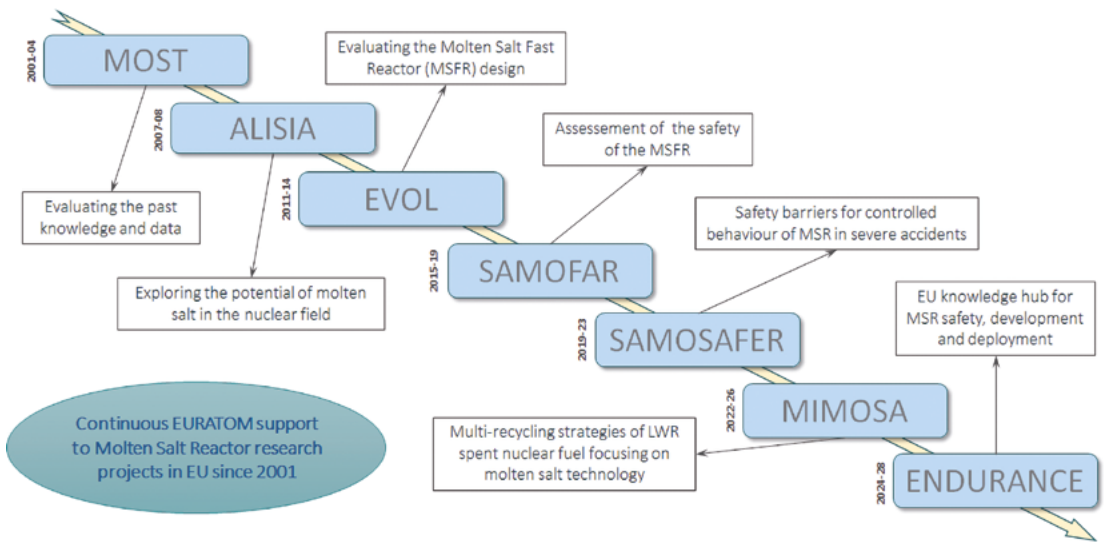
The JRC Molten Salt Database (JRCMSD) describing the main MSR fuel and coolant systems has been further developed and is one of the key ongoing activities. The database has been improved with new experimental data on some of the binary and ternary systems and expanded to include a number of systems containing corrosion and fission products. Selected systems have been modelled to predict viscosity and density behavior. The JRCMSD database is an international collaborative effort between JRC, Delft University of Technology, ORANO Group and CEA, and is open for further partners to join.

Within the framework of the Euratom Research and Training Program, two MSR-related EU Horizon Europe projects are currently ongoing: the MIMOSA project and the ENDURANCE project, the latter commenced in October 2024. An overview of all EU funded projects related to MSR technology is summarized in Figure MSR-3, indicating the time frame and the main focus of each project.

The MIMOSA project, now in its third year, focuses on developing a multi-recycling strategy for spent nuclear fuels from LWRs. Its main objectives include:

- designing and demonstrating an integrated multi-recycling strategy for plutonium and uranium, combining multi-recycling options in LWRs with recycling in chloride MSRs;
- demonstrating key aspects of technical feasibility and performance, including the development of synthesis routes for chloride fuel salts and the qualification of optimized fuel salt compositions;
- qualifying innovative materials and developing new corrosion monitoring and mitigation methods;
- enhancing control of accidental situations and improving safety measures;

Figure MSR-3: **An overview of the EU granted MSR projects**



Source: IAEA (2023).

- developing pyrochemical processes to recycle plutonium and minor actinides;
- innovating methods for the removal, disposal, extraction and purification of fission products.

The ENDURANCE project focuses on advancing MSR technology in Europe, with the following main objectives: 1) to enhance the safe operation of MSR technology through comprehensive research and safety assessments; 2) to advance critical technology elements essential for the industrial deployment of MSRs; 3) to connect the needs of reactor designers and industry with the capabilities of universities and research centres, as well as regulatory requirements; and 4) to promote knowledge advancement in various fields of MSR research, including fuel salt chemistry, material selection, safety phenomena and sustainability. A specific task of the ENDURANCE project will be to organize a worldwide round robin test on the thermophysical properties measurement of molten halide salts. This initiative was communicated to the MSR GIF community at the Orsay pSSC meeting and received a high level of interest.

In France, the R&D programs around MSRs initiated in recent years by the French National Centre for Scientific Research (CNRS), and more recently by the CEA, were continued and developed. The CEA developed its first MSR program in 2020, supported by ORANO, around the Advanced Reactor for Actinides Management in Salt (ARAMIS) concept. The CEA focused its program on reactor design, neutronics studies, salt depletion evaluation, code development, and first experiments on active salt synthesis and material corrosion studies induced by inactive chloride salt. During this period, the CNRS, also supported by ORANO, has also contributed to neutronic studies around actinide management solutions based on fast chloride MSR. In the framework of the collaboration between CNRS and ORANO, work has been launched to study the impact of turbulence on neutronics with coupled neutronics and fluid mechanics, and to study of neutronic noise. This collaboration also concerns the CROCUS reactor at Ecole Polytechnic Federal de Lausanne (Laureau and Begue et al., 2024a). Some code developments implement the Transient Fission Matrix (TFM) neutronic approach developed at CNRS in the OpenMC code, allowing coupled calculations and noise study (Laureau et al., 2024), see Figure MSR-4. Finally, an optimization of the CNRS REM code for burnup calculations has been performed including a Jacobian approach (Clot et al., 2024).

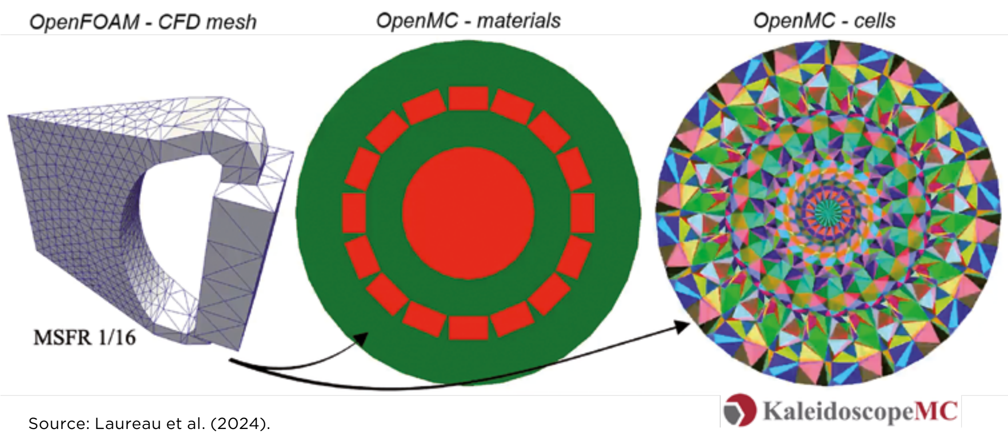
Since 2022, the CEA and the CNRS, along with industrial partners, have been contributing to the French common project, Innovative System for Actinide Conversion (ISAC), supported by the France 2030 investment plan. The main objective of this project is to assess the feasibility of a fast chloride MSR for americium. Three options are being considered, all in a fast spectrum: 1) iso-generator; 2) Plutonium burner; and 3) minoractinide transmuter. These programs are multidisciplinary and cover:

- the reactor system (i.e. neutronics, salt depletion, materials, components);
- the reactor operation and safety (i.e. normal transients, accidental transients, start-up, draining);
- the associated fuel cycle (i.e. salt behavior, corrosion, fission product management, salt purification, salt synthesis, scenario studies) and the refueling strategy;
- multiphysics and chemistry modeling and simulation (neutronic/thermal-hydraulic simulations, coupling between salt depletion and thermochemical calculations, etc.).

The French 2030 call, Innovative Nuclear Power Plant, also supports three start-ups based on MSR technology:

- NAAREA is developing a modular nuclear microgenerator that operates using high-temperature

Figure MSR-4: Coupled calculations with the TFM-OpenFOAM tool



Source: Laureau et al. (2024).

molten chloride salts in a closed fuel cycle. It is designed to support diverse applications, including industrial and remote power needs. NAAREA's R&D explores both aqueous and pyrochemical reprocessing methods to enable low-waste fuel management. In 2024, NAAREA teamed up with CNRS IJCLab and University Paris-Saclay to create the joint MSR lab.

- Thorizon is developing an innovative MSR concept that utilizes a cartridge-based core design with the aim of addressing traditional challenges in MSR technology, including fuel management and material durability. Each cartridge encapsulates the fuel, coolant (molten salt), pump and heat exchanger, making it modular and replaceable every five years. The design is adaptable to various fuel types, with plans for demonstration in 2026 and deployment by 2032.
- STELLARIA is developing a small nuclear reactor that operates in natural convection using high-temperature molten chloride salts. The concept proposes a specific "iso-reactivity" mode, enabling over 20 years of autonomous operation. This feature allows the reactor's fissile material to regenerate at the same rate it is consumed, eliminating the need for fast-reactivity control systems. The reactor's closed fuel cycle recycles spent fuel and minor actinides, reducing nuclear waste. STELLARIA's roadmap anticipates initial demonstrations by the late 2020s and potential commercialization by the mid-2030s.

A number of both salt-cooled and salt-fuelled MSR supportive activities were performed in the United States in 2024. MSR development projects supported by the DOE Office of Nuclear Energy continue to make progress. TerraPower has begun construction of an electrically heated mock-up of the molten chloride reactor experiment (MCRE) in support of future testing in INL's Laboratory for Operation and Testing in the United States (LOTUS) test bed. Google and Kairos Power announced a partnership to deploy 500 MWe of electricity generation by 2035 (Kairos Power, 2024a). Through the partnership, Kairos Power will develop, construct and operate a series of advanced reactor plants and sell energy, ancillary services and environmental attributes to Google under power purchase agreements. Additionally, Kairos Power broke ground on a salt production facility that includes a proprietary process to separate lithium isotopes (Kairos Power, 2024b). Kairos Power also started construction activities for its Hermes reactor in Oak Ridge, Tennessee. The Nuclear Regulatory Commission (NRC) issued a construction permit (NRC, 2024a) and a final environmental assessment (with a finding of no significant impact) for Kairos Power's Hermes II reactor (NRC, 2024b). Hermes II builds on the success of the Hermes project and will generate electricity. Natura Resources received an approved construction permit for its MSR-1 to be constructed at Abilene Christian University (Naturaresources, 2024), with operation intended for 2026.

Terrestrial Energy entered into a memorandum of understanding with EnergySolutions to collaborate on the siting and deployment of Terrestrial Energy's Integral Molten Salt Reactor (IMSR) design at EnergySolution-owned sites. Terrestrial Energy, working with Argonne National Laboratory (ANL), received an award from the DOE Office of Technology Transitions to advance their system analysis capabilities. Terrestrial Energy also received a Gateway for Accelerated Innovation in Nuclear (GAIN) award, in cooperation with Pacific Northwest National Laboratory (PNNL), to analyze fuel salt under a wide range of operating conditions (Terrestrial Energy 2024). ThorCon Technology continues to collaborate with ANL on the National Nuclear Security Administration, Advanced Reactor International Safeguards (ARISE) program, which explores reactor and fuel cycle facility safeguards by design.

The US NRC continues its activities to develop technology-inclusive, performance-based, risk-informed licensing practices for advanced reactors. Multiple proposed rules are currently pending, including a risk-informed, technology-inclusive regulatory framework; alternative physical security requirements; emergency preparedness; generic environmental impact statement; and alignment of licensing processes and lessons learned (NRC 2024c). A proposed rulemaking package, 10 CFR Part 53, which includes a non-light-water technology-inclusive licensing framework and utilizes a probabilistic risk assessment (PRA)-led approach, is now in progress, aligning with the DOE cost-shared, industry-led Licensing Modernization Project (LMP) methodology (NRC 2024d). This approach aims to support MSR deployments domestically and inform deployments internationally.

Fuel salt is the defining element of liquid-fuelled MSRs, serving as both the nuclear fuel and coolant. Fuel salt properties derive from its composition and state (primarily temperature). Mapping fuel salt composition to thermophysical and thermochemical properties is consequently a major area of emphasis. Six US national laboratories are developing fundamental fuel salt property data to enable stakeholders to make informed decisions. Updated versions of the Molten Salt Thermal Properties Database – Thermochemical (MSTDB-TC) and the Molten Salt Thermal Properties Database – Thermophysical (MSTDB-TP) are now available for public use (ORNL, 2025). The updated databases have increased the amount of information and increased the confidence in the validity of the data.

The DOE also continues to support multiple projects focused on developing understanding of MSR accident progression sequences such as performing salt spill testing (Thomas, 2024) and measuring the properties of molten salts doped with surrogate fission products (Gardner, 2024). INL is in the process of deploying a combined set of hot cells and glove boxes to focus on high-temperature molten salt chemistry (NRIC, 2024). Oak Ridge National Laboratory's (ORNL) engineering scale chloride salt pumped test loop was employed for sensor performance validation testing during 2024. ANL is working on developing a pumped actinide salt loop in existing glove boxes in an existing laboratory.

Canadian Nuclear Laboratories (CNL) continues to develop expertise and capabilities in support of molten salt SMR concepts. CNL's Canadian Nuclear Research Initiative (CNRI) program enters its fifth year as a flagship program within CNL's New Nuclear & Emerging Technologies program, which is designed to help fast-track promising research and technologies towards commercialization and deployment.

Under Atomic Energy of Canada Limited's Federal Nuclear Science & Technology Work Plan, CNL is developing modeling and experimental molten salt capabilities. In 2024, several MSR R&D activities were performed. In particular, machine learning is being applied to develop interatomic potentials from small cell density functional theory calculations to predict the thermophysical properties of molten salts. Progress was also made in the measurement of thermophysical properties of fuel and coolant salts, with the development of a hermetically sealed capsule that enables high-temperature differential scanning calorimetry measurements of fluoride and chloride salts. A natural circulation corrosion loop was commissioned, and corrosion experiments of steel alloy 316 under flowing molten chloride salt conditions were successfully completed. Additionally, electrochemical sensors for detecting impurities and corrosion products in molten salts are being developed, along with a particle image velocimetry (PIV) to perform hydrodynamics studies of molten salts using surrogates with relevant density and viscosity.

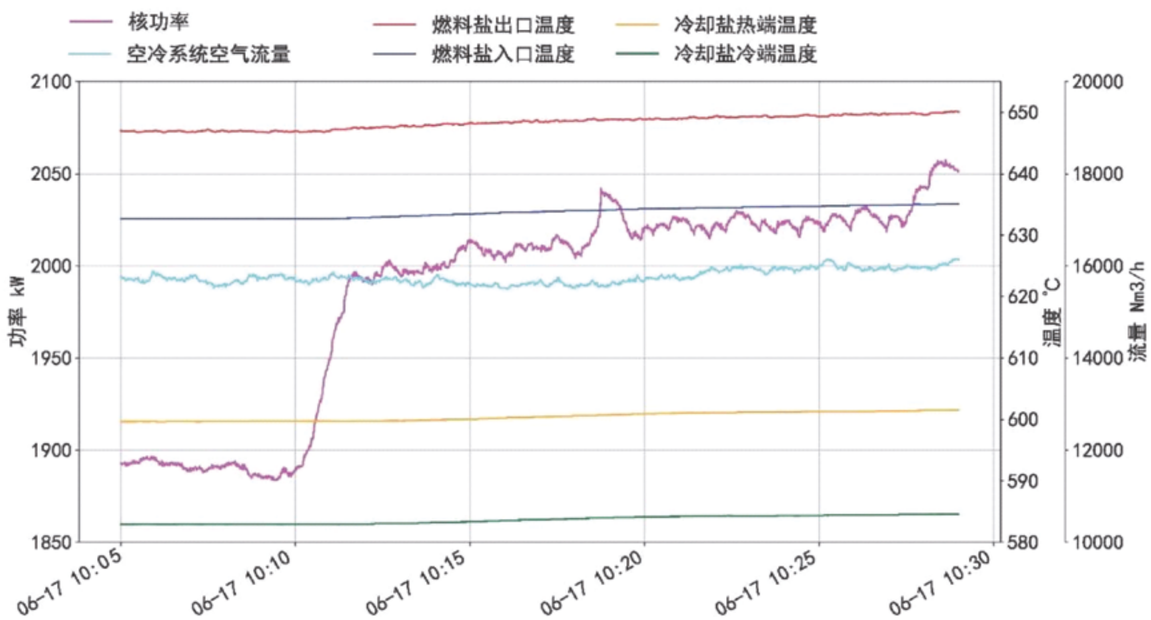
In Switzerland, MSR research is centralized at the Paul Scherrer Institute (PSI), which cooperates with the universities of ETH Zurich and EPFL Lausanne. The long-term aim of the research is the safety and fuel cycle sustainability, without particular focus on specific MSR concepts. This research relies on national and international projects and student education. One major publication in 2024 was a contribution to the book by T.J. Dollan, in particular Chapter 4 on MSR reactor physics (Krepel and Ragusa, 2024).

A project dedicated to dual fluid reactor concept assessments was finalized in the first quarter of 2024. This project focuses on transmutation and should include fuel cycle simulations of major MSR types. Switzerland (ETH Zurich and PSI) also participated as a third country in the EU project, ENDURANCE preparation, which started in October 2024. The Swiss contribution to this project is substantial and covers both safety and fuel cycle sustainability.

In 2024, PSI and Copenhagen Atomics signed a large-scale experimental collaboration agreement. With the Copenhagen Atomics Onion Core, critical experiments should be carried out in collaboration with the Hotlab department at PSI. The partnership between PSI and Copenhagen Atomics aims to conduct a thorium molten salt critical experiment in 2026.

In China, significant progress has been made in the Thorium Molten Salt Reactor (TMSR) project. The 2 MWt liquid-fuel test reactor (TMSR-LF1) was built in the Wuwei Campus of the Shanghai Institute of Applied Physics, Chinese Academy of Science (SINAP), in 2023. On 11 October 2023, the TMSR-LF1 successfully achieved criticality. On 17 June 2024, the TMSR-LF1 achieved 100% power operation for the first time (Figure MSR-5), with the core fuel salt

Figure MSR-5: First full power operation of TMSR-LF1



outlet temperature rising to 650°C, meeting the design specifications and verifying the key technologies of the self-developed TMSR. On 8 October 2024, TMSR-LF1 operated at full power for 10 days with thorium fuel, and Pa-233 (protactinium-233) was detected. SINAP will continue to research and develop key technologies for TMSR to promote their industrial application in the future.

Jiri Krepel
Chair of the MSR SSC,
with contributions from MSR members

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Super-critical water reactor

Signatories of the System Arrangement for collaboration on supercritical water-cooled reactor (SCWR) R&S are GIF members Canada, China, Euratom, Japan and Russia. Three technical projects have been established for GIF collaborations:

- the provisional SCWR system integration and assessment project, with all signatories;
- SCWR thermal hydraulics and safety project, with Canada, China and Euratom;
- SCWR materials and chemistry project, with Canada, China and Euratom.

Main characteristics of the system

The SCWR is a high-temperature, high-pressure water-cooled reactor that operates above the thermodynamic critical point of water – 374°C, 22.1 megapascal (MPa) (Figure SCWR-1).[1] In general terms, the conceptual designs of SCWRs can be grouped into two main categories: 1) pressure-vessel concepts proposed first by Japan and more recently by a Euratom partnership and China; and 2) a pressure-tube concept proposed by Canada. Other than the specifics of the core design, these concepts have many similar features, such as outlet pressures and temperatures, thermal neutron spectra, steam cycle options, and materials. The R&D needs for each reactor type are therefore common, which enables collaborative research to be pursued.

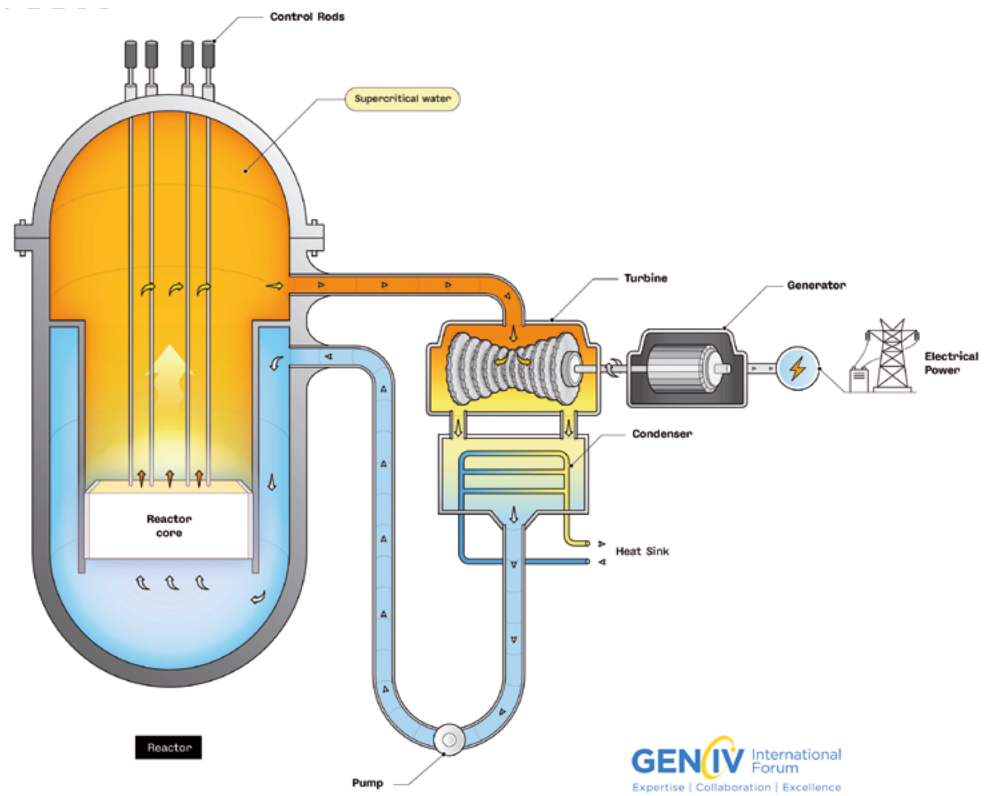
Table SCWR-1: Key parameters of international small modular reactor concepts

	Canadian SCW-SMR[1]	CRS-150[2]	ECC-SMART[3]
Parameters			
Thermal power [MW]	800	375	290
Electric power [MWe]	298	150	
Efficiency %	~37	~40%	
Pressure [MPa]	25	25.0	25
Reactor type	Pressure tube	Pressure vessel	Pressure vessel
Core inlet temp. [°C]	290	280	280
Core outlet temp.[°C]	500	520	500

Note: [1] Canadian Supercritical Water Reactor – Small Modular Reactor (SCW-SMR); [2] Chinese Small Modular Reactor cooled with supercritical water (CRS-150); [3] Joint European Canadian Chinese – Small Modular Reactor Technology project (ECC-SMART).

Sources: [1] Nava Dominguez et al. (2024); [2] Ning et al. (2023); [3] Schulenberg and Otic (2022).

Figure SCWR-1: GIF supercritical water reactor



1. www.gen-4.org/generation-iv-criteria-and-technologies/super-critical-water-reactors-scwr.

The main advantage of the SCWR is improved economics because of high thermodynamic efficiency, the potential for plant simplification, and decades of combined experience operating commercial water-cooled reactors and supercritical fossil-fired plants. Improvements in the areas of safety, sustainability, and proliferation resistance and physical protection are also possible and are being pursued by considering several design options using thermal and fast spectra, including the use of advanced fuel cycles. Table SCWR-1 provides some technical specifications of recent SCWR concepts.

Technical highlights – Thermal hydraulics and safety project

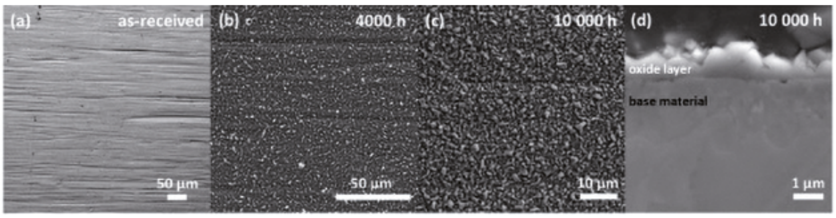
In 2024, several reports were completed under the ECC-SMART international collaboration.[2] The most relevant highlights achieved are detailed below.

A reference database was created to collect existing and new data for thermal-hydraulic investigations performed at supercritical conditions to support SCWR technology. One main goal of this activity is to perform studies of corrosion impact on heat transfer to coolant and moderator under supercritical pressure conditions. Among the data generated, the Karlsruhe Institute of Technology (KIT) in Germany conducted heat transfer and hydraulic resistance experiments under supercritical Freon (R134a) conditions (Wiltschko et al., 2024). The experiments aimed to study the effect of surface finishing on heat transfer and used smooth and artificially roughened test sections. The results show that heat transfer deterioration is delayed using a rough surface. Centrum Výzkumu Řež (CVR) in Czechia constructed the test sections, and KIT performed the thermal-hydraulic tests (Figure SCWR-2). These experiments are scarce yet important for supporting the deployment of advanced nuclear reactors that use supercritical fluids in the main heat transport system or secondary circuit (Sandia National Laboratories, 2025).

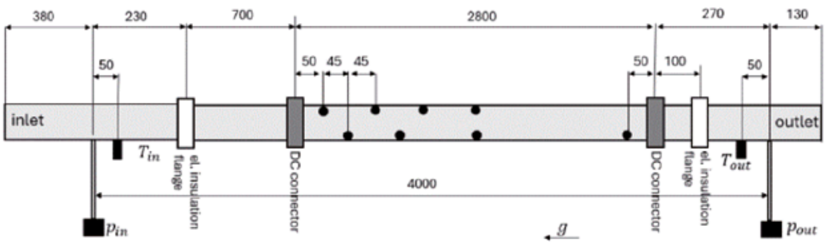
In Canada, CNL and Carleton University performed direct numerical simulations (DNS) using ANSYS CFX computational fluid dynamics (CFD) software. The investigation analyzed the effects of smooth and rough surfaces on turbulent forced convection at the inflow Reynolds (Re) number 12 000. CNL also measured the roughness height and the thermal conductivity of several cladding candidate coupons exposed to supercritical water conditions at different times, testing up to 10 000 hours. This activity aims to develop a model to study the effect of corrosion deposits on heat transfer under supercritical conditions (Otic et al., 2024).

The University of Sheffield also conducted DNS of flow over rough surfaces using the immersed boundary method for in-house DNS solver CHAPSm2 (CHAPSim, 2025). The investigation also covered

Figure SCWR-2: KIT test section, surface finish and uncertainties of experimental loop



Parameter	Uncertainty
Fluid temperatures	max (1K, 0.75% of measured in °C)
Wall temperatures	Max (0.5K, 0.4% of measured in °C)
Pressure	0.1% (of full sensor range)
Flow rate	0.15 %
Datalogger voltage	0.03 %
Datalogger temperature	0.5 K
Current	1.5%
Length	0.5 mm
Tube inner diameter	0.03 mm



Source: Wiltschko et al. (2024).

2. https://ecc-smart.eu.

asymmetrically heated channel flow and analyzed smooth and pyramid-roughened surfaces in supercritical water. In Germany, KIT developed a customized compressible DNS solver for flow, heat and mass transfer; the new solver was implemented in the open-source CFD code, OpenFOAM. KIT also validated the new solver against literature data and analyzed turbulent natural convection for different temperature ranges in supercritical water (Otic et al., 2024).

Regarding the pre-conceptualization of SCW-SMRs, safety systems were proposed and assessed under the ECC-SMART and GIF collaborations. In Europe, the University of Pisa proposed several safety system options and assessed the ECC SMART concept using the system code RELAP. In parallel, the Budapest University of Technology and Economics performed a similar analysis using the APROS thermal-hydraulic system code. The results suggest that a minimal configuration of passive systems may be sufficient to assure adequate natural circulation and core cooling during a postulated long-term station blackout (Otic, 2024).

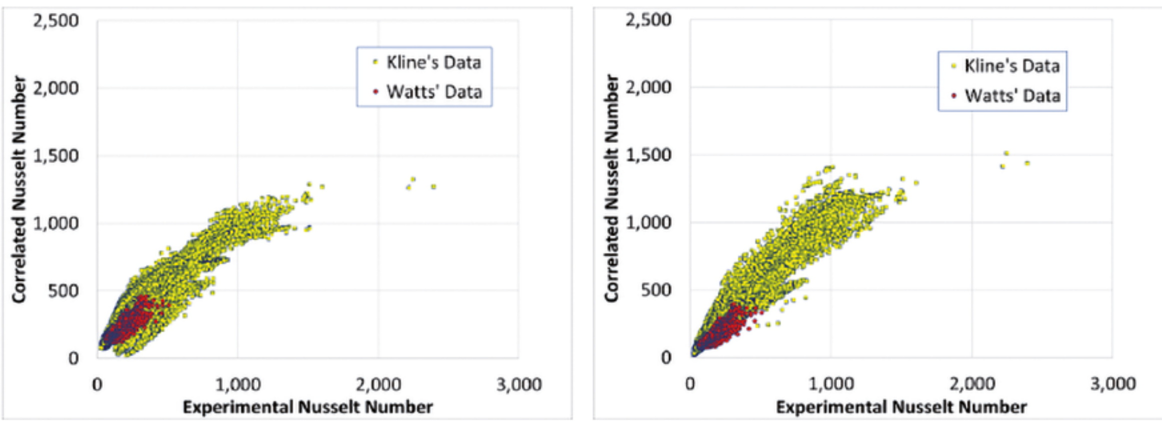
CNL conducted a similar safety analysis for the Canadian SCW-SMR. The results point to the same conclusion: the use of an isolation condenser system is sufficient for long-term cooling of the reactor (Otic, 2024). The Nuclear Power Institute of China (NPIC) also conducted multiple safety analyses for the CSR-150 SMR design developed by China. Thermal-hydraulic system code improvements focused on the stability of the predictions.

IPP-CENTRE in Ukraine carried out severe accident modeling for the ECC-SMART configuration having horizontal channels in the reactor core, for which the classical MELCOR code models are not directly applicable. The problem was circumvented by using MELCOR alongside a CFD code; with the latter, it was possible to evaluate the loads on the internal vessel structures caused by the depressurization from supercritical pressure. Base MELCOR models were adopted to consider the phases of core degradation and corium progression toward the bottom of the vessel and the final vessel attack and failure (Otic, 2024).

Most European participants conducted CFD studies to gain more knowledge on the effects of turbulence models on the heat transfer of a nuclear fuel bundle operating under supercritical conditions. The University of Pisa performed a comprehensive study of existing heat transfer correlations, assessing their effectiveness in predicting two sets of experimental data taken as reference, those with CO_2 by Kline (2017) and those with water by Watts (1980). The work focused on developing and validating a CFD model to predict heat transfer along rough surfaces under supercritical pressure conditions. The model was validated against two distinct experimental datasets: one utilizing CO_2 flow in a vertically heated tube (Kassem et al., 2023) and another employing Freon R134a under similar conditions (Kassem et al., 2025). Results demonstrated the model's capability to effectively capture wall roughness effects on heat transfer, particularly at higher roughness values, although some discrepancies were observed at lower roughness levels (Figure SCWR-3).

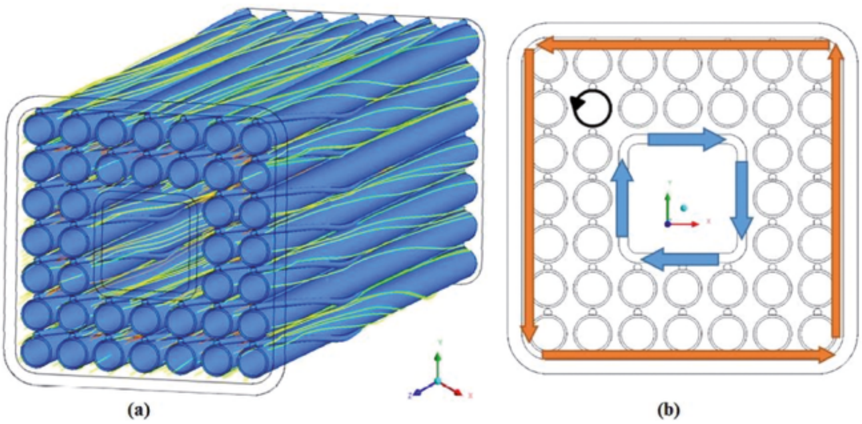
The Budapest University of Technology and Economics conducted comprehensive CFD analyses using ANSYS CFX to study supercritical water flow in nuclear fuel assemblies. The methodology progressed from simple geometries with smooth tubes to complex configurations (2×2 rod bundles and horizontal SCW-SMR fuel assemblies) to CFD analysis of heat transfer characteristics of supercritical water flowing through a horizontal rod bundle with heated fuel rods (Figure SCWR-4). The University of Nottingham also performed CFD simulations to study the effect of surface roughness on heat transfer (Otic et al., 2024). The results demonstrated that the non-uniform rough tubes exhibited higher friction factors than uniform ones, and the SST k-ω model outperformed both standard and buoyant k-ε models in capturing roughness effects and overall flow characteristics, mainly due to its superior handling of surface roughness

Figure SCWR-3: Comparison of calculated Nu values vs. experimental value



Note: Nu values using the original correlation (left) and optimizing the correlation coefficients (right).

Figure SCWR-4: **Flow circulation testing in the ECC-SMART fuel assembly**



Note: Computation model used to test modeling assumptions and surface roughness trends (Otic et al., 2024).

impacts. Similarly, the Royal Institute of Technology developed numerical models to predict supercritical heat transfer along rough corroded surfaces using CFD with specialized wall treatments. Two low-Re turbulence models were formulated with modified source terms and boundary conditions for turbulent kinetic energy and dissipation, and validated against experimental data using supercritical CO_2 and R134a.

Technical highlights – Materials and chemistry project

Water radiolysis is an important knowledge gap for the SCWR as it can affect reactor chemistry, both in-core and downstream of the core, and ultimately the corrosion behavior.

In Canada, CNL performed a preliminary radiolysis study, which showed promising results, demonstrating effective suppression of the effects up to 500°C through hydrogen injection at concentrations of ≤40 $mL \cdot kg^{-1}$ H_2. In Prague, the University of Chemistry and Technology and CVR performed electrochemical investigations in supercritical water that highlighted temperature- and pressure-dependent behaviors, with peaks near the critical point, minimal impact from dissolved oxygen, and significant effects from surface treatments. Electrochemical impedance spectroscopy (EIS) effectively validated weight gain measurements indicative for corrosion.

Material evaluations under supercritical water conditions at 380°C and 500°C revealed high corrosion resistance across most materials, except for 316L stainless steel produced via cold spray, which exhibited notable susceptibility. Predictive models indicate that alloys 310S and 800H perform exceptionally well, with preliminary projected penetration rates below 20 µm after 30 000 hours of operation. The preliminary corrosion resistance ranking is: 310S ~ 800H > Alumina-forming austenitic (AFA) > 316L-CS. However, at 1 200°C in steam, both 310S and AFA experienced severe spallation.

Stress corrosion cracking evaluations showed no signs of cracking in 310S, 800H and AFA alloys at 380°C, with only minor indications at 500°C. Neutron irradiation up to 0.3 displacements per atom (dpa) did not significantly alter the corrosion behavior of 800H and 310S at 500°C and 25 MPa, although differences in mechanical properties were observed.

The group at the University of Science and Technology Beijing tried to replace part of the nickel (Ni) with manganese (Mn) for reduced neutron absorption and helium bubbles from alpha decay. The results showed that the addition of 4% Mn to substitute 2% Ni can inhibit B2-NiAl phase precipitation, increase the aspect ratio of the B2-NiAl phase, promote Laves phase precipitation and refine grain size. Mn reduced the stacking fault energy (SFE) of AFA steel and promoted the formation of coincidence site lattice (CSL) grain boundaries and Goss texture, which are beneficial for mechanical properties. After ageing at 700°C, the ultimate tensile strength (UTS) at room temperature and 700°C increased up to over 1 000 MPa and 300 MPa, while elongation kept above 35% and 60.5%, respectively (Figure SCWR-5).

The materials and chemistry group at Shanghai Jiao Tong University prepared and tested AFA steels with increased fractions of chromium (Cr) and Ni for reducing the general corrosion rate with refined grain size and increased ductility. Among the newly prepared AFA steels, 19Cr-2.5Al, which contains 19%Cr, 26%Ni and 2.5%Al, showed single austenitic phase and excellent general corrosion performances.

With the fast development of the nuclear power industry in China, Shanghai Nuclear Engineering and Design Institute, a major designer and construction contractor of nuclear power plants, has shown very high interest in R&D on SCWR, and a new project with a budget of around USD 200 million has been approved by Shanghai municipal government to fund the development of fuel-cladding materials for SCWR. AFA was proposed as the major candidate to be studied systematically. A new test loop for out-of-pile tests of fuel claddings is being funded to study the general corrosion, water chemistry and corrosion product deposition of fuel-cladding tubes under the conditions of internal heating and high flow rate of water.

In Canada, CNL completed the first phase of high-energy proton irradiations on two advanced nuclear materials – alloys 800H and 310S – at the TRIUMF proton accelerator facility. This study aims to assess the effect of irradiation dose on the microstructure and mechanical properties of the materials. Small punch testing was conducted on the proton-irradiated samples to determine the impact on tensile properties and estimate yield and ultimate tensile strengths. Additionally, Canada has measured the conductivity of oxides formed in supercritical water and is studying the effect of various coatings as protective barriers for materials in such environments. These collective findings offer valuable insights into the performance of materials under extreme SCWR conditions, supporting the advancement of safer and more efficient nuclear technologies.

Technical highlights – Licensing project

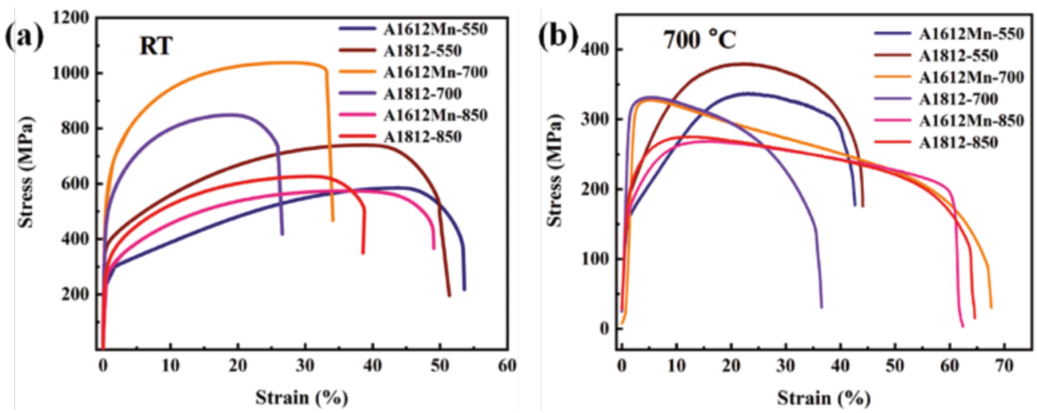
A pre-licensing study was conducted by international SCWR experts to identify SCWR specific safety criteria and to identify gaps in knowledge regarding the safety-related behavior of SCW-SMRs (Prošek and Cizelj, 2024). The study categorized safety criteria into three groups: 1) those that can be met with existing knowledge; 2) those that likely can be met with further research; and 3) those that will require design changes. This classification aims to address specific knowledge gaps, particularly regarding structural materials (of the reactor technology and the fuel cladding), radiation effects, validation of engineering simulation tools, core design, and the licensing process itself. As future SCW-SMR conceptual designs are in the scope of follow-up projects, as an example, the conceptual design of the European High-Performance Light Water Reactor was provided. This conceptual design serves as a reference to guide future development and identify critical areas for further research in SCW-SMR technology (Schulenberg and Starflinger, 2012).

Specific SCW-SMR aspects are absent in existing nuclear regulations. Thus, safety criteria must be developed alongside ECC-SMART design features. Four guiding principles have been developed that emphasize compatibility with new reactor safety elements, case-by-case application of SMR-specific elements, adherence to GIF safety requirements, and the need for robust safety demonstrations. ECC-SMART's safety principles should integrate prior standards, particularly using IAEA SSR-2/1 (Rev. 1) as a design basis.

A PIRT (Phenomena Identification and Ranking) analysis was conducted to evaluate phenomena based on importance and knowledge levels (Prošek and Cizelj, 2024). The report presents areas requiring further research to enhance the safety of SCW-SMR technology.

The scope of the pre-licensing study for SCW-SMR has also been outlined, covering the safety criteria and requirements for the SCW-SMR concept and presenting a review of two relevant IAEA standards – *Fundamental Safety Principles* (IAEA, 2006) and *Safety of Nuclear Power Plants: Design* (IAEA, 2016a) – for design and their applicability to SCW-SMRs. This report assesses conformance to Principle 3 (leadership and safety assessment) and Principle 8 (accident prevention) of the *Fundamental Safety Principles* (IAEA, 2006). In relation to the *Safety of Nuclear Power Plants: Design* (IAEA, 2016a), the report also provides: a description of the standard for the design selection process of relevant requirements; the applicability of selected requirements (i.e. 42 to 58) to SCWR; and safety considerations and options to enhance the performance of the engineered safety features of water-cooled SMRs, incorporating lessons learned from the Fukushima Daiichi accident (IAEA, 2016b).

Figure SCWR-5: Stress-strain curves of the AFA steels



Note: The stress-train curves of the AFA steels are shown at room temperature (a) and at 700°C (b).

The report also discusses conformance to 23 fuel safety criteria by the NEA (NEA, 2012). For each fuel criterion, a brief description is given first, followed by the requested information needed for future SCW-SMR conceptual design compliance judgement, the relation of each selected criterion with safety-related behavior of future SCW-SMR conceptual designs, and compliance of knowledge. The report examines the alignment of future SCW-SMR technology with Gen IV nuclear energy system goals.

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Chair of the SCWR SSC, with contributions from SCWR members

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Sodium-cooled fast reactor

The System Arrangement for Gen IV international R&D collaboration on the sodium-cooled fast reactor (SFR) nuclear energy system became effective in 2006 and was extended for a period of ten years in 2016. Several new members have been added to the original agreement, most recently the United Kingdom in 2019. The present signatories are: the China National Nuclear Corporation, China; the Alternative Energies and Atomic Energy Commission (CEA), France; the JRC, Euratom; the Japan Atomic Energy Agency (JAEA), Japan; the Ministry of Science and Information and Communication and Technology, Korea; Rosatom, Russia; the Department for Energy Security and Net Zero, United Kingdom; and the DOE, United States. Four technical projects have been established for GIF collaborations:

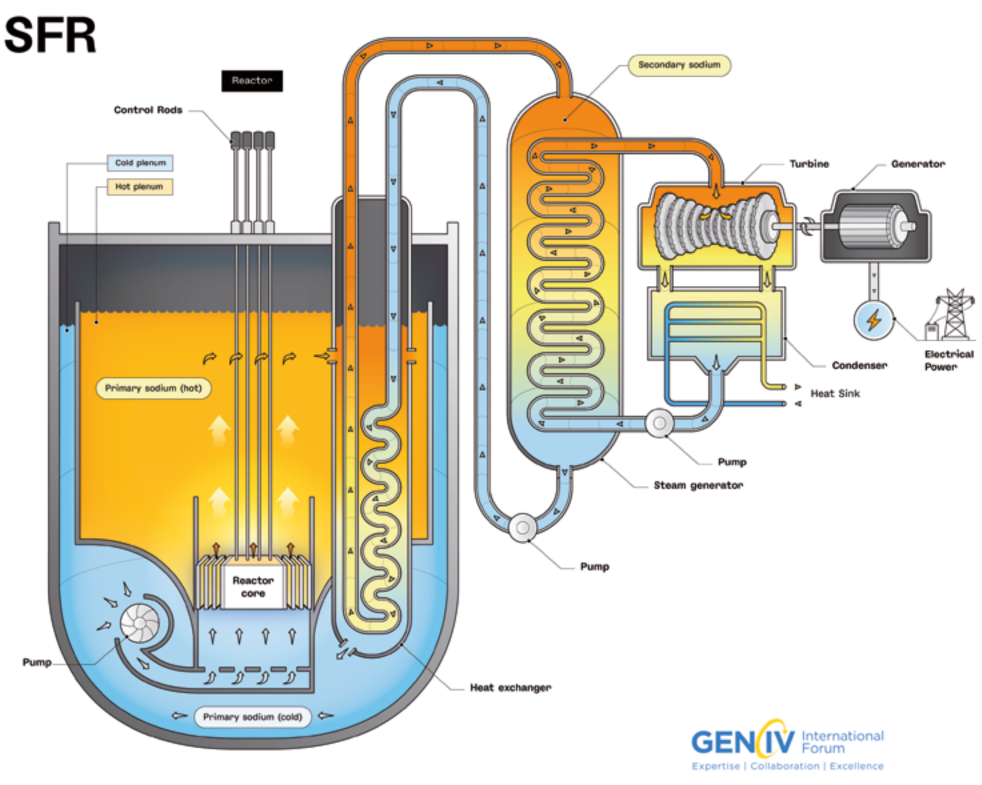
1) SFR system integration and assessment, with seven members participating;
2) SFR safety and operations, with six members participating;
3) SFR advanced fuels, with seven members participating;
4) SFR component design and balance-of-plant, with France, Japan, Korea and the United States as members.

Main characteristics of the system

The SFR system uses liquid sodium as the reactor coolant, allowing high-power density with low coolant volume fraction (Figure SFR-1).[1] Because of the advantageous thermophysical properties of sodium (high boiling point, suitable heat capacity and high thermal conductivity), there is significant thermal inertia in the primary coolant. While the low oxygen content environment reduces corrosion, sodium reacts chemically with air and water and requires a sealed coolant system. The primary system operates at near-atmospheric pressure, with typical core outlet temperatures of 500-550°C. In these conditions, austenitic and ferritic steel structural materials can be used and are highly compatible with sodium, while a large margin to coolant boiling at low pressure can be maintained. The reactor unit can be arranged in a pool or a compact loop layout. Table SFR-1 summarizes the typical design parameters of the SFR concepts being developed by GIF members, with plant sizes ranging from small modular systems to large monolithic reactors being considered.

Three general classes of SFR design concepts have been identified for Gen IV SFR research collaboration: loop configuration, pool configuration and SMRs. Within this structure, several design tracks that vary in size, key features (e.g. fuel type)

Figure SFR-1: GIF sodium-cooled fast reactor



1. www.gen-4.org/generation-iv-criteria-and-technologies/sodium-fast-reactor-sfr.

and safety approaches have been identified with pre-conceptual design contributions by Gen IV SFR members. These are the Chinese sodium-cooled fast reactor (CFR1200, China), the European SFR (ESFR, Euratom), the Japanese sodium-cooled fast reactor (JSFR, Japan), Korea's advanced liquid metal reactor (KALIMER, Korea), the BN-1200 (Russia) and the advanced fast reactor (AFR-100, United States). Gen IV SFR design tracks incorporate significant technology innovations to reduce capital costs through a combination of configuration simplicity, modular construction, compact systems and components, advanced fuels and materials, and refined safety systems. They are thus used to guide and assess Gen IV SFR R&D collaborations.

Table SFR-1: **Typical design parameters for the Gen IV sodium-cooled fast reactor**

Reactor parameters	Reference value
Outlet temperature	500-550°C (often close to 550°C)
Pressure	~0.1 MPa
Power rating	30-5 000 MWt (10-2 000 MWe)
Fuel	Oxide, metal alloy and others
Cladding	Ferritic-martensitic, ODS and others
Average burnup	150 GWtD/MTHM
Breeding ratio	0.5-1.30

Note: MWt: megawatt thermal; MWe: megawatt electrical; ODS: oxide dispersion-strengthened; GWtD/MTHM: gigawatt thermal days per metric ton of heavy metal.

Industry engagement and near-term demonstrations

The SFR System Steering Committee hosted a panel session for SFR demonstrations at the Generation 4 Small Reactors International Conference (G4SR-4) in October 2022 in Toronto and invited international SFR companies to discuss potential collaboration opportunities to accelerate the demonstration of Gen IV SFRs. Several SFR companies were interested in collaborating through existing or new GIF projects. Follow-up discussions have since taken place between GIF and some companies. This is the first time in a decade that a GIF project will involve industry members. As of November 2024, TerraPower, Oklo, DOE (US), JAEA (Japan), and KAERI (Korea) have completed negotiations for the project arrangement, which has been sent to members for formal signatures.

In the near term, SFR demonstrations continue to be developed in GIF countries. China continues the operation of the China Experimental Fast Reactor with 20 MWe and the construction of two CFR-600 units, which are demonstration SFRs generating 600 MWe (WNN, 2020). China is also planning to build a commercial-scale unit with a capacity of 1 000-1 200 MWe (WNN, 2021). Based on metal-fuel and pyro-processing technologies, China is developing integrated fast reactor systems with a capacity of 1 000-1 200 MWe. To accelerate R&D, and with joint efforts from the whole nuclear industry and research institutes, an innovation consortium led by China National Nuclear Corporation (CNNC) was established in August 2024 (CNNC, 2024).

Within the EU's research and innovation funding program Horizon Europe, the Euratom Research and Training Program is funding the ESFR-SIMPLE project as a follow-up of the previous ESFR-SMART project (2014-2018) to further improve the ESFR concept, which is a large pool-type SFR developed by 25 European partners within the ESFR project (2009-2013) (CORDIS, 2019). The ESFR-SIMPLE project aims to improve the safety of the European SFR through innovative monitoring, power level flexibility and experimental research (ESFR-SIMPLE, 2025). In addition, the Sustainable Nuclear Energy Technology Platform (SNETP), through the European Sustainable Nuclear Industrial Initiative (ESNII), supports FR R&D coordination activities (SNTEP, 2025).

In France, a wide-ranging investment plan, France 2030, was set up in October 2021 to transform key sectors of the French economy through innovation, industrialization and research. Support from France 2030 includes developments focusing on disruptive nuclear reactor concepts and the fostering of new, emerging players. A first call for proposals was launched in 2022 aimed at start-ups involved with the development of innovative modular nuclear (fission or fusion). Currently, 11 projects have been selected, two of which are being led by new companies HEXANA and OTRERA to develop new reactors based on SFR technology.

In Japan, the Fast Reactor Cycle System Project Management Office was established within JAEA in July 2024, based on the Strategic Roadmap for Fast Reactor Development, which was revised in 2022. This office has begun conceptual design of a demonstration SFR until 2028 in cooperation with Mitsubishi Heavy Industry Co., Ltd, which was chosen as the core company for the design, manufacturing and construction.

In Korea, the engineering design of Prototype Gen IV Sodium-cooled Fast Reactor (PGSFR) was completed in 2020, and a new SFR program is underway aimed at developing an SFR-based SMR (SALUS). SALUS will be a pool-type SFR with an electric output of 100 MWe. It will operate on a 20-year refueling cycle utilizing metal fuel (Eoh et al., 2024). On 4 June 2024, the Korean government announced an investment of USD 1.8 billion to develop next-generation SMR technologies by 2034. This initiative aims to foster private companies capable of building and commercializing next-generation SMRs. To support the deployment of fourth-generation SMRs, including SFRs, high-temperature gas-cooled reactors (HTGRs) and MSRs, the government released a specific roadmap in December 2024. Additionally, an R&D research association has been established to implement the government's *Strategy for Promoting Public-Private Cooperation in Next-Generation SMRs*. This R&D research association will be led by the government, and the memorandum of understanding (MOU) signing was completed with eight domestic leading engineering, procurement, and construction companies. This MOU is designed to accelerate the development of Gen IV nuclear reactors through public-private matching funds.

Russia is operating commercial SFRs such as the BN-600 and BN-800. The BN 600 first began its operation in 1981, extended its operating license by a further five years in 2020, and is seeking a further license extension to 2040 (WNN, 2024a). The BN-800, which entered commercial operation in 2016 with uranium oxide (UO_2) fuel, was fully loaded with uranium-plutonium mixed oxide (MOX) fuel and continues its operation (WNN, 2022). The construction of BN-1200 is planned to start in 2027 (WNN, 2024b).

In the United Kingdom, the Department for Energy Security and Net Zero is providing funding for the Advanced Modular Reactor (AMR) Knowledge Capture Project to facilitate knowledge capture and sharing with the aim of reducing the time, risk and cost of AMR deployment. The project includes the collection and transfer of all legacy knowledge gained in developing a range or reactor types, including SFR (Bangor University, 2023).

In the United States, the first Natrium demonstration SFR plant by TerraPower/GE-Hitachi is planned for construction in Kemmerer, Wyoming. The plant's construction permit application was submitted to the US NRC in March 2024, and groundbreaking for the non-nuclear portion of the unit took place on 10 June 2024 (TerraPower, 2025a). Natrium is an 840 MWt pool-type SFR that contains a compact nuclear grade footprint and a molten salt energy storage system which enables the plant to vary its supply of energy to the grid, up to 500 MWe net, while maintaining constant reactor power. The design and construction is funded by a public-private partnership through the US DOE Advanced Reactor Demonstration Program, which authorizes a 50/50 cost share (TerraPower, 2025b). In addition, two other US SFR companies, Oklo and ARC Clean Technology (ARC, 2025), have commercialization efforts underway. Both designs are based on metal alloy fuel, sodium coolant, and have the potential for recycling. In January 2024, the Safety Design Strategy for Oklo's Aurora Fuel Fabrication Facility in Idaho was approved (Oklo, 2024a), and the company began public trading on the New York Stock Exchange on 10 May 2024 (Oklo, 2024b).

Technical highlights – System integration and assessment project

The CEA continues to consider the application of a selected set of GIF Safety Design Criteria and Safety Desing Guidelines (SDC-SDG) to the ASTRID-600 plant design with the aim of providing recommendations and highlighting potential gaps. A 2024 contribution reviewed the application of the SDC-SDG related to prevent significant energy release during a core damage accident. The ASTRID-600 adopted a low sodium void worth core concept for limiting total reactivity during unprotected transients. A core catcher is also equipped at the bottom of the primary vessel as a mitigation measure of a large-scale core melt. The out-of-vessel fission chamber power level detectors in ASTRID can be considered as a particular class of severe accident instrumentation to diagnose conditions of the reactor core during the core degradation. From these assessments, the CEA confirmed that the ASTRID-600 design met all essential requirements of the SDC-SDG.

The ESFR concept is being further developed within the Euratom project, ESFR SIMPLE, which focuses on innovative monitoring, power level flexibility and experimental research. The Euratom contribution looks at the safety of a metallic fuel core option, including the methodology for the design of the safety architecture and for the demonstration of the safety provisions. The safety approach for the ESFR concept relies mainly on the European Safety Framework developed for new LWRs (in particular the European Utility Requirements and the safety approach for European Pressurized Reactors [EPR]) and on SFR operational and licensing feedback. The systems, structures and components are identified and classified with respect to their safety importance, and requirements are defined in accordance with their safety classification. The general safety objectives are completed by a set of more practical qualitative and quantitative safety targets to guide the safety design. No specific safety concerns have been identified in relation to a metallic fuel core.

The JAEA are applying the SDC-SDG to the pool-type JSFR to draw recommendations on how to apply the guidelines to a specific SFR design and to highlight any potential gaps. Following the decay heat removal systems study last year, the validity of the reactivity shutdown systems (RSS) of the pool-type JSFR were assessed according to the SDC-SDG. The assessment concludes that the primary RSS with mechanical de-latch devices accelerated by gas pressure for insertion of the control rods and the back-up RSS with electromagnets for the detachment devices with the flat contact meet the GIF SDC-SDG. The reliability of the RSS was also evaluated by deterministic and probabilistic analyses. Owing to the stiff core support with seismic isolation of the reactor building, the core seismic analysis demonstrated that the failure of rod insertion would be extremely unlikely, hence subcriticality is maintained.

KAERI contributed to the evaluation of uncertainty on physics parameters for a transuranic metal-fuel core. In this study, the feasibility of applying the bias trending approach, which in previous work was established for the evaluation of uncertainty of multiplication factor, to quantify the uncertainty of reactivity changes such as control rod worth and sodium void reactivity worth was assessed. However, there are issues with this approach, such as a lack of validation data with high similarity to obtain a reliable bias trend. The relative uncertainties of both the total rod worth and the sodium reactivity for inner core void scenario were evaluated (Jo et al., 2024). As a future plan, uncertainty quantification for the depleted transuranic core considering the fission yield covariance will be conducted.

Rostom carried out scenario studies of a two-component energy system, which is a closed fuel cycle with thermal and fast reactors, to assess its impacts and benefits. Results show that a phased transition into this two-component system enables a closed fuel cycle with various potential targeted benefits (minor actinide burning, isotope production, recycling, hydrogen production, etc.) while potentially reducing infrastructure costs and the unit levelized cost of electricity production.

ANL and PSI have made joint contributions to the Euratom project ESFR-SIMPLE, which includes an integrated system design and assessment of a metal alloy-fuelled SFR design option. As one of the first activities, ANL developed a suite of benchmarking cases for metallic fuel performance under steady-state and transient conditions to support the verification and calibration of European and US software. The results of the reference and parametric studies from this report will also support the design of the ESFR-SIMPLE metallic core and provide meaningful insights on metallic fuel behavior.

Technical highlights – Safety and operations project

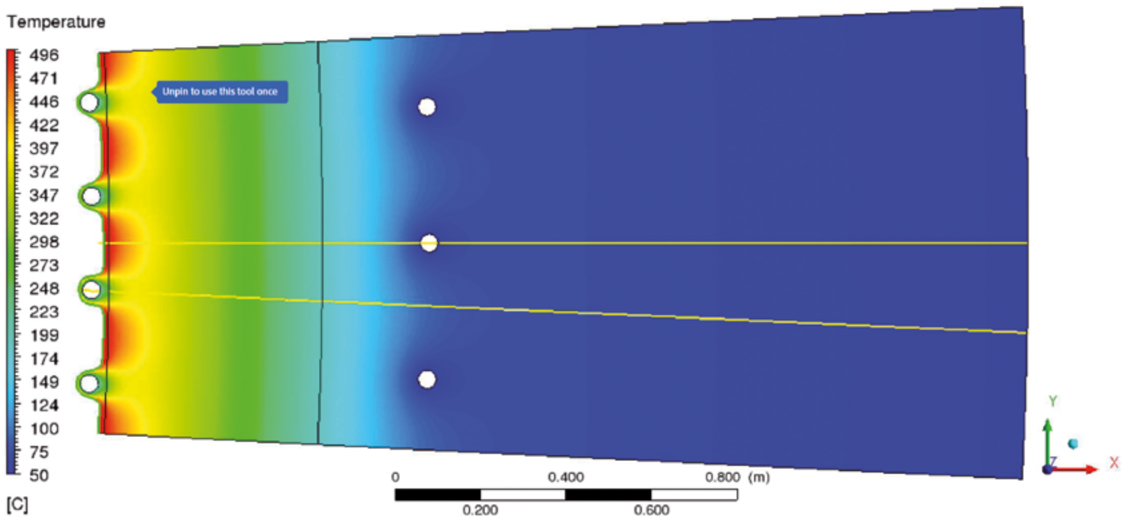
The CIAE investigated the feasibility of a loop-type SFR with a 0.5 gigawatt hour (GWh) heat storage based on its pool-type SFR design concept, which has a molten salt thermal energy heat storage system consisting of a 280 MWt core, and a heat storage system designed in a previous study. The CIAE conducted a preliminary safety analysis using a numerical model developed for its loop-type SFR with storage.

The CEA has been preparing the Severe Accident In-pile experiments for Gen IV reactors and ASTRID project (SAIGA) test to study the efficiency of corium transfer tubes in an SFR core in case of severe accidents. The multi-assembly test consists of two fuel bundles with different powers and one transfer tube in the Impulse Graphite Reactor. This project is managed by NNC-RK (Kazakhstan) in tight collaboration with the CEA. SIMMER-V pre-calculations performed by the CEA show that fuel-pin degradation, transfer tube wall break-up and molten materials relocation occur. The CEA also conducted calculations to support an NNC safety analysis as a part of the preparation of this test. Experimental components and equipment such as sodium loop, UO_2 fresh fuels and instrumentations are being manufactured. The test is planned for the end of 2025.

The CEA carried out the conceptual design of a future experimental platform called newPLINIUS, with the basic design stage now initiated. The new facility is planned to include a 100-kg cold-crucible induction system, experimental halls for fuel-coolant interaction and corium-material interaction, and a thermophysical properties laboratory. A test of melting 55 kg zirconium dioxide (ZrO_2) as a surrogate for corium has been successfully carried out. A program of commissioning tests such as a melt release system, in-service reloading and metal-containing loads is underway.

Euratom evaluated decay heat removal system performance in the ESFR-SMART reactor to examine the effectiveness of three system types, analysing a protected station blackout transient scenario using different system codes: TRACE, SIM-SFR, RELAP5-Na and CATHARE. The first system is implemented at each of the six intermediate heat exchangers, and the heat is rejected to the environment using a sodium/air heat exchanger. The second system encloses modularized steam generators and uses air in natural or forced convection to cool these modules. The third system uses two independ-

Figure SFR-2: **Assessment of the DHRS-3 system using computational fluid dynamics**



Source: Lombardo et al. (2021).

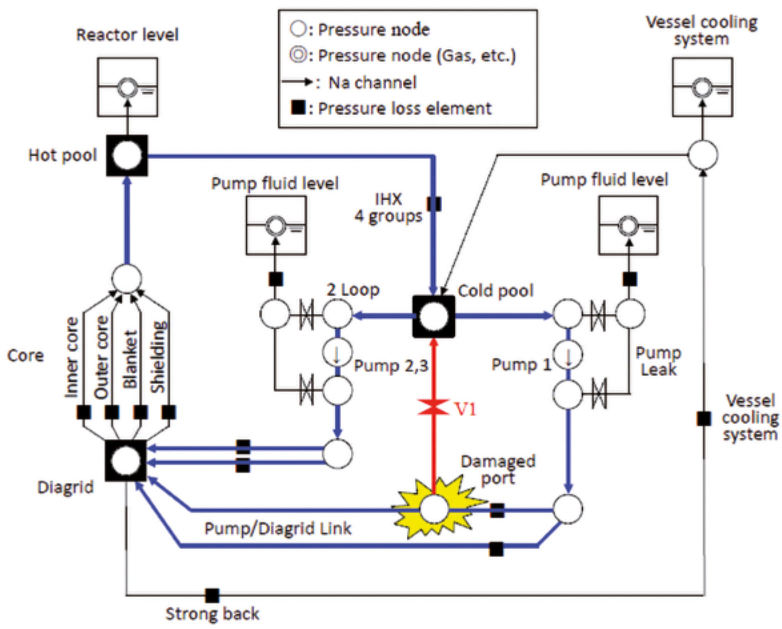
ent active cooling systems: 1) an oil-cooled system installed in the gap between the insulation and the reactor vessel or inside the insulation; and 2) a water-cooled system for the concrete to maintain a temperature under 70°C in all situations, even if the oil system is lost. The analysis shows that the ESFR-SMART reactor can be safely cooled down using the first system. It also found that for the second system, no coolant boiling occurred, but the temperatures of the vessel and main structures exceeded the design temperature limit of 650°C. For the third system (Figure SFR-2), the analysis found that the oil cooling system was too close to the heat source, and the number of water cooling pipes should be increased to operate at moderate cooling temperatures.

Euratom also conducted the verification of its numerical models for the evaluation of the ESFR's two groups of absorber rods for reactor shutdown: control and shutdown devices/rods and diversified shutdown devices/rods. Two diversified shutdown device options are employed in the ESFR: a Curie Point Electromagnetic lock option and a hydraulically suspended option. To verify calculation models for the prediction of effectiveness of DSDs during accidents, Euratom conducted simulations such as scenarios of unprotected loss-of-flow with either device or unprotected loss-of-heat-sink with the electromagnetic device using a variety of system codes such as SIM-SFR, CATHARE and RELAP5. All three codes calculated very similar core power evolutions in each event.

The JAEA used the FINAS/STAR code to conduct a structural analysis under extreme high temperature of a protected loss-of-heat-sink event for a top supported reactor vessel design of the next-generation loop-type SFR. The purposes of this study are to understand the reactor vessel deformation behavior, to clarify the effect of the internal pressure and to investigate counter measures against the internal pressure during a protected loss-of-heat-sink event. The results show that the depressurization due to a rupture disk is necessary to improve the grace period for accident management. Additional simulations compared design options of a simple flat-bottom or curved-bottom containment vessel. Results indicate that the curved-bottom structure contributes to enhancing the structural resilience by smoothly supporting the vessel and constraining downward deformation.

To ensure the detectability of a pipeline rupture event in a 1 500 MWt pool-type SFR, the JAEA examined available plant protection signals using a reactor system dynamic response analysis, assuming a guillotine-like large break in a single primary pipe (for a configuration with three pumps and two pipes per pump, as shown in Figure SFR-3) during normal power operation and 30% partial power operation. For considering the uncertainty of the analysis, the JAEA prepared and used two combinations of reactivity parameter sets to represent a rapid power increase and a slow power increase within uncertainty ranges of parameters. The analysis concluded that the event is detectable by monitoring five signals: 1) neutron flux at high-power range; 2) primary flow rate to neutron flux ratio; 3) primary pump speed to neutron flux ratio; 4) primary pump sodium level; and 5) reactivity. The results of this analysis also indicate that in the rated and partial power states, at least one independent signal is secured for each of the main shutdown systems and the back-up system.

Figure SFR-3: Plant dynamics model for evaluation of pipe break detectability



Source: JAEA.

KAERI conducted benchmark analyses of shared Experimental Breeder Reactor-II (EBR-II) transient test results by employing its GAMMA+ code. In the previous study, the measured reactor power was imposed as a boundary condition. In this study, the analysis was performed with a point kinetic model. The calculation results reasonably agreed with the measured data. KAERI is planning to improve a core radial expansion reactivity feedback model.

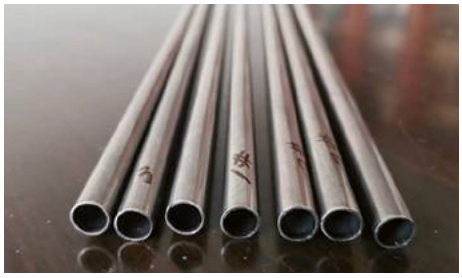
KAERI selected a two-train decay heat removal system in STELLA-2 for preliminary code analyses, and developed its numerical model by using its system code MARS-LMR. The simulation predicted that the flow would be maintained by natural circulation after the pumps stop. The simulation results commonly underestimated the flow rate, which results in overestimated core outlet temperatures. General temperature trends were similar between simulation and experiments, while the peak temperatures and the elapsed time to reach the peaks differed. These differences are mainly caused by the primary flow rate and heat loss. The major heat loss was identified to be the hot pool due to the internal structure through the reactor head. KAERI is working on implementing a simple model to account for heat loss in this region.

Technical highlights – Advanced fuels project

The CIAE has been developing oxide dispersion-strengthened (ODS) steel tubes for metal-fuel claddings. As a part of this R&D, CIAE has undertaken the composition design, microstructure characterizations, thermophysical properties measurements (thermal expansion coefficient, thermal conductivity and specific heat) and a test of tube rolling of ODS steel. The CIAE obtained rolled ODS alloy (Fe-11Cr with yttrium oxide (Y_2O_3) dispersion particles) cladding tubes (Figure SFR-4) and confirmed that the mechanical properties of ODS bars and tubes meet their design requirements of a yield strength not less than 430 MPa, elongation >10% at 650°C.

The CEA conducted a study looking at optimizing a co-milling powder metallurgy stoichiometry for manufacturing MOX considering high plutonium (Pu) content (60-70% of heavy metal) for thermophysical properties measurements and characterization of these samples. A higher Pu content is expected at the center of the pellet due to the redistribution of plutonium caused by the thermal gradient along the fuel pellet radius during irradiation, which results in a decrease of the melting temperature. However, there is a lack of experimental data on the thermal properties for a Pu content above 0.45. As the first step to fill this gap, the CEA optimized each sample manufacturing step such as blending, co-milling, sieving, pelletizing and sintering in order to obtain dense, monophasic, stoichiometric and homogenous materials for suitable samples. A multi-scale characterization strategy was then used to determine sample microstructural properties, including density measurements, thermal-ionization mass spectrometer (TIMS), ceramography, electron probe micro analyses (EPMA), µ-Raman spectroscopy and X-ray diffraction (XRD). The results obtained show that dense (> 95% theoretical density), homogenous (chemical distribution of cations and oxygen), monophasic and stoichiometric (oxygen-to-metal ratio = 2.00) samples were achieved (Desagulier et al., 2024).

Figure SFR-4: **ODS cladding tubes for metal-fuel cladding**



Note: Tubes have outer diameter of 9 mm, wall thickness of not less than 0.62 mm and length greater than 3 m.

To investigate the effect of oxygen vacancies on thermodynamic properties, the CEA carried out molecular dynamics simulations to compute the main properties of sub-stoichiometric MOX fuels (oxygen-to-metal ratio less than 2) such as enthalpy and heat capacity, lattice parameter and thermal expansion, and elastic properties. The simulations covered the whole range of Pu content (0-100%), the oxygen-to-metal (O/M) ratios of 1.92-2.0, and high temperatures from 1 000 Kelvin (K) to melting points. At low temperatures up to 2 000 K, the calculation results were in good agreement with the experimental data. At high temperatures, notable discrepancies emerged, which could be due to the uncertainties associated with measurements under extreme conditions and/or difficulty of accurately controlling the O/M ratio (Porto et al., 2024).

The JAEA investigated the dependence of Pu content on the oxygen potential of MOX. The oxygen potential of MOX fuel is thermodynamic data used to evaluate the O/M ratio, and is therefore an important property in fuel production and the analysis of irradiation behavior. In this study, the oxygen potential of MOX with plutonium content 4-8% was obtained. The new data allows for the evaluation of the oxygen potential of MOX with a wider Pu range. From the oxygen potential data, the dependence of Pu content on defect structure was also analysed.

The JAEA also studied the phase separation of MOX. The phase separation of MOX that occurs in the region of low O/M ratio is an important phenomenon that affects the occurrence of microcracks in pellets and the redox behavior of MOX. In this study, phase separation data on PuO_2 and MOX with Pu=0.3 and 0.45 was experimentally obtained. From the data obtained, the relationship between temperature at which the phase separation occurs and the corresponding O/M ratio for each composition were analysed. The existing phase diagram of a U-Pu-O system was reevaluated based on the analysis (Vauchy et al., 2024).

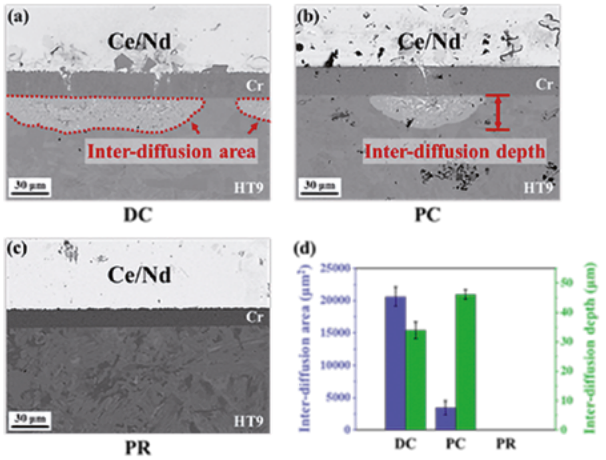
In Japan, 20% cold-worked modified 316 austenitic stainless steel (PNC316) has been widely used as claddings and wrapper tubes in the experimental SFR Joyo and the prototype SFR Monju, and is planned to be applied for claddings in an early stage of a future demonstration reactor. JAEA extended the database of properties of PNC316 after neutron irradiation by examining claddings and wrappers irradiated in Joyo at irradiation temperatures between 400°C and 735°C and fast neutron doses ranging from 21 to 125 dpa (Yano et al., 2024).

KAERI has been developing a transuranic burner core concept with three layers of different fuel zones in terms of fuel height, smear density and fuel rod diameter, assuming metal alloy fuel composition with 49% TRU, 5% rare-earths and 25% zirconium. To ensure fuel rod integrity and functional requirements, KAERI conducted a preliminary performance evaluation of fuels under its design criteria: total diametral inelastic strain of the cladding shall be less than 1%, cumulative damage fraction (CDF) of cladding shall be less than 0.05, and fuel slug melting shall not occur (<1 150°C for U-49TRU-5RE-25Zr). KAERI confirmed that the design criteria are satisfied under normal operating conditions in terms of peak linear power, peak burnup, peak cladding mid-wall temperature, maximum fuel centerline temperature, cladding strain and CDF.

KAERI has been developing barrier cladding tube technology to suppress fuel-cladding chemical interactions (FCCI), particularly for minor actinide-bearing metal fuel, using an electroplating method. KAERI continues investigating the influence on the property of barrier of three options of electroplating: direct current, pulse current and pulse-reverse current. FCCI tests using cerium/neodymium (Ce/Nd) at 650°C confirmed that the pulse-reverse coating demonstrated excellent diffusion barrier performance, with no Ce/Nd diffusion into the steel substrate, unlike the significant diffusion observed with other coatings (Figure SFR-5). Scanning Electron Microscope, Electron BackScatter Diffraction and Thermal Desorption Spectrometry analyses indicate that pulse-reverse electroplating maintains stable bcc chromium structures and exhibits the lowest hydrogen content, even under SFR operating conditions, thereby effectively mitigating FCCI (Yoo et al., 2024).

The DOE recognizes that FCCI is a key life-limiting phenomenon in the metal-fuel design and has identified an R&D gap due to uncertainties and limited data, especially for prototypic length fuel. Thus, it has been conducting new FCCI measurements and evaluations of legacy metallic fuel pins irradiated in the EBR-II and Fast Flux Test Facility to achieve a reliable, reproducible and statistically robust analysis of FCCI under various operational conditions. A holistic approach is being adopted, which includes simulations of legacy fuel performance for guiding sampling, electron microscopy techniques for observing clear contrast for FCCI zones (inter-infiltration of cladding and fission product elements) and a computer-assisted analysis of post-irradiation examination data. The examination of the effect of temperature and burnup on FCCI emphasizes the importance of temperature on FCCI. Intense Fe infiltration into the fuel and high lanthanide infiltration into the cladding were observed in high-temperature and low-burnup conditions, while they were limited in low temperature and high burnup conditions.

Figure SFR-5: **SEM-BSE images for FCCI testing of Cr barrier**



Note: (a) FCCI layer scan for direct current coating; (b) pulse current coating; (c) pulse-reverse current coating; (d) comparison of the inter-diffusion area and depths.

The DOE carried out a study to assess the material balance of the injection casting metal-fuel production process by using the process data from EBR-II to identify potential issues regarding efficiency and waste management (material loss) and to obtain feedback for a commercial process. Metal-fuelled reactors are basing the near-term commercial fabrication of metal fuel on the legacy EBR-II fuel fabrication process. Through the investigation, the production rate was estimated to be 36.4 kg/3 days (limited batch throughput). In terms of material efficiency, most of the fuel material "waste" was recycled in the process. However, approximately 4.5% of the material would require further processing. In the case of molds for the injection casting, quartz waste was produced. Eliminating molds or making them reusable was identified as an improvement. Extrusion and continuous casting were also considered as promising alternatives for longer-term commercial application.

Technical highlights – Component design and balance-of-plant project

The consequences of sodium-water reactions (SWR) in an open environment is being studied in France. SWR is a complex interaction that involves both physical and chemical processes. The reaction is fast, exothermic and can be explosive under particular conditions. This work focuses on how SWR can trigger explosions, which is not fully understood. The objective is to accurately identify the onset process of explosive sodium-water interaction, first by investigating the formation and evolution of the gas film between reactants (small-scale experiments with a high-speed camera), and second by improving the phenomenological model and realizing numerical simulations.

An experimental campaign was carried out with the aim of deepening knowledge on SWR in an open environment, to determine the influence of the initial water temperature on the runaway and to study the initiation of the reaction. Tests consisted of propelling (by pushing with argon gas) 1 g of solid sodium, in the form of a ball, into excess water at a desired temperature. The implementation of suitable instrumentation (pressure and temperature sensors) and rapid visualization of up to 130 000 frames per second has allowed the collection of fundamental data for parametric analysis and phenomenological study.

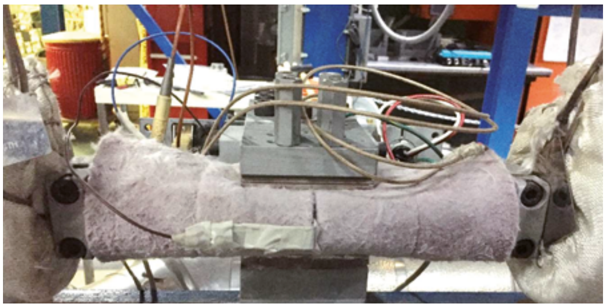
Various SWR models have been suggested in the past, but there are still uncertainties. For example, a simplified modeling of a sodium sample inside water has been proposed. The sodium, surrounded by a gas film throughout which steam diffuses, is assimilated to a heat sink absorbing energy produced at its surface by the chemical reaction. The results are consistent with experimental observations, which strengthen the proposed phenomenology, confirm the critical role of sodium vaporisation in the onset of runaways and set a basis for future modeling developments.

The JAEA has been developing a 3D seismic isolation system by using rubber bearings as a key device for plant operation technology. In 2024, the results from the seismic response analyses of 2D (horizontal) and 3D (horizontal + vertical) seismic isolation systems were reported and compared. The comparison proves that the 3D isolation system is superior to the 2D isolation system from the viewpoint of reducing the vertical floor response. The JAEA continues to develop R&D topics, including dynamic loading experiments, confirmation of the reliability of long-term use, and standardization of each component and integrated unit.

KAERI has been developing a plate-type ultrasonic waveguide sensor array for under sodium viewing. In 2024, several basic experiments were carried out at high temperature using silicone oil in a newly constructed test facility for the design of a plate-type ultrasonic waveguide sensor array. Beam profiles of leaky waves were measured under different temperature conditions. Tests at different distances between the sensor and the target were also conducted to determine the receiving face angle of the receiving sensor in the sensor array. The results were not clear enough due to the natural circulation of silicone oil, indicating the necessity of additional insulation to reduce the temperature variation causing natural circulation.

KAERI has also been studying a Raman distributed temperature sensing monitoring system for advanced instrumentation in high-temperature sodium loops. In 2024, the test section with two cartridge heaters for simulating a straight pipe and a curved pipe was fabricated, and thermocouples, insulators, a reference component and the monitoring equipment were installed. To identify instrumentation issues, preliminary tests were conducted, and issues found included the necessity of insulation of unheated sections of heaters, a heater power monitoring system for further analysis (uncertainty analysis, etc.) and improvements of optical fiber sensor reliability through the installation of dummy fibers. The test equipment was enhanced to address the instrumentation issues and will be used to test the high-fidelity distributed sensing and monitoring system in a high-temperature environment.

Figure SFR-6: **Permanent magnetic flowmeter installed at METL facility**



In the United States, the Mechanisms Engineering Test Loop (METL) facility is an intermediate-scale facility for testing systems and components in sodium. The facility has a purification and diagnostic loop with flow meters based upon Hall effect sensors. These flow meters had degraded due to temperature and needed to be replaced. After evaluation, it was decided to convert the flowmeters to permanent magnetic flowmeters. Design requirements such as reuse of the existing conduit and structure, temperature limit, necessary signal strength, and measurement ranges were examined. A new flowmeter was designed, fabricated and installed at the facility (Figure SFR-6). The converted flowmeters were experimentally calibrated by pushing sodium from the expansion tank to an empty vessel. Through this work, several lessons were learned, such as the use of higher temperature rated magnets to avoid overheating, a custom designed mount for flexibility in the design, and streamlined implementation. These lessons will be used to upgrade the main loop flowmeter and recalibrate the flowmeters.

Bo Feng
Chair of the SFR SSC,
with contributions from SFR members

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Very-high-temperature reactor

The System Arrangement for Gen IV international R&D collaboration on the very high-temperature reactor (VHTR) was extended in 2016 for ten years. The current signatories are Australia, Canada, China, Euratom, France, Japan, Korea, Switzerland, the United Kingdom and the United States. The VHTR System Research Plan outlines four active projects with the following members and observers:

1) **VHTR fuel and fuel cycle**: China, Euratom, France, Japan, Korea and the United States as members. Canada and the United Kingdom are currently observers.
2) **VHTR materials**: Australia, Canada, China, Euratom, France, Japan, Korea, Switzerland, the United Kingdom and the United States as members.
3) **VHTR hydrogen production**: Canada, Euratom, France, Japan, Korea and the United States as members. China, Switzerland and the United Kingdom are currently observers.
4) **VHTR computational methods validation and benchmarks**: China, Euratom, Japan, Korea and the United States as members. Australia, Canada and the United Kingdom are currently observers.

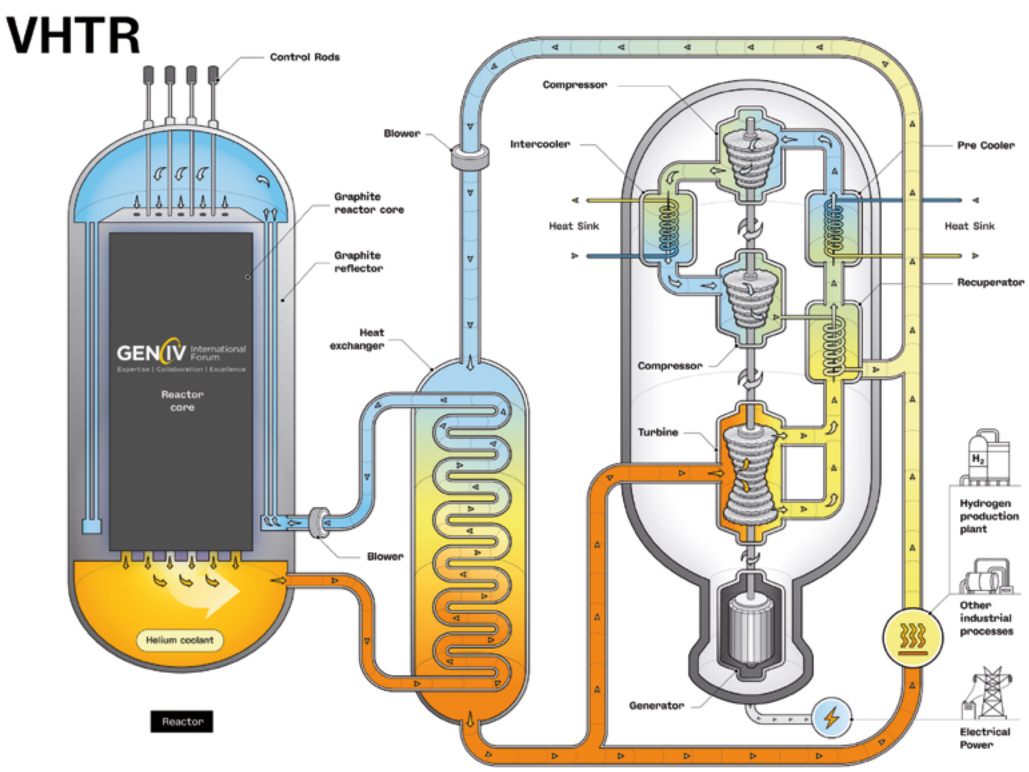
High core outlet temperatures enable high efficiencies for power conversion and hydrogen production, as well as cogeneration of high steam qualities (superheated or supercritical). Current VHTR R&D focuses on the demonstration of inherent safety features and high fuel performance, hydrogen production, the validation of new computational methods and code developments, coupling with process heat applications, cogeneration of heat and power, and the resolution of potential conflicts between these challenging goals. The international HTGR community, including GIF VHTR SSC members, gathered at the High-Temperature Reactor (HTR) 2024 conference hosted by the Institute of Nuclear and New Energy Technology (INET) on 14-18 October 2024 in Beijing, China, providing a panoptic of progress on the technology globally.

In terms of GIF VHTR SSC collaboration activities in 2024, the GIF Risk and Safety Working Group (RSWG) and the Proliferation Resistance and Physical Protection Working Group (PRPPWG) are working on a joint study on Safety, Security and Safeguards by Design ("3S"). This joint study utilizes a generic pebble-bed HTGR model developed by the DOE.

Main characteristics of the system

HTGRs are helium-cooled graphite-moderated nuclear fission reactors that use fully ceramic tri-structural isotropic (TRISO)-coated particle-based fuels (Figure VHTR-1).[1] They are characterized by inherent safety

Figure VHTR-1: **GIF VHTR gas reactor**



1. www.gen-4.org/generation-iv-criteria-and-technologies/very-high-temperature-reactor-vhtr.

features, excellent fission product retention in the fuel, and high-temperature operation suitable for the high-efficiency generation of power and industrial process heat, particularly for hydrogen production. Typical coolant outlet temperatures range between 700°C and 950°C, thus enabling power conversion efficiencies of up to 48%. The VHTR is understood to be a longer-term evolution of the HTGR, targeting even greater efficiency and more versatile use by further increasing the helium outlet temperature to 1 000°C or higher, which will require new structural materials, especially for the intermediate heat exchanger. Power conversion options include indirect Rankine cycles or direct or indirect Brayton cycles.

The operational envelope of HTGRs can be adapted to specific end-user needs, and a significant near-term market exists for process steam of approximately 400-550°C, which is achievable with lower temperature HTGR designs. Inherent safety in accident conditions is assured by the low power densities and high thermal inertia of typical HTGR designs. The potential for high fuel burnup (150-200 gigawatt days per metric ton of heavy metal [GWtd/tHM]), high efficiency and modular construction are all advantages that favor commercial HTGR deployment.

The HTGR standard fuel form is based on UO_2 TRISO-coated particles (UO_2 kernel, buffer/inner pyrocarbon/silicon carbonide/outer pyrocarbon coatings) embedded in a graphite matrix, which is then formed either into 6 cm diameter pebbles or compacts of various geometries embedded in hexagonal fuel blocks. This fuel form exhibits temperature tolerance of 1 600°C in accident situations, with sufficient safety margin. Recent research has shown that the safety performance may be further enhanced through using a uranium oxycarbide (UCO) fuel kernel, a zirconium carbide coating layer instead of silicon carbide (SiC), or the replacement of the graphite matrix material with SiC.

The current HTGR fuel cycle is a once through, very high burnup, low-enriched uranium fuel cycle, with solutions to adequately manage the back-end of the fuel cycle or synergetic fuel cycles under investigation. Significant research is being performed internationally on TRISO and graphite waste processing, in particular to reduce waste volumes.

High-temperature reactor demonstration projects

Several demonstration projects are currently being pursued to meet the needs of industries interested in electrical and process heat applications. Both prismatic and pebble-bed HTGR designs are being developed, ranging from small transportable units with typical power outputs of less than 10 MWt to multi-unit plants generating more than 1 000 MWt.

China's High-Temperature Gas-Cooled Reactor – Pebble-Bed Module (HTR-PM) entered commercial operation in late 2023. A demonstration utilizing heat from this reactor was connected to a local heating grid in March 2024 (WNN, 2024a). Significant progress has also been made on the detailed design of the HTR-PM600, a 600 MWe commercial plant with six modules for cogeneration of steam and electricity (Figure VHTR-2).

The high-temperature engineering test reactor (HTTR) in Japan was restarted in 2021 after a decade

Figure VHTR-2: **China's six-module HTR plant for cogeneration of electricity and steam collocated with Hualong One LWRs**

Source: Tsinghua University.

of shutdown due to the Great East Japan Earthquake in 2011. Following a successful simulated loss-of-coolant test in 2022, in which all cooling systems were shut down with the reactor at 30% power and no control rod actuation, a third loss of forced coolant test was conducted in 2024 with the reactor at 100% power to further demonstrate the inherent safety shutdown mechanism in this test reactor. There are also plans to perform various tests concerning safety, core physics, thermal-fluid characteristics and fuel performance, including a heat application test that will couple the HTTR and a hydrogen production plant. These tests support Japan's plans for a 150-250 MWt HTGR demonstration reactor, targeting hydrogen production and industrial heat applications. The demonstration reactor is slated for operation in the 2030s and builds on Japan's extensive experience with the HTTR.

The UK is advancing its HTGR demonstration program under its AMR R&D initiative, targeting deployment by the early 2030s. Coated particle fuel development efforts are underway, including the production of a prototype TRISO fuel block for irradiation testing by 2025. Demonstration reactor plans focus on industrial decarbonization and clean hydrogen production. The National Nuclear Laboratory (NNL) partnership with JAEA aims to address technical risks and accelerate progress (WNN, 2024b).

France's HTGR development under the France 2030 initiative includes two demonstration projects. Jimmy Energy is working on a 15 MWt prismatic HTGR microreactor designed to operate at high temperatures. Blue Capsule is advancing a compact 150 MWt TRISO-fuelled HTGR with sodium as a heat carrier to provide industrial heat at 700°C.

Poland's first HTGR, the 30 MW HTGR-POLA, has completed its basic design by the National Centre for Nuclear Research (NCBJ) in collaboration with JAEA. Designed for cogeneration, HTGR-POLA can provide 11.5 MWe of electricity and high-temperature steam at 750°C for industrial applications and district heating. This demonstration project is integrated with the GEMINI 4.0 initiative, which focuses on expanding industrial decarbonization solutions using HTGR technology.

Canada's Global First Power Micro Modular Reactor (MMR) demonstration project at the CNL Chalk River campus continues to progress, targeting operation in the 2030s. This 5-15 MWe HTGR-based demonstration reactor aims to validate the application of SMR technology for remote and industrial use cases. The project serves as a key milestone in advancing HTGR technology in Canada, focusing specifically on reactor demonstration.

The US DOE is supporting several HTGR-related demonstration projects. TRISO-fuelled and graphite-moderated SMR is being developed by X-energy and microreactor designs are being developed by BWXT and Westinghouse, in addition to privately funded microreactor projects by Radiant and Antares. Both Radiant and Westinghouse's eVinci design plan to test their microreactor designs in the new Demonstration of Microreactor Experiments (DOME) test bed at INL, with planned first criticality as soon as 2026. Amazon has invested USD 500 million in X-energy's Xe-100 pebble-bed development, with options to procure up to 5 GWe by 2039 (WNN, 2024c).

Technical highlights – Fuel and fuel cycle project

The VHTR Fuel and Fuel Cycle (FFC) project is intended to provide demonstrated solutions for VHTR fuel (design, fabrication and qualification) and for its back-end management, including novel fuel cycle options. TRISO-coated particles, which are the basic fuel concept for the VHTR, need to be qualified for relevant service conditions. Furthermore, the standard design – UO_2 kernel surrounded by successive layers of porous pyrocarbon, dense inner pyrocarbon (iPyC), SiC, and finally an outer pyrocarbon (oPyC) – could evolve, along with the improvement of its performance through the use of a UCO kernel or a zirconium carbide (ZrC) coating for enhanced burnup capability, minimized fission product release and increased resistance to core heat up accidents (above 1 600°C).

A fuel performance database will include fuel characterization work, post-irradiation examinations (PIE), high-temperature safety testing, fission product release evaluation, and the measurement of chemical and thermomechanical material properties in representative conditions. The further development of physical models enables the assessment of in-pile fuel behavior under normal and off-normal conditions. The fuel cycle back-end encompasses spent fuel treatment and disposal, as well as used graphite management.

Although a once-through cycle is envisioned initially, the potential for deep burn of plutonium and minor actinides in a VHTR, as well as the use of thorium-based fuels, will be accounted for as an evolution towards a closed cycle.

An experimental round robin exercise on the leach-burn-leach TRISO fuel characterization method has been completed by three FFC project participants (China, Korea, United States). Sample specimens provided by the United States (ORNL) and China (INET) were analyzed by each participant using their own procedures to quantify the number of defective particles and the quantity of metallic impurities. Results were then compared to draw conclusions about the impact of process variation. The results indicate that differences in the parameters used for the leaching steps among the participants had a noticeable impact on the amount of recovered uranium in the solutions, while difference in the parameters of the burn (oxidation) step had little impact on the overall results. An example of the results comparison is shown in Figure VHTR-3, which indicates the total recovered inventory of uranium (in particle equivalents) in samples containing a single known particle defect. The solid line corresponds to the expected distribution of uranium inventory based on statistical variation in kernel inventory. The results indicate that all analyses were within the expected range of values (indicating correct assessment of the single particle defect) except one (corresponding to analysis "INET-G"). A full presentation and discussion of results is provided in (Hunn, 2024).

The FFC PMB organized the 7th Workshop on Materials Properties of TRISO Fuels, hosted at the University of Manchester, UK, on 9-10 July 2024. The workshop enjoyed a high level of international interest and had the highest attendance in this series of meetings so far, with approximately 80 participants. The workshop was organized in four sessions. The session topics included data gaps for TRISO fuel material properties, challenges with accelerated testing of TRISO fuel, performance considerations for new fuel designs, and research challenges from the limited deployment of TRISO-based reactors.

Several members are performing PIE and safety testing of irradiated TRISO fuel. Work in the United States is currently focused on the examination of compacts and coated particles from the AGR-5/6/7 fuel qualification irradiation experiment. Destructive examinations include compact cross-section analysis, deconsolidation-leach-burn-leach analysis to assess particle failures and fission product inventory in the fuel matrix, x-ray analysis of fuel compacts and individual particles, and detailed microanalysis of particles. A total of 17 post-irradiation safety tests at temperatures of 1 600°C or 1 800°C have been performed to date. China has performed deconsolidation and burnup analysis on pebbles discharged from the HTR-10 reactor. In addition, a microanalysis of fuel particles from HTR-10 pebbles and from pebbles previously irradiated in the HFR-EU1 experiment is in progress.

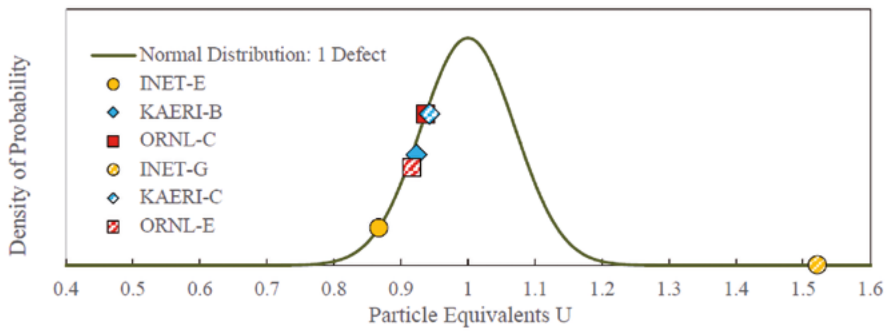
New post-irradiation fuel heating test capabilities are being developed in China and the United States. The new KÜFA furnace installation in the hot cells at INET is progressing towards the first heating tests. This system will perform heating tests in pure helium (similar to those performed in the German KÜFA furnace in the 1980s and 1990s at FZJ and up to the early 2020s at JRC). In the United States, development has continued on the air moisture ingress experiment furnace system. This system will heat fuel specimens in atmospheres containing various concentrations of oxygen or moisture to assess the behavior of fuel in oxidizing environments that could occur during HTGR air or moisture ingress scenarios. Operation of the AMIX system is expected to begin in 2025.

The development of advanced TRISO fuel particles is being pursued by several PMB members. Korea has been establishing fabrication methods for alternate (i.e. non-UO_2) kernel compositions, including UCO (to achieve higher burnup compared to UO_2) as well as uranium carbide (UC) and uranium nitride (UN) (for nuclear thermal propulsion applications). Numerous trials are being carried out to fabricate ZrCO kernels (using Zr as a surrogate for U). INET is developing ZrC coating technology as a potential substitute for the conventional SiC coating layer. Annealing tests have been performed at temperatures as high as 2 200°C to assess grain growth in chemical vapor deposition ZrC layers.

KAERI has performed computational modeling work to predict thermal properties and fission product diffusion in ZrC as an alternate coating layer. The modeling work has also included fuel performance analysis with a goal of optimizing particle geometry (i.e. coating layer thicknesses) to minimize particle failure. Work has continued in the United States to refine fuel performance modeling to account for complex coating layer behaviors observed experimentally.

Euratom, as part of the GEMINI 4.0 project (Pasquet et al., 2024), has performed analyses on spent fuel and graphite management for HTGR (Olin et al., 2024). This is strongly impacted by the large graphite and coating volumes compared to the small portion of the fissile kernel. Therefore, separation of

Figure VHTR-3: **Normal uranium distribution for simulated samples with one defect vs. measured values**



Source: ORNL (2024).

the fuel compacts from the graphite block has been investigated. Disposing of spent fuel compacts separately from the graphite blocks is expected to significantly reduce high-level-waste (HLW) volumes. Processes for separating the coated particles from the compacts and extracting the fuel kernels have also been evaluated. They can be considered as a head-end step for reprocessing. Irradiated-graphite management is a specific challenge for all graphite-moderated reactors, due to the large associated volume, the specific contamination and the degradation caused by neutron irradiation. Long-lived activation products, such as ^{14}C and ^{36}Cl, lead to the categorisation of irradiated graphite as intermediate -level-waste (ILW) in most countries. Therefore, treatment methods for reducing and/or stabilizing such isotopes for achieving a lower waste category, at much lower disposal cost, have been assessed. Reuse and refabricating options for irradiated graphite would be an attractive strategy towards a "closed HTGR graphite cycle".

Technical highlights – Hydrogen production project

The VHTR hydrogen production project remains focused on advancing high-temperature thermochemical and electrolysis water-splitting processes. The primary objective is to define and validate technologies and processes that effectively couple Gen IV reactor systems to these hydrogen production methods. Key areas of research include process flow development, material and catalyst selection, and experimental validation of process parameters.

Research activities in 2024 continued to emphasize the scalability and efficiency improvements of high-temperature steam electrolysis (HTSE). Multiple participating countries reported advancements in HTSE technology, particularly in stack efficiency, materials research and pilot-scale demonstrations.

In Canada, CNL expanded research on HTSE and CO_2 co-electrolysis for hydrogen and syngas production. The ongoing pilot demonstration assesses the feasibility of producing synthetic diesel from biomass-|derived hydrogen using clean electricity. CNL also emphasized hydrogen safety and established a dedicated Safety Centre to address risks.

The US DOE has allocated USD 7 billion to establish hydrogen hubs, with significant investment in HTSE research. Recent studies have focused on degradation mechanisms of solid oxide electrolyser cells (SOECs), integration with nuclear power plants and cost reductions by improving balance-of-plant components. Pressurized SOEC testing has yielded insights into system durability and performance prediction. Several MW-scale hydrogen production projects are being pursued through industry partnerships.

The CEA in France has achieved progress in HTSE technology with the successful demonstration of the Sunfire high-temperature electrolyser, which produced hydrogen at a rate exceeding 60 kg H_2/h. Future plans include scaling up HTSE applications to a 200 kg/day demonstrator and further integration with nuclear heat sources.

In Korea, KAERI expanded experiments with its helium loop and HTSE system, successfully testing a 6 kW SOEC module at 800°C. KAERI has also expanded its Alliance for Nuclear Heat Utilization, which includes chemical and steel industry participants interested in leveraging nuclear-generated hydrogen for industrial applications.

As a provisional member of the hydrogen production PMB, representatives from the United Kingdom emphasized its national hydrogen strategy, aligning with planned HTGR deployment and hydrogen production initiatives. In 2024, Great British Energy was established, which is a state-backed entity with a GBP 8.3 billion budget that aims to accelerate clean energy projects, including nuclear-powered hydrogen production.

Research on thermochemical hydrogen production pathways, including the iodine-sulfur and hybrid sulfur cycles, also continued in 2024, with experimental validation of decomposer components and material improvements. The JAEA in Japan advanced the iodine-sulfur process by resolving leakage issues in glass-lined steel pipe connections through refined fastening techniques. Heat cycle tests confirmed reduced leakage, allowing for stable, long-term hydrogen production. Further studies focused on transient operational data to improve process control and efficiency.

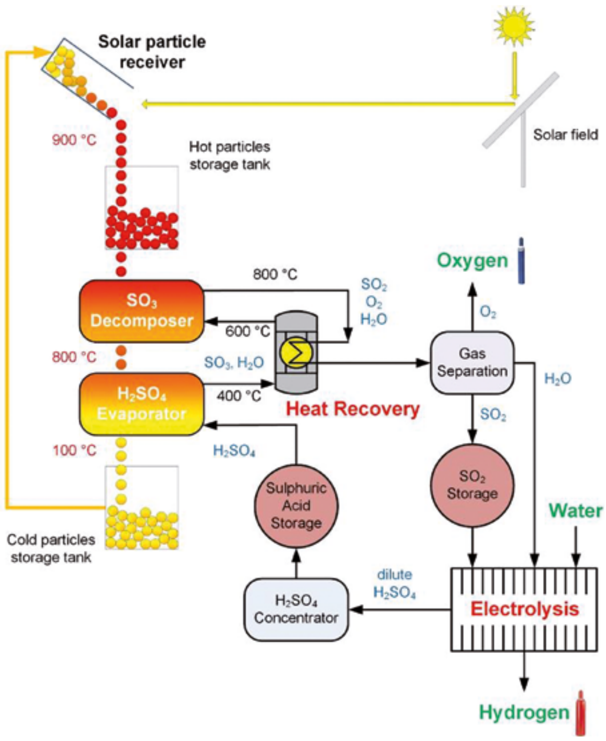
In Europe, there is a significant body of research related to hydrogen production, including the HySelevt project, which advances research on the hybrid sulfur cycle focused on electrochemical efficiency improvements. Figure VHTR-4 shows a system flowchart based on concentrated solar power. A collaboration among partners from Austria, Finland, Germany, Greece and Italy targeted scalable implementations of thermochemical hydrogen production. Specifically on nuclear hydrogen production, the TANDEM (Vaglio-Gaudard et al., 2024) and GEMINI 4.0 (Pasquet et al., 2024) projects are investigating power, heat and hydrogen cogeneration with light water SMR and HTGR. The work includes the definition of flow sheets for coupling the nuclear and the hydrogen production plant, economic considerations, safety aspects, and energy system integration.

As a provisional member of the HP PMB, INET at Tsinghua University in China also reported progress in the development of the iodine-sulfur process, including the successful operation of a sulfuric acid decomposer coupled with a helium heating loop. Further work is planned on safety analysis and scaling up the technology.

In 2024, the PMB also engaged with researchers at PSI in Switzerland to understand their potential role in the HP Project Arrangement. PSI research examines synthetic fuel production through heat-assisted processes, focusing on sustainable aviation fuel synthesis.

Finally, the VHTR HP PMB has been engaged to support system analysis activities led by the NECA Working Group within GIF to evaluate the technical and economic viability of coupling Gen IV systems with HTSE. A forthcoming report, expected in early 2025, will consolidate contributions on system performance and potential deployment scenarios.

Figure VHTR-4: **Block flow diagram, mass and energy flows of the process articulated through the European HySelect project**



Source: HySelect (2025).

Technical highlights – Materials project

Although the term of the original VHTR Materials Project Plan was completed in 2012, the Materials Project Arrangement (MPA) continued until 2021 under its Second Amendment. The Third Amendment became effective on 3 January 2024 and continues the work of the MPA.

After the United Kingdom provided a proposal for joining the VHTR MPA in 2021, and Canada provided its proposal to rejoin, an updated Project Plan was prepared covering the period 2018 to 2024. Contributions were provided by all existing signatories (Australia, China, European Union, France, Japan, Korea, Switzerland and United States), as well as by Canada and the United Kingdom. The updated plan was unanimously approved by the VHTR Materials PMB and the SSC in September 2023 and October 2023, respectively.

The development and qualification of materials are crucial for the advancement of the VHTR system. Key challenges include irradiation-induced and/or time-dependent failure, and microstructural instability in operative environments. Existing materials can suffice for core coolant outlet temperatures below 950°C, while novel materials must be developed and qualified for higher temperatures (stretch goal of 1 000°C) and harsher conditions, including corrosive process fluids and off-normal operations. Multi-scale modeling is indispensable for optimizing design methodologies. Besides high-temperature heat exchangers, steel performance in steam generators is receiving increased attention, given the growing interest in steam-based processes at moderately lower core outlet temperatures (750-850°C). Materials are categorized into graphite for core structures and fuel matrices, very/medium-high-temperature metals, and ceramics and composites. A comprehensive materials handbook has been compiled, serving as a platform for efficient data management, international R&D coordination, and prediction of damage and lifespan through modeling. Emerging advanced manufacturing techniques, such as additive manufacturing, offer new possibilities for innovative material classes, potentially addressing the above-mentioned challenges. Qualifying these methods and their resulting materials has become an integral part of the R&D objectives.

As part of the second MPA amendment, a comprehensive review of all high-level deliverables was conducted. The review ensured that all previously scheduled deliverables were either completed or modified to be finished during the updated Project Plan term. Notably, by the end of 2024, the Gen IV Materials Handbook, the centralized database for sharing materials information among project members, received over 550 technical reports and numerous materials test records. This impressive achievement demonstrates the remarkable technical expertise of the project's participants, whose contributions have significantly advanced system design and code development.

After showcasing the project accomplishments to a broader audience, including industry representatives, the group's primary output, the Gen IV Materials Handbook, generated significant interest. As a result, in recent PMB meetings the accessibility options for the handbook have been discussed, ultimately leading to the development of a plan for third-party sharing. This plan includes the publication of a table of contents that can be openly accessed.

In 2024, the research focus remained towards near- and medium-term projects, with emphasis on developing graphite and high-temperature metallic alloys. Meanwhile, work on longer-term initiatives, such as ceramics and composites, progressed at a slower pace.

The Graphite Working Group has made significant progress in advancing the understanding and application of graphite materials. The group has examined the properties of virgin graphite, including its oxidation, irradiation and creep behavior, with Canada, the United Kingdom and the United States leading the effort. The United Kingdom and the United States have also worked on irradiation and irradiation-creep studies, as well as on developing codes and standards for graphite.

The Graphite Working Group has developed a graphite qualification research strategy plan, which includes participation from new signatories Canada and the United Kingdom. This plan has helped to focus the group's research efforts and ensure that they are aligned with the needs of the graphite community. The group has also made progress in linking existing graphite behavior databases and developing graphite behavior models, with contributions from Australia and the United Kingdom. These efforts have aided in the qualification of graphite grades and have helped to capture the mechanical properties and behavior of graphite under different conditions.

Figure VHTR-5 shows the modeling of graphite-molten salt interactions, illustrating the successful implementation of a crosscutting activity, where research on graphite is being applied to the MSR. Despite challenges such as limited experimental data and analysis methods, the NRC is developing computational tools to simulate salt infiltration into graphite, demonstrating a valuable collaboration across different research areas. A 2D geometry and mesh of IG-110 graphite has been created to visualize this process, showcasing the potential of crosscutting research to advance our understanding of complex systems.

In the field of metals and design methods, high-temperature creep, fatigue and creep-fatigue testing are being conducted on various alloys, including diffusion-bonded materials for compact heat exchangers. High-temperature testing capabilities are being expanded to perform creep and fatigue testing on alloys such as Alloy 800 and Haynes 230. Additionally, fatigue, creep and creep crack growth are being studied on stainless steel and alloys such as 316 and 617. Advanced constitutive models are being developed for inelastic analyses, supported by experimental studies on the creep fatigue of high-temperature alloys. Furthermore, efforts are underway to develop Class B design rules for structural materials in nuclear reactor systems, with materials being irradiated using ion and neutron irradiation to support these efforts. Ion and neutron irradiation are also being used to develop materials models of advanced alloys, with advanced manufacturing techniques being explored. Common alloys of interest are being identified to accelerate parallel efforts on material testing, qualification and modeling.

Several members have conducted extensive research into cutting-edge manufacturing techniques for nuclear components, such as laser fusion, metal powder consolidation and direct deposition. In addition, novel high-temperature structural materials have been developed using innovative synthesis methods. Recognizing the significance of these advancements, a dedicated task on advanced manufacturing methods has been incorporated into the Third Amendment of the VHTR MPA to further explore and develop these technologies. Efforts in this area are being performed in conjunction with the Advanced Manufacturing and Materials Engineering Working Group (AMME WG).

Figure VHTR-5: **Molten salt ingress into a CT slice of IG-110 graphite: Extracted 2D geometry and mesh**

Note: Molten salt in blue penetrating into the Argon filled pores in red.

Technical highlights – Computational methods validation and benchmarks (CMVB) project

The validation of new computational methods and codes in the fields of HTGR thermal hydraulics, thermal mechanics, core physics and chemical transport is crucial for ensuring the reliability and accuracy of reactor performance assessments under normal, upset and accident conditions. This validation process involves benchmark, code-to-code comparisons, and the use of diverse data sources, such as operating experience from existing HTGRs, for example the HTTR, HTR-10 and HTR-PM (Figure VHTR-6), historical data from past HTGRs, for example the AVR, THTR and Fort Saint Vrain, and results from separate and integral effect tests at facilities such as the Natural Convection Shutdown Heat Removal Test Facility (NSTF) and the High Temperature Test Facility (HTTF). Successful validation helps reduce design conservatisms, refine cost estimates, enhance safety margins and facilitate licensing assessments by providing robust and validated tools.

At the Chinese INET, the development of a state-of-the-art HTGR design software package continued in 2024. New models and capabilities were added to the reactor physics code PANGU, including improved resonance and double-heterogeneity treatment, kinetics calculation, random fuel-shuffling simulation, and diffusion coefficient calculation of general pebble-bed. A new 3D system analysis code named DAYU3D was preliminarily developed. The new codes are used as design verification tools in the following HTR-PM600 and future HTR-PM1000 projects.

After a 168-hour demonstration with continuous running, HTR-PM (see Figure VHTR-6) has entered commercial operation. On 13 August 2023, a loss of off-site power test was carried out on reactor module No. 1, and on 1 September 2023, an emergency shutdown test was carried out on reactor module No. 2. The tests confirmed that the reactors could be naturally cooled down by the laws of nature without relying on any emergency core cooling systems. For the first time in the world, the inherent safety of VHTR reactor has been confirmed in a full-scale demonstration plant.

Figure VHTR-6: **Nuclear island of HTR-PM demonstration**

Source: Image from Tsinghua University.

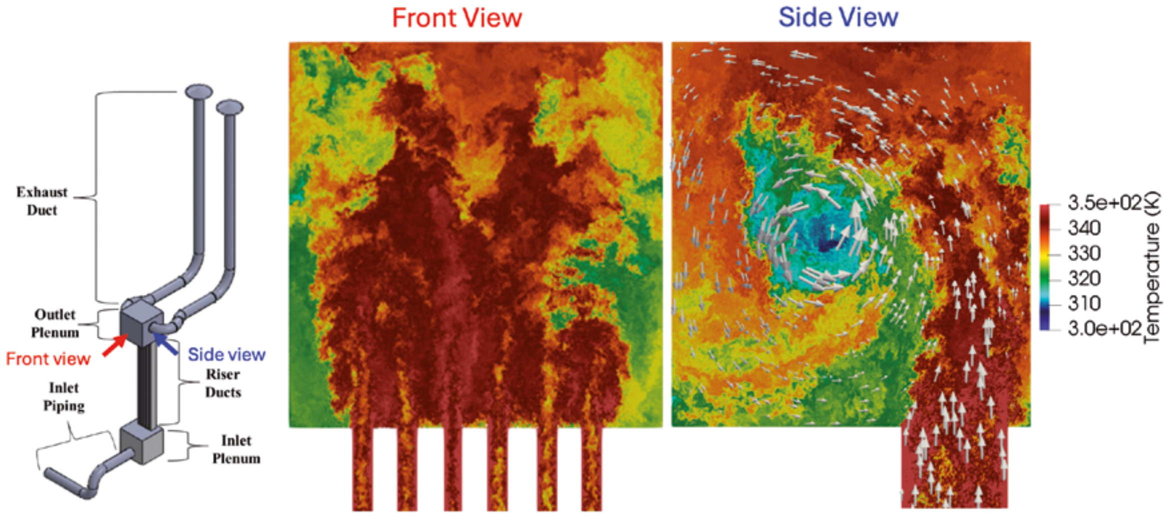
In Japan, JAEA completed the HTTR safety demonstration test from 27 to 28 March 2024 in the framework of an NEA project. It has been confirmed that during 100% reactor power operation, and under the condition of restricted control rods insertion, the reactor power of the HTTR naturally decreases and maintains stable even after a loss of forced cooling. There are also plans to perform various tests, including a heat application test, which will involve coupling the HTTR and a hydrogen production plant. JAEA's R&D includes a benchmark activity on burnup analysis using irradiation data from the US Advanced Test Reactor. JAEA has constructed a calculation model of the Advanced Test Reactor using the JAEA-developed Monte Carlo simulation code MVP (Nagaya et al., 2017).

In Korea, R&D aims to improve design code development and the evaluation of key technologies for very high-temperature systems. The McCARD code has implemented functions to design a shield for the VHTR system, and a basic study on the AGR-1 benchmark is under verification. The tritium transport code TROPY is being modified to enhance the accuracy of tritium production by comparing with McCARD calculation results. The MENTAS code has been developed to investigate fission product transport in the confinement after an accident. The accuracy of the point kinetics model and multidimensional flow model of a safety analysis code GAMMA+ was also improved.

In the European Union the Horizon Europe Framework Program project GEMINI 4.0 (GEMINI For Zero Emission) has completed the first 30 months of activities related to HTRs (scheduled until May 2025). The focus areas are optimization of safety and competitiveness, decarbonization of industry, fuel and fuel cycle, licensing readiness, and socio-economic impact. The GEMINI HTGR design was further improved to consolidate the safety case and address the recommendations of the licensing readiness assessment completed in 2023. Investigations into different and new TRISO fuel forms were concluded and considered in the fuel cycles and back-end solutions. The GEMINI 4.0 summer school was hosted by the Świerk Research Centre in Otwock, Poland from 24-26 September 2024 with 70 participants from across Europe, Africa, Asia and South America, along with representatives from nine industrial enterprises.

In the past year, the US DOE has made significant strides in advancing HTGR technology through various experimental, computational and collaborative efforts. The NSTF reconfigured its chimney piping, increasing coolant volume but potentially decreasing natural circulation efficiency. Ten tests revealed that while system responses were generally similar, higher inventories caused flow oscillations to grow, and lower inventories triggered instabilities, with extended testing indicating improved performance at lower inventories (Qiuping, et al., 2024). Concurrently, work on the NEA's "Thermal hydraulic code validation benchmark for high-temperature

Figure VHTR-7: **Front and side views of the instantaneous temperature at the outlet plenum of the CFD model of the University of Wisconsin-Madison air-cooled RCCS experiment**



Source: Okyay et al. (2023).

gas-cooled reactors using HTTF data (HTGR T/H)" continued, with RELAP5-3D demonstrating reasonable agreement for steady-state temperatures and transients after refining its radial nodalization model and applying a new 1/6 azimuthal sector model (Kile, Barthle and Epiney, 2024), On the modeling and simulation front, the DOE has invested in initiatives to advance and test software tools such as Pronghorn (Novak et al., 2021), Griffin (Wang et al., 2024) and BISON (Jiang, et al., 2022) for comprehensive HTGR analysis. Griffin's multiphysics capabilities were successfully tested for simulating pebble-bed reactor running-in scenarios and successfully compared with high-fidelity Monte Carlo running-in calculations using Kugelpy (Stewart et al., 2024). The use of reduced-order models (ROMs), specifically deep neural networks (DNNs), is being investigated to accelerate cross-section evaluation in Griffin, promising enhanced pebble-bed reactor simulation fidelity with manageable computational costs (Che et al., 2024; Hanophy et al., 2024). Collaborative efforts with Japan continue, focusing on data from the recently restarted HTTR to advance the HTTR thermal-hydraulic model using the Pronghorn code (Kile, Strydom and Balestra, 2024). Within the GIF VHTR-CMVB framework, numerous activities across various work packages have improved the accuracy and regulatory compliance of HTGR analysis tools, including integrating the HTR-PM PIRT into a comparative PIRT, preparing and finalizing a burnup analysis benchmark, validating lower plenum hot gas mixing models, and validating air-cooled Reactor Cavity Cooling System (RCCS) models using experimental data from INET and the University of Wisconsin-Madison (Figure VHTR-7), respectively (Okyay et al., 2023).

Ali Siddiqui
Chair of the VHTR SSC, with contributions from VHTR members

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4 Working group reports

Advanced Manufacturing and Materials Engineering Working Group

Working group goals and industry engagement

The Advanced Manufacturing and Materials Engineering Working Group (AMME WG) promotes the use of advanced manufacturing and materials engineering to reduce the time to deployment of Gen IV reactors. Specifically, it aims to promote international collaboration with a focus on crosscutting technologies with the potential to impact multiple Gen IV reactor technologies.

The AMME WG undertakes activities in four topical task groups:

1) A regular industry-focused survey on advanced manufacturing applications designed to gauge current sentiment towards advanced materials and manufacturing technologies.
2) Development of a forum for sharing, coordinating and demonstrating work on the qualification of advanced materials and manufacturing techniques.
3) Activities and projects to promote the qualification of advanced manufactured systems, components and structures through the innovative use of modeling and simulation.
4) Activities and projects to promote the qualification of advanced manufacturing systems, components and structures through innovative testing and monitoring techniques.

Industry engagement has been further developed through direct contacts with relevant companies and a number of industry representatives, for example, Westinghouse, Newcleo, Ansaldo Nucleare and Blykalla have participated in WG monthly meetings and task activities.

2024 accomplishments

A new survey started in late 2023 was completed and results were analyzed. Participation was similar to that seen in the 2019 and 2021 surveys, with over 40 experts responding, more than 60% coming from an industry background. Several significant trends in industry sentiment were observed compared to the 2021 and 2019 surveys:

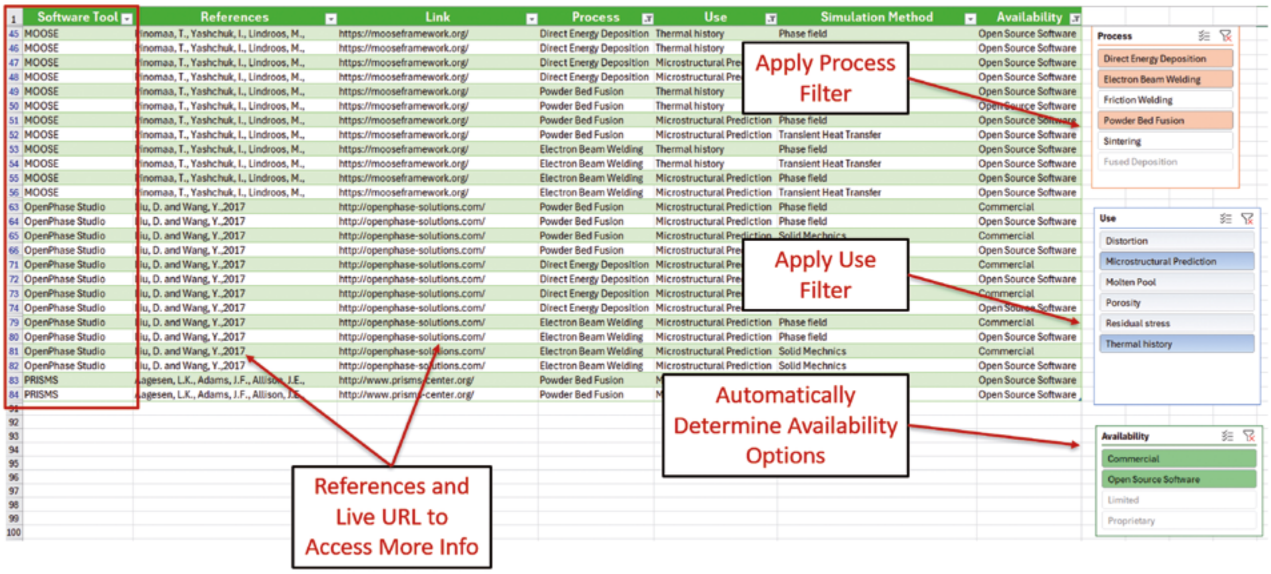
- An increase in active efforts to secure regulatory approval for one or more advanced manufacturing processes (22% in 2019 compared to 40% in 2023).
- A similar increase in active efforts to include materials and methods in consensus codes and standards (31% in 2019 compared to 48% in 2023).
- Decreased interest in applying advanced manufacturing for fuel and fuel cladding, but an increase in interest for reactor internals.
- A significant increase in interest in powder metallurgy hot isostatic pressing and advanced welding processes, which may reflect the increasing maturity of these technologies.
- Consistency in the main materials of interest, with steels and nickel alloys being of greatest interest.
- Continued interest in international collaborative activities, with at least 75% of respondents expressing interest in specific activities focusing on material qualification and modeling.

The WG has engaged with stakeholders and promoted GIF participation through invited talks both within GIF and at the following working groups and technical meetings:

- EPRI technical exchange meeting on non-destructive evaluation of Advanced Manufactured components, 17-18 April 2024, www.epri.com/events/5b788af0-2337-4e86-81dd-048858d3c820.
- AI in advanced manufacturing workshop, 2-3 May 2024, Idaho Falls, https://caes.org/events/workshop-intelligent-manufacturing-for-extreme-environments-2024.
- IAEA International Network on Innovation to Support Operating Nuclear Power Plants (ISOP) Topical Working Group, 13 February 2024, virtual, https://nucleus.iaea.org/sites/connect/ISOPpublic/SitePages/Home.aspx.
- IAEA Nuclear Harmonization and standardization initiative, 30 April 2024, virtual, https://nucleus.iaea.org/sites/smr/SitePages/Nuclear-Harmonization-and-Standardization-Initiative.aspx.
- Technical meeting on deployment on Advanced Manufacturing solutions for the Nuclear Power Industry, 19-22 August, Vienna, Austria, www.iaea.org/events/evt2304638.

In addition, an 81-question survey designed to collect qualification specific activities and interests was distributed by AMME members to industry partners in their countries. Twelve responses have been received so far from R&D organizations, suppliers and reactor designers. The initial data suggest significant interest in integrating additive manufacturing as the dominant technology in codes and standards.

Figure AMME-1: **Database filtering to identify computational tools available for specific processes and usage**



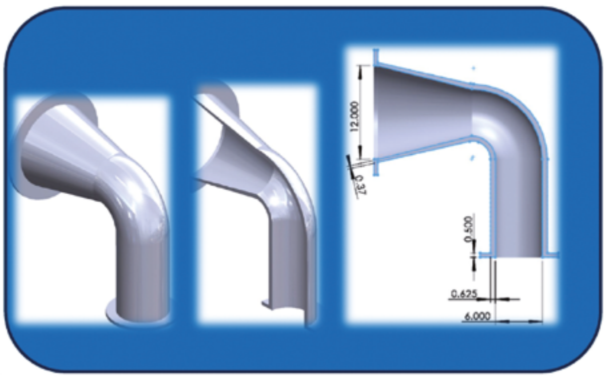
To facilitate the wider adoption of modeling and simulation techniques in the nuclear industry, the group will identify and maintain an inventory of current state-of-the-art computational methods and computer codes that are useful in 1) informing and assessing the properties (e.g. microstructure) of materials; and 2) the components and structures resulting from advanced manufacturing technologies (AMT). To this end, the group has started to develop a database to store information about available modeling and simulations tools with at least some application to AMT processes of interest to nuclear systems. The summary of such modeling tools by Nicolas et al. (2020) provided the initial information used for the database.

Each record in the Excel-base database captures information about a particular software tool (i.e. its name and website link), the processes it is intended for (e.g. powder bed fusion), its application use (e.g. microstructural or thermal history prediction), the underlying simulation methods (e.g. phase field) used by the tool, and whether the simulation code is available either commercially, as an open-source solution or as a limited distribution. There are currently 13 simulation tools recorded in the database, which also associates a list of reference publications to each of the tools included.

The database also allows the collection of related data to be analyzed, maintained and filtered, facilitating the identification of a particular computational tool for modeling a specific property or process. Figure AMME-1 illustrates the outcome of applying data filtering based on two features of the code, where a user interested in identifying a computational tool for predicting the microstructure and the thermal history of a component manufactured by either direct energy deposition, electron beam welding or powder bed fusion would be provided with three computational choices that have either commercial or open-source availability: 1) MOOSE; 2) OpenPhase Studio; and 3) PRISMS. The user is provided with the link to access the software and references to works demonstrating the application of the software tool.

The objective of Task Group 4 is to accelerate the qualification and adoption of additive manufacturing systems, components and structures by coordinating international efforts to produce reactor-agnostic parts that will increase the readiness level of the technologies and be the basis for addressing the qualification challenges through innovative testing and monitoring techniques.

Figure AMME-2: **Expander elbow pipe component selected for benchmark study**



The members of the AMME WG have identified the building capabilities, potential partnerships, funding and the potential for leveraging existing research activities in their respective countries. This information, along with expressed interest from members for the subject of a benchmark study, was used to select the materials for the study (316 steel), the techniques to be used (laser powder bed fusion, directed energy deposition, both with powder and wire), and the simple shape component to manufacture (an expander elbow pipe, Figure AMME-2). Each country is currently considering the characterization to be generated and shared with the group.

The AMME WG is also working to identify components containing material produced by advanced manufacturing that have been installed in existing reactors in order to collect data on material changes instilled by service. It is understood that planned retrieval and characterization is currently under consideration from a number of reactors. The potential roles of the GIF AMME working group in this process are being investigated. The collection, and sharing, of data may be limited by the need to protect intellectual property, but some information may be shareable. For example, a limitation could be the qualification of material (like Inconel 718) for applications where surface condition is critical. Shareable information could be on the irradiation effect on the bulk microstructure without the critical step of generating the resistant surface condition.

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Lyndon Edwards
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Mark Messner
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Isabella van Rooyen
Co-Chair of the AMME-WG, with contributions from AMME members

Economic Modelling Working Group

The Economic Modelling Working Group (EMWG) was established in 2003 to provide a methodology for the assessment of Gen IV systems against two economic-related goals:

- The life-cycle cost advantage of Gen IV systems over other energy sources (i.e. a lower levelized unit cost of energy).
- The level of financial risk comparable to other energy projects (i.e. a similar total investment cost at the time of commercial operation).

In 2007, the EMWG published *Cost Estimating Guidelines for Generation IV Nuclear Energy Systems* (GIF, 2007) and released the Excel-based software package G4ECONS, which was updated and released as G4ECONS v3.0 in October 2018. This tool provides the means to calculate the levelized cost of energy and total investment cost, and therefore to evaluate Gen IV systems against GIF economic goals. These resources are made available to the public through the GIF Technical Secretariat. Subsequent publications have demonstrated the EMWG methodology for the economic assessments of Gen III and Gen IV systems, and enabled benchmarking against economic models developed by the IAEA, including the Nuclear Economics Support Tool and the Hydrogen Economic Evaluation Program.

In 2018, the terms of reference for the EMWG were amended to incorporate the expanded mandate to inform the GIF Policy Group and Experts Group on the policies and R&D needs for the future deployment of Gen IV systems.

In 2021, the EMWG launched a survey to collect user feedback on G4ECONS and identify potential model improvements to be considered for version 4.0. The unique aspects of SMRs, non-electric applications and embedded sensitivity analysis were identified as areas of the greatest interest for future developments. Many users also expressed interest in additional training sessions on the G4ECONS tool.

In 2021, the EMWG worked with the finance industry to produce the report *Nuclear Energy: An ESG Investable Asset Class*. This report considered the nuclear industry's ability to report against a broad range of environmental, social and governance (ESG) data collection and accounting metrics (GIF, 2021).

Also in 2021, the Advanced Nuclear Technology Cost Reduction Strategies and Systematic Economic Review (ANTSER) process was developed to provide a methodological framework for evaluating nuclear cost-reduction strategies. This initial report provided an example strategy on "functional confinement" barriers to simplify radionuclide retention. In 2022, a second ANTSER cost-reduction strategy was developed for "modularity at scale" (GIF, 2022).

In October 2022, the EMWG participated in the GIF Industry Forum, leading the EMWG session "Economic Challenges and Opportunities for Gen IV Reactors". The technical session was an engaging and dynamic discussion looking at the economic challenges and how the impact of the way in which projects are established can considerably influence their financing. In 2022, the EMWG agreed to undertake an update to the *Cost Estimating Guidelines for Generation IV Nuclear Energy Systems* document and the G4ECONS tool. A small team of EMWG members was formed and the table of contents was drafted to be shared with others within the EMWG (SIAP and NEANH) to receive early feedback.

Figure EMWG-1: **Special Gen IV financing workshop at London Experts Group/ Policy Group meeting**

EMWG activities in 2024

In April, the EMWG presented a draft of the third instalment of the ANTSER framework to the GIF Experts Group. *ANTSER Strategy #3: Technology-Diverse Cost Reduction* is aimed at optimizing project organization for cost trade-offs. The EMWG is performing revisions of the ANTSER document based on the feedback received from the GIF Experts Group, and is expected to publish by April 2025. The group also agreed to work collaboratively on a coal-to-nuclear related ANTSER Strategy #4 for Gen IV reactor systems.

The EMWG financing taskforce held a workshop on 15 October (Figure EMWG-1) involving generic role-playing between a nuclear technology developer, a project developer and the various types of investors, followed by an exchange of questions and comments from the audience. The role-play was designed to simulate the multifaceted challenges and opportunities associated with financing, developing and deploying advanced nuclear technologies, bringing together key stakeholders to navigate the complexities of nuclear project development. The financing group will continue engaging with stakeholders by carrying out similar efforts at future NEA meetings.

Also in October, GIF and the IAEA organized a deep dive on economics following a recommendation from the GIF-IAEA Interface meeting. The GIF EMWG and the IAEA's Planning and Economic Studies section and Innovative Nuclear Reactors and Fuel Cycles (INPRO) section shared recent and planned activities for economics and explored areas to enhance collaboration between the two groups. Proposed topics for collaboration include financial risk and investment, coal-to-nuclear transition studies, peer-review involvement, workforce, and supply chain capacity studies.

In December, the EMWG also held a joint workshop, Nuclear Energy Economics and Finance, with the NEA Working Party on Nuclear Economics and the NEA Working Group on SMR Economics. This workshop was designed to take stock of recent and ongoing activities in the areas of nuclear economics and finance, with a focus on SMRs and Gen IV nuclear technologies, and to explore opportunities for future activities and cooperation.

The EMWG continued progressing with the update to the cost estimating guidelines by completing a review of current state-of-the-art approaches documented in literature, producing a first rough draft that includes expanding discussion on scale and modularity to better address SMRs, and further exploring how to best provide cost estimates for direct steam use and cogeneration of both heat and electricity. The group is planning to present the first draft of the guidelines, as well as the plans for the development of G4ECONS v4.0, in April 2025 for review.

Megan Moore
Co-Chair of the EMWG

Fiona Reilly
Co-Chair of the EMWG

Jason Hansen
Co-Chair of the EMWG

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Education and Training Working Group

The GIF Education and Training Working Group (ETWG) was created in November 2015 and launched a GIF webinar series in September 2016. Since then, the webinar series has continuously expanded to meet the growing demand of developing a skilled and trained workforce. By the end of 2024, 96 webinars had been proposed, recorded and archived on the GIF portal (www.gen-4.org/resources/webinars), these webinars are also accessible on the GIF ETWG YouTube channel (www.youtube.com/@gifetwg/videos) and the Bilibili Channel (https://space.bilibili.com/435834911/lists). The objectives of the webinars are to 1) provide information on Gen IV reactor systems and the nuclear fuel cycle, 2) address ongoing research in support of reactor development and deployment; and 3) maintain, preserve and transfer knowledge of these advanced reactors.

To encourage and stimulate students to join the workforce, and to support the next generation's workforce development, the GIF ETWG has launched the "2025 Pitch your Gen IV Research" competition, which calls PhD students, postdoctoral fellows and early career professionals who received their PhD after 1 January 2023, and whose research is related to Gen IV advanced nuclear energy systems, to submit a one-page executive summary of their research to the Gen IV website. This competition provides a platform for entrants to showcase their research and gain recognition within the nuclear energy community.

Table ETWG-1: **GIF webinars organized, presented and archived in 2024**

Presenter	Title of Webinar	Date
Jonah Lau, Purdue University, US	Revolutionizing Nuclear Engineering Education: Developing Virtual Labs for Neutron Detection, Geiger Counter, and Reactor Experiments	31 Jan. 2024
Victor Viallon, first winner of the 2023 Pitch your Gen IV Research Competition, CEA, France	Analysis of the Reactivity Loss of the Phénix Core Cycles for the Experimental Validation of the DARWIN-FR Code Package	28 Feb. 2024
Lori Walters, CNL, Canada	Overview of Canadian R&D Capabilities to Support Advanced Reactors	20 March 2024
Samuel Walker, second winner of the 2023 Pitch your Gen IV Research Competition, INL, US	Multiphysics Depletion & Chemical Analyses of Molten Salt Reactors	17 April 2024
Joint GIF/IAEA webinar Panellists: Paula Calle Vives, IAEA; Greg Oberson, NRC, USA; Tarek Tabikh, CNSC-CCNS, Canada Organizers and moderators: Vladimir Kriventsev, IAEA, and Patricia Paviet, PNNL, US	Regulatory Activities in Support of SMRs and Advanced Reactor Systems	22 May 2024
Gidong Kim, popular vote winner of the 2023 Pitch your Gen IV Research Competition, UNIST, Korea	Directed Energy Deposition Process of Corrosion Resistant Coating for Lead-Bismuth Eutectic Environment	5 June 2024
Sam Bryan and Amanda Lines, PNNL, US	Online Monitoring Development in Support of the Nuclear Fuel Cycle	31 July 2024
GIF panel session Panellists: Aslak Stubsgaard, Denmark; Isabelle Morlaes, France; Ed Pheil, US; Markus Piro, Canada; Jeremy Pearson, US Organizer and moderator Patricia Paviet, PNNL, US	International Molten Salt Research in Support of MSR Development	28 August 2024
Yoshikata Chikazawa, JAEA, Japan	Overview and Update of SFR activities within GIF	25 Sept. 2024
Petr Vacha, UJV Center, Czechia	Prospects and Challenges of the GFR Technology	2 Oct. 2024
Armando Nava, CNL, Canada	Overview and Update of SCWR activities within GIF	26 Nov. 2024
Mariano Tarantino, ENEA, Italy	Overview and Update of LFR activities within GIF	5 Dec. 2024

2024 GIF Webinar Series

Eleven webinars, depicted in Table ETWG-1, were presented live in 2024 and are archived on the GIF portal. Additionally, a joint GIF/IAEA webinar, organized by Vladimir Kriventsev from the IAEA and Patricia Paviet from PNNL, United States and entitled "Regulatory activities in support of SMRs and advanced reactor systems" was presented on 22 May 2024. This webinar featured three panellists: Paula Calle Vives from IAEA, Greg Oberson from NRC and Tarek Tabikh from Canada Nuclear Safety Commission. They highlighted the IAEA nuclear standardization and harmonization initiative and the importance of early engagement of developers with regulators. They also gave an overview of the various licensing approach requirements and guidance.

As of 31 August 2024, attendance during the live webcasts was 8 501, and the number of viewings of recorded webinars in the online archive was 7 748, totalling 16 249 webinar viewings in eight years. These webinars have reached scientists and engineers across 84 countries.

Future GIF webinars have been planned until June 2025 and include the completion of Gen IV system overviews, an IAEA presentation on nuclear power information system, Gen IV advanced manufacturing, maritime applications, and fuel fission gas release modeling. The registration link for each webinar will be available on the GIF portal (www.gen-4.org/list-gif-webinars).

2025 Pitch your Gen IV Research Competition

The ETWG launched the 2025 Pitch your Gen IV Research competition on 1 October 2024. This competition aims to involve junior researchers within the Gen IV community, stimulating their interest in advanced reactor systems, and to inform the public about Gen IV reactors and related topics. The public is also given the opportunity to participate by voting for a preferred video/candidate/topic. The selected candidates will pitch their research with an informative video that will be available on ETWG's YouTube and Bilibili channels, as well as the GIF portal, where the videos of the 2021 and 2023 competitions can also be found. Winners of the 2025 competition will be announced in June 2025. The first and second place entrants will be invited to attend a GIF event, while the popular vote winner, as well as the first and second place entrants, will receive the opportunity to present a GIF webinar.

Patricia Paviet
Chair of the ETWG,
with contributions from ETWG members

Non-Electric and Cogeneration Applications Working Group

The direct use of nuclear-generated heat or process intermediates from nuclear heat and electricity to support energy demands in the industrial sector offers significant potential for emission reductions. Nuclear energy has been used for such non-electric industrial applications for several decades, but these systems have faced strong economic competition. Given the changing energy landscape, the suitability of nuclear energy systems must be reevaluated to consider new applications.

In response to this need, the GIF Policy Group established the Non-Electric Applications of Nuclear Heat Task Force (NEANH TF) at its meeting on 20-21 May 2021. The task force began its work in October 2021 and concluded its term in October 2024. In October 2024, the transition of the task force into a sustained working group was approved during the 58th GIF Policy Group meeting on 17 October 2024.

The Non-Electric and Cogeneration Applications of Nuclear Energy (NECA) Working Group will build on the success of the GIF task force, which established a baseline knowledge of energy system design, analysis and tools, and clarified a need among GIF member countries to stay engaged in analysing these systems.

The overall objective of the NECA Working Group is to advance knowledge and access to energy system design, analysis and optimisation tools that may allow decision makers to find optimal energy system solutions for different socio-economic and geographical contexts.

In particular, the NECA Working Group is actively working among members and internationally, within and beyond the GIF ecosystem, to:

- conduct system analysis on non-electric applications of nuclear heat;
- engage potential end users who are exploring the use of nuclear energy for their industrial applications;
- maintain a publicly available database of relevant studies and commercial systems;
- support analysis by nuclear and conventional regulators on non-electric applications of nuclear energy;
- engage internationally to leverage similar efforts taking place globally.

Task Force and Working Group highlights in 2024

In 2024, the NECA Working Group was officially launched after the GIF task force concluded its mandate, with many notable accomplishments that supported the decarbonization of industrial sectors using nuclear energy.

Most notably, the task force and KAERI co-organised the Non-Electric and Hybrid Applications of Nuclear Energy Workshop on 26 April 2024, in Busan, Korea (Figure NECA-1). The event was hosted by the Korean Nuclear Industry Association and the Korea Nuclear International Cooperation Foundation on the margins of the 39th Korea Atomic Power Annual Conference (GIF, 2024a).

The workshop included approximately 75 participants from around the world and featured participation from international organisations, energy end users in hard-to-abate industrial sectors, regulators, and nuclear technology developers targeting non-electric applications. Participants shared information on specific needs, requirements, and potential challenges or concerns associated with coupling nuclear energy to industrial applications in pursuit of advancing technologies toward a net zero future. In addition to scene-setting remarks, information was primarily provided through presentations, which are available on the GIF website (GIF, 2024a).

On 28 February 2024, the task force presented its activities at the SIAP Special Session on Non-Electric Applications in Ottawa, Canada, which was attended by industrial end users, regulators and other stakeholders (GIF, 2024b).

Figure NECA-1: GIF Workshop on non-electric and hybrid applications at KAP Conference

With a focus on its objective of engaging internationally to leverage similar non-electric applications efforts, the NECA Working Group is collaborating with the Hydrogen Value Chain working group of the NEA, the Hydrogen from Nuclear Energy Task Group of the IEA and the non-electric applications initiatives of the IAEA and the Nuclear Cogeneration Industrial Initiative in Europe.

Following an initial system analysis workshop as part of the Joint IEA-GIF Meeting on Hydrogen from Nuclear Energy on 23-25 January 2024 at INL, the NECA Working Group agreed to focus on the system analysis of hydrogen production through HTSE using HTGRs. This analysis includes assessments of the cost and characteristics of a system where hydrogen production using HTSE is coupled to a HTGR. Results will cover system modeling on a generic system scenario using existing modeling tools among GIF member countries. A draft report on the techno-economic feasibility of this system is expected in early 2025. The report will also summarise expert views on the perceived technological and commercial readiness of this system and seek to identify associated gaps.

There were dedicated panel sessions on non-electric applications at Euratom's annual SNETP Forum on 17-19 April 2024 in Rome, Italy (SNETP, 2024). The results from these sessions, specifically those on quantifying several heat markets and on adapted nuclear solutions to deliver the required power, were shared with the task force.

Finally, the working group finalized a public database cataloguing over 60 studies, 25 international collaborative initiatives, and an inventory of previous demonstrations or commercial systems where nuclear energy has already been used for non-electric purposes. The Non-electric Applications of Nuclear Heat Database is being maintained and will continue to evolve to become a trusted source of information related to using nuclear energy for non-electric or cogeneration applications (GIF, 2025).

Future work will continue to advance systems analysis on other non-electric and cogeneration systems that could be adapted to use nuclear energy. This is expected to include work to address regulatory gaps and other activities in collaboration with international organizations.

Shannon Bragg-Sitton
Chair of the NEANH TF,
with contributions from NEANH TF members

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Proliferation Resistance and Physical Protection Working Group

The Proliferation Resistance and Physical Protection Working Group (PRPPWG) was established to develop, implement and foster the use of an evaluation methodology to assess Gen IV nuclear energy systems with respect to the GIF proliferation resistance (PR) and physical protection (PP) goal (www.gen-4.org/gif/jcms/c_9502/generation-iv-goals). The methodology provides designers and policy makers with a technology-neutral framework and a formal comprehensive approach to evaluate, through measures and metrics, the PR and PP characteristics of advanced nuclear systems. As such, the application of the evaluation methodology offers opportunities to improve the PR and PP robustness of system concepts throughout their development and deployment cycle. The working group released the sixth revision of the methodology for general distribution in 2011 (GIF, 2011), and translations in Japanese and Korean of the methodology report have been produced for national use.

A review conducted in 2023-2024 of the current PR and PP evaluation methodology highlighted how the PP aspect might benefit from an update of the considered measures and metrics. The update activity was decided at the 33rd PRPPWG meeting and was followed up by dedicated internal workshops, where a new framing for the PP measures and metrics was proposed and discussed. The group is considering adding three new metrics which better represent intrinsic PP aspects of reactors including dispersibility, energetic mechanisms and inherent coolability. The group will continue the revision in 2025.

As a follow-up to the suggestions given to the PRPPWG at the GIF Industry Forum in Toronto, Ontario, 3-7 October 2022, the group started to work on a report examining PR and PP implications of siting options for SMRs and microreactors. The report considers the following four siting options for SMRs: 1) remote locations; 2) near population centers; 3) floating or underwater power stations; and 4) civilian marine propulsion. In addition, five additional crosscutting aspects are discussed: 1) single versus multi-modules; 2) ultimate heat sink; 3) autonomous and remote operation; 4) high-assay low-enriched uranium (HALEU) versus low-enriched uranium; and 5) transit of reactors. Each section ends with high-level conclusions, which are then summarized at the end of the report. The report is currently in a draft state ready for final reviews in the first half of 2025. Completing the report and getting it approved for public release will be a priority for 2025.

An important activity in 2024 has been the continued collaboration with the RSWG and the VHTR SSC on a case study to identify 3S (safety, security, safeguards) interfaces on a generic small modular VHTR pebble-bed reactor design through a bottom-up exercise. The report consists of several sections covering the generic pebble-bed reactor design being considered, followed by sections on safety, security and safeguards assessments. The report identifies the interfaces, focusing on understanding areas of alignment or tension, and ends with key insights and recommendations for vendors. The final two sections are still in progress. In addition to the 3S study, the PRPPWG/RSWG/VHTR SSC collaboration aims to draw generalized conclusions on how safety, security and safeguards interfaces can be analyzed in a technology-neutral, bottom-up approach. The insights gained from this study will help in implementing 3S by design for near-term reactor implementations.

As part of its knowledge management activities aimed at maintaining cognizance of the relevant ongoing PR and PP activities inside and outside GIF, the PRPPWG maintains an annually updated bibliography of official publications that refer to the PR and PP methodology, and of relevant issues. The latest edition, revision ten, was published in November 2023 (GIF, 2023). The bibliography is going through changes in 2024 and 2025 to convert it into a website format with linked references for easier external use.

The PRPPWG maintains regular exchanges with the IAEA's INPRO and its departments of Nuclear Safeguards and Nuclear Safety & Security. An IAEA representative is appointed as a permanent observer in the PRPPWG and participates regularly in the group's activities. The PRPPWG made a presentation at the 18th GIF-IAEA Interface meeting on 9-10 July 2024, highlighting the ongoing PRPPWG-IAEA collaborations on PR and 3S by design.

PRPPWG members present the work of the group regularly at international conferences and other forums (Renda, 2024; Cipiti, 2024; Nguyen, 2024). The current status of the 3S activity has been presented in several workshops and meetings throughout 2024 (van der Ende, 2024), always receiving positive feedback and expressions of interest in the expected outcome.

Figure PRPP-1: **34th PRPPWG Annual Meeting in Paris, March 2024**

Collaboration with the RSWG continued through exchanges at each group's meetings. PRPPWG representatives attended the 2024 RSWG semi-annual meetings, and RSWG representatives participated in the 34th PRPPWG annual meeting.

The PRPPWG is also engaged with the EMWG in exploring areas of potential collaboration. Potential areas of mutual interest are the addition of safeguards and security costs to an economic analysis of Gen IV reactor systems and an economic analysis of the benefits of a 3S by design approach. In 2023 and 2024, a representative of the PRPPWG attended EMWG meetings, presenting the content of selected PR and PP activities and discussing their relevance for potential collaborations.

The PRPPWG holds monthly teleconferences to report on the progress of group and member activities. The 34th Annual Meeting (Figure PRPP-1) was held in Paris on 19-21 March 2024, hosted by the OECD-NEA. It provided an excellent opportunity to meet with the full group in person and further the current efforts of the group. The group will hold its 35th annual meeting in Ispra, Italy in February 2025, hosted by JRC.

Frédéric Nguyen
Co-Chair of the PRPPWG

Guido Renda
Co-Chair of the PRPPWG

Ben Cipiti
Co-Chair of the PRPPWG

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Risk and Safety Working Group

The Risk and Safety Working Group (RSWG) was formed in 2005 to promote a consistent approach to safety, risk and regulatory issues among Gen IV systems. It also advises the GIF Experts Group and Policy Group on matters such as:

- Gen IV safety goals and evaluation methodologies to be considered in design and R&D programs.
- Interactions with the nuclear safety regulatory community, the IAEA and relevant stakeholders.

In 2024, RSWG membership included representatives from Canada, China, the European Union, France, Japan, Korea, Russia, South Africa, the United Kingdom and the United States. The IAEA Department of Nuclear Safety and Security also participated as an observer.

The Integrated Safety Assessment Methodology (ISAM) was developed by the RSWG as a technology-neutral toolkit that supports design, safety and risk evaluation. The RSWG has subsequently coordinated with the SSCs to apply ISAM to selected Gen IV designs, as documented in a series of white papers and system safety assessments. These documents are available on the GIF RSWG web page (GIF, 2025).

The RSWG and SSCs have also collaborated on the development of safety design criteria (SDC) and safety design guidelines (SDG) for specific Gen IV systems. These SDC and SDG are intended to bridge the gap between the high-level GIF safety goals and country-specific codes and standards by establishing minimum requirements for design, fabrication, construction, inspection, testing and operation of the first Gen IV reactor demonstrations.

In 2024, the RSWG published the second SFR SDG report on structures, systems and components (GIF, 2024). A report describing SDC for the fast-spectrum SCWR system was also drafted and is undergoing internal review by the RSWG and the SCWR SSC prior to publication.

The RSWG also welcomes reviews of its publications by the international regulatory community as represented by organizations such as the NEA Working Group on New Technologies (WGNT) and the IAEA. Proposed resolutions to review comments on the LFR SDC (GIF, 2021) were returned to the WGNT and IAEA in 2024. The WGNT also provided review comments on the VHTR SDC (GIF, 2023a) and has agreed to review the RSWG's position paper on the risk-informed framework for safety design of Gen IV systems (GIF, 2023b). The IAEA has also agreed to review the VHTR SDC and risk-informed approach position paper, and the RSWG is waiting to receive feedback before addressing the comments of the WGNT in new revisions of both documents.

The RSWG maintains a direct technical interface with the IAEA, and this relationship was reaffirmed during the virtual GIF-IAEA Interface meeting that took place on 9-10 July 2024. As part of this interface, the RSWG co-chair served on the organizing committee for the IAEA's Nuclear Harmonization and Standardization Initiative Industry Track Topic 3 on experiments and safety analysis code validation. This initiative has created the NEXSHARE platform (IAEA, 2024) that contains a database of experimental facilities that can provide validation data and a platform for the exchange of information between the operators of these facilities, reactor designers, code developers and technical support organisations. The NEXSHARE platform was officially launched at a workshop hosted by the IAEA in Vienna on 18-21 June 2024, where the RSWG co-chair represented GIF in several sessions. An IAEA consultancy meeting on 4-6 December 2024 officially transformed the organizing committee to a formal steering committee for the NEXSHARE platform, where GIF (as represented by the RSWG co-chair) has a permanent seat.

The RSWG continued to collaborate with the PRPPWG and the VHTR SSC on the 3S interface investigation. The objective of this activity is to generate new insights on the interaction between the 3S using the VHTR system as the basis for a case study. In 2024, RSWG members completed the safety assessment of the generic VHTR concept used for the case study and contributed to the assessment of the interfaces (i.e. safety-security and safety-safeguards). A paper summarizing the progress in this initiative was presented by an RSWG member at the IAEA's International Conference on Small Modular Reactors and their Applications on 21-24 October 2024 (Ammirabile et al., 2024).

Two new investigations for Gen IV systems were started by the RSWG in 2024: 1) identification of practically eliminated situations (PES); and 2) mechanistic source term (MST) assessment methodologies. For both, the RSWG distributed questionnaires to experts to establish the international state-of-the-art for each topic. In the case of the PES initiative, the responses received from RSWG members were used to plan the future direction of the work, which is anticipated to produce a white paper describing the approach for Gen IV systems. For the MST initiative, the RSWG connected with the Design and Safety Analysis Working Group of the SMR Regulator's Forum, which had just distributed a questionnaire to its members on the same topic. The RSWG was able to distribute the same questionnaire to its own members while getting access to the responses already received by the DSA Working Group. Discussions to coordinate the RSWG and SMR Regulator's Forum activities on MST are ongoing.

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GIF Senior Industrial Advisory Panel report

GIF Senior Industrial Advisory Panel activity in 2024

The GIF SIAP was established in 2005 to provide strategic guidance on the commercialization potential of Gen IV nuclear energy systems, leveraging industry insights and expertise.

In 2024, SIAP convened two meetings to consider specific topics identified by the Policy Group to address the following charges:

1. How would Gen IV developers approach a new build project in a vendor host country, a nuclear country and a newcomer country? For example, how do vendors envisage the breakdown of local vs. non-local sourcing of materials and supply chain access? (The Policy Group recognizes that the new build approach might vary among GIF member countries)
2. What additional steps need to be taken to achieve consistent safety standards of Gen IV designs across regulators, recognizing that each host country would need to step up effective regulatory oversight? Are there gaps for international regulation and are these gaps generic or specific to Gen IV technology features?

Based on the feedback and discussions at the SIAP meetings, SIAP provided advice to the GIF Policy Group on these issues, which is set out below.

Charge 1: Local approach to a new build project with different nuclear infrastructures

Gen IV developers must adopt flexible and strategic approaches when considering new build projects across different country contexts. In vendor host countries, the focus is on leveraging established supply chains and regulatory familiarity to optimize project timelines and costs. For nuclear countries with existing regulatory capabilities, developers should aim to align their designs with local codes and pursue harmonization with international standards to minimize re-designs and licensing complexities. In newcomer countries, capacity building, knowledge transfer and supporting local regulators in adopting international standards are crucial to establishing a robust regulatory framework.

Localization is a key strategy to foster socio-economic benefits in the hosting country, but it requires balancing economic feasibility with supply chain stability. For critical components like nuclear heat supply system and Gen IV-specific systems, developers must carefully evaluate local suppliers' capabilities and collaborate early in the design and planning stages. This approach enhances local supply chains' technical capacity while ensuring cost-efficiency and quality control.

New technologies play a vital role in reducing costs and improving efficiency. The standardization and modularization of components can significantly reduce construction time and costs, while advanced manufacturing techniques, such as 3D printing and robotics, improve production efficiency and quality. Furthermore, AI applications in design, manufacturing, supply chain management and project scheduling help to optimize logistics, reduce delays and streamline operations.

Regulatory harmonization and code convergence are foundational for global Gen IV deployment. Aligning standards across countries enables smoother licensing processes, cost reductions in design and sourcing, and more efficient use of the supply chain. Efforts to limit the divergence of nuclear codes produced by various national standards organizations, as well as adopting international conventions (e.g. ISO standards), are critical to achieving consistent safety standards and promoting international collaboration.

By developing comprehensive strategies that address the unique requirements of each country type and balancing regulatory, technical and economic factors, Gen IV developers can achieve significant cost savings and ensure the successful and standardized deployment of advanced reactors worldwide.

Charge 2: International safety standards

Achieving consistent safety standards for Gen IV reactor designs across different regulatory bodies is crucial for the global deployment of these advanced technologies. Addressing gaps in regulations – whether they pertain to high-temperature materials, advanced fuel cycles, passive safety systems, digital instrumentation and control, or coolant technologies – requires a harmonized and coordinated international effort. The role of existing initiatives, such as the IAEA's Nuclear Harmonization of Standards Initiative[1] and Euratom's HARMONISE project,[2] is vital in driving the convergence of safety standards and fostering a shared understanding of safety requirements across nations.

GIF is uniquely positioned to lead efforts in closing these regulatory gaps by developing safety design criteria and guidelines that align with global standards, promoting international collaboration and knowledge sharing, and contributing to the development of harmonized regulatory frameworks in GIF member countries. Furthermore, GIF's support for capacity building in newcomer countries, as well as the development and validation of safety assessment tools, will strengthen regulatory oversight and enhance the safe deployment of Gen IV reactors.

However, the successful realization of these contributions is contingent on the active participation of member countries through increased financial resources and dedicated expert involvement. By bolstering support for technical development and regulatory harmonization, and by building a central digital repository of Gen IV research and capacity building initiatives, member countries can empower GIF to effectively drive the consistent and safe deployment of Gen IV reactors worldwide. Such a concerted effort will ensure that Gen IV technologies can be developed and licensed under consistent, high safety standards, supporting the efficient advancement of nuclear innovation globally.

By working together to harmonize safety standards, streamline regulatory processes and share best practices, the global nuclear community can address the unique challenges posed by Gen IV technologies and ensure their successful and safe integration into the future energy landscape.

SIAP special sessions on selected topics

In 2023, SIAP initiated special sessions as an innovative platform to engage existing members and a broader spectrum of stakeholders, particularly from the industrial sector, in discussions about GIF activities. This move came following the success of a special session held in Canada in 2022 that underscored significant interest and potential for collaboration in the field of advanced nuclear technologies. The SIAP session was a strategic response to both the evolving landscape of nuclear energy development, which increasingly involves private sector participation, and the specific directives outlined in the SIAP charge, which focuses on assessing effective industry engagement opportunities and enhancing the visibility of GIF achievements.

In 2024, SIAP conducted two special sessions in February and October:

- In February, Ramesh Sadhankar (CAN) introduced GIF's non-electric application activities during a special session at the Canadian Nuclear Association 2024 Conference. The session, held as a side event, included digitalization of the task force database, upcoming working scope and advertisement of a System Readiness survey.
- In October, an NEA workshop on digital innovation and AI was held, with SIAP joining for a special session. The workshop included four sessions, including: 1) using AI to accelerate the deployment of nuclear power; 2) rethinking nuclear applications around AI; 3) changing organizations with AI: from data management to cultural shift; and 4) regulating AI: opportunities and challenges. The SIAP Chair, Professor Nawal K. Prinja, gave a presentation in Session 2 and in a special session, "Hands on experience: Unlocking AI for engineering excellence", and chaired Session 3. Forty-one attendees from academia, government and industry participated in the workshop.

SIAP plans to continue hosting multiple special sessions to facilitate exchanges between GIF and industry. SIAP's goal remains to steer Gen IV technology towards commercial success, ensuring a collaborative and progressive pathway for nuclear innovation.

1. https://nucleus.iaea.org/sites/smr/SitePages/Nuclear-Harmonization-and-Standardization-Initiative.aspx.

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Appendix 1. Country reports 2024

Australia

Australia continues to be a committed and cooperative GIF member, with a focus on the mutual benefits reaped from international cooperation in collaborative programs.

ANSTO is pleased to announce that the OPAL reactor has resumed full operations after a planned shutdown. The project involved the replacement of the first reactor protection system and the cold neutron source, marking the most extensive maintenance and upgrade program in the reactor's 17-year history. The restoration of OPAL's operations ensures the production of medical isotopes and supports ongoing research utilizing OPAL's neutron beamlines.

ANSTO is currently constructing the Synroc® Waste Treatment Facility to treat and manage waste generated from its nuclear medicine production activities. The plant is progressing through the commissioning phases to assess the effectiveness of ANSTO's proprietary Synroc® technology in real-world waste treatment scenarios. Once operational, the facility will be a fully-automated waste treatment plant, providing an end-to-end life cycle on radioactive waste for ANSTO's nuclear medicine precinct. Additionally, ANSTO is developing Synroc®-type waste-forms for fluoride molten salt immobilisation, which is relevant to Gen IV reactor systems, further enhancing long-term waste management solutions.

To address the ongoing and future demands for skilled nuclear professionals in Australia, ANSTO has developed a strategic nuclear workforce development plan aimed at cultivating an engaged, capable and adaptable nuclear workforce. This plan outlines a comprehensive framework consisting of five core workforce development pillars designed to build and retain a skilled and resilient workforce. The plan intends to position ANSTO to support opportunities presented by developments in nuclear science and technology for priority government programs. ANSTO also collaborates closely with Australian universities, supporting various academic programs by hosting undergraduate and postgraduate students and providing them with access to its advanced nuclear research infrastructure.

In Australia, nuclear science and technology is used to drive real-world outcomes in nuclear medicine and cancer care, and in health, food and environmental research, and to benefit and grow the country's industries. Australia has chosen not to deploy nuclear energy for electricity generation. Nevertheless, the country recognises the broader benefits that the peaceful uses of nuclear science and technology can bring to global communities, nations and the environment. Australia will continue to deploy its own leading nuclear science and technology expertise and world-class nuclear science infrastructure to address global challenges.

The Commonwealth Scientific and Industrial Research Organisation (CSIRO), in collaboration with the Australian Energy Market Operator, released its annual GenCost report in May 2024. The report estimates the cost of new build electricity generation and storage. In 2024, the report included updated data and for the first time Australian costings for nuclear-generated electricity.

These coordinated efforts across policy, economic analysis, infrastructure maintenance, waste management, international partnerships and workforce development collectively demonstrate Australia's comprehensive approach to advancing nuclear science and technology. By fostering collaboration, innovation and education, Australia is well-positioned to contribute meaningfully to the global nuclear landscape, supporting both national objectives and international United Nations Sustainable Development Goals.

Canada

Government of Canada policy and actions: Federal

Support for new builds and the nuclear sector

The Government of Canada is supportive of nuclear energy and has taken several actions to advance nuclear investment and deployment. For example, it announced CAD 50 million (Canadian dollars) in February for preliminary work for an expansion of the Bruce Power nuclear plant via Natural Resources Canada's Clean Electricity Pre-development Program. The work will include launching Indigenous consultations, getting regulatory approvals and preparing the construction site. The program additionally announced CAD 25 million to New Brunswick Power for predevelopment work for up to 600 megawatts of new SMR capacity at the Point Lepreau Nuclear Generation Station.

The first four Clean Economy Investment Tax Credits (ITC) were passed into Canadian law in June. The credits now include the Clean Technology ITC, the Carbon Capture, Utilization and Storage ITC, the Clean Technology Manufacturing ITC, and the Clean Hydrogen ITC. The Clean Technology ITC includes a 30% credit for private companies for SMRs. In August, draft legislation for the Clean Electricity ITC was published for public comment. When legislated, this ITC will provide 15% to utilities for nuclear energy projects. In addition, the federal government updated its Green Bond Framework to include certain nuclear energy expenditures such as investments in new reactors, refurbishment of existing facilities, R&D, and Canada's nuclear supply chain. Canada's framework is now the first sovereign Green Bond Framework to include nuclear energy.

The Government of Canada has announced important steps to modernize the assessment processes for nuclear projects. These steps include establishing a three-year target for reviewing nuclear projects and promoting the principle of "one project, one review". It has also committed to getting nuclear projects built in a timely, predictable and responsible manner, including setting a three-year target for nuclear project reviews. In December, the Government of Canada announced potentially having the Canadian Nuclear Safety Commission process apply to certain brownfield nuclear projects, as opposed to also requiring a federal impact assessment.

Investments in innovation

The Government of Canada announced CAD 3.1 billion over 11 years, starting in 2025-26, to Atomic Energy of Canada Limited to support and oversee CNL's ongoing nuclear science research, environmental protection and site remediation work.

Fuel supply

Additionally, the Government of Canada announced a CAD 500 million fuel supply program to backstop enriched nuclear fuel purchase contracts from the United States and other allied countries.

Provincial government actions

Nuclear-interested jurisdictions (namely the governments of Ontario, New Brunswick, Saskatchewan and Alberta) remain committed to nuclear development and deployment in their respective regions and are taking collective actions in this regard. Key considerations of energy reliability and affordability were raised in 2024 and are likely to remain considerations in the near future.

In January 2024, Capital Power Corporation in Alberta and Ontario Power Generation (OPG) entered into an agreement to jointly assess the development and deployment of SMRs to provide nuclear energy for Alberta. Through the agreement, the utilities will complete a feasibility assessment within two years. In March 2024, the Government of Saskatchewan established the Small Modular Reactor Investment Fund, which is a segregated fund designed to support the future development of the province's first SMR. The SMR will provide zero emission baseload power. The governments of Saskatchewan and Alberta also signed a memorandum of understanding in May 2024 to advance the development of nuclear power generation in support of both provinces' need for affordable, reliable and sustainable electricity grids by 2050.

Canadian Nuclear Safety Commission (CNSC)

In March, the CNSC, US Nuclear Regulatory Commission (NRC), and UK Office for Nuclear Regulation (ONR) signed a trilateral memorandum of cooperation on new nuclear technologies, providing a framework for the exchange of information and sharing of best practices. In September, the *Trilateral Principles Paper on the Deployment of Artificial Intelligence in Nuclear Activities* was released, which outlines high-level principles for integrating AI technologies into nuclear operations.

In November, Candu Energy Inc. announced it was entering into a special project with the CNSC to plan a Pre-Licensing Design Review of the new CANDU MONARK reactor's suitability to be licensed and built.

Nuclear Waste Management Organization (NWMO)

In November, NWMO announced the selection of Wabigoon Lake Ojibway Nation and the Township of Ignace as the host communities for the future site for Canada's deep geological repository for used nuclear fuel. The NWMO launched its community-driven, consent-based site selection process in 2010, and the project is expected to have a timeline of 175 years.

Canadian industry and nuclear energy projects (new builds and refurbishments)

Domestic new builds

In June 2024, OPG and the government of Ontario announced the on time and on budget completion of the first phase of site preparation for the BWRX-300 SMR, the first SMR in the G7, being built at Darlington. The site has transitioned into the care of the Darlington New Nuclear Project's construction partner, Aecon, and the main site preparation is underway.

In addition, the Government of Ontario requested in November that OPG begin discussions with Indigenous, community and municipal leaders on its existing sites in Port Hope, Haldimand County and St. Clair Township to determine community support for all types of new energy generation, including nuclear, to meet Ontario's increasing demand for electricity. The Port Hope site could host up to 10 000 MWe of new nuclear generation alone.

Refurbishments

Building on its on time, on budget track record, the Government of Ontario announced in January 2024 that it will support OPG's plan to proceed with the next steps toward refurbishing Pickering Nuclear Generating Station's "B" Units 5-8.

In August, the Bruce 3 Major Component Replacement (MCR) completed the reactor removal refurbishment stage in record time and ahead of schedule. The Unit 3 MCR is the second of six refurbishment projects set to extend the Bruce Power site's operational life to 2064. Innovations since the Unit 6 MCR outage have led to improved performance.

In November, OPG announced the completion of the refurbishment of Unit 1 at the Darlington Nuclear Generating Station five months ahead of schedule. Unit 1 is the third of four units that have been successfully refurbished to date by OPG, with the overall project tracking on time and on budget; Unit 4 is progressing according to plan and will be completed in quarter 4 2026.

Exports

In June, Romania's Nuclearelectrica and Canadian Nuclear Partners (an OPG subsidiary) signed a long-term framework agreement to provide services for the refurbishment of Cernavoda nuclear power plant's CANDU Unit 1. In December, Nuclearelectrica, subject to approvals, awarded a contract to Candu Energy and the Canadian Commercial Corporation (a Canadian crown corporation), in a consortium with other international partners, to life-extend Unit 1. In November, Candu Energy, in a joint venture with international partners, was awarded a contract to build two new CANDU reactors at Cernavoda (Units 3 and 4), which when completed would be the first CANDU reactors built globally since 2007. Financing is to be supported by up to CAD 3 billion from the Government of Canada, administered by Export Development Canada and subject to due diligence, with additional capital from other governments.

China

Nuclear energy development

By the end of September 2024, there were 56 nuclear power units in operation and 46 nuclear power units approved and under construction on the Chinese mainland, with a total installed capacity of 113.13 GW.

From May to the end of September 2024, Unit 4 of Guangxi Fangchenggang was put into operation and four units started construction: Liaoning Xudapu Unit 2 on 17 July, Fujian ningde Unit 5 on 28 July, Shandong Shidao Bay Phase I expansion project on 28 July, and Fujian Zhangzhou Unit 4 on 27 September.

On 16 September 2024, during the IAEA general conference in Vienna, China announced its plan to open 12 nuclear research facilities, including the China Advanced Research Reactor and the new-generation tokamak device, Huanliu-3, to international scientists and institutions with the aim of building a high-level global technical cooperation platform.

On 16 August 2024, phase I of Jiangsu Xuwei Nuclear Power Plant received an official approval to start. It will be the first one coupled with a HTR with a PWR in the world.

GIF activities in China

VHTR

HTR-PM reached commercial operation on 6 December 2023. Operation feedback from HTR-PM will improve the HTR plant design. The HTR 2024 conference was held from 14 to 18 October 2024 in Beijing. The basic designs for a new HTR-PM600 for electricity generation and an HTR-PM600S for the cogeneration of high-temperature steam and electricity are finished, with both having six nuclear steam supply system modules and one steam turbine. The construction of HTR-PM600S was approved by the government on 19 August 2024. R&D in GIF projects is going as planned, with intent to join the hydrogen production project.

SFR

Design is underway for China's integrated fast reactor (CiFR1000), which is composed of several fast reactors and one fuel regeneration facility on the same site. The fuel regeneration facility will integrate pyro-processing and a metal-fuel fabrication line for fuel reprocessing and regeneration. China will build the CiFR1000 international platform by extensive cooperation at home and abroad. The CiFR1000 is expected to be completed by 2035.

SCWR

For the small modular SCWR known as CSR 150 proposed by China, a new fuel assembly with mixed moderators is devised that has the advantages of being simple in design, economical and safe. In the SCWR Information Exchange Meeting, which was organized by Shanghai Jiao Tong University from 10 to 13 June, GIF member countries exchanged progress on their work.

Euratom

Ensuring technology autonomy, supply chain independence and energy security remain among the main challenges and priorities in the present geopolitical context. Several EU member states are expressing or reaffirming interest in the deployment of new or additional nuclear energy technologies, including SMRs, many of which are of a Gen IV type. However, the decisions on the national energy mix remain a competence of each individual member state.

Policy developments

In July 2024, European Commission President Ursula von der Leyen was elected for a second five-year mandate, and a new College of Commissioners was nominated for 2024-2029.

Responsibilities for nuclear energy have been placed under the following commissioners:

- The Commissioner for Startups, Research, and Innovation, Ekaterina Zaharieva. She will take responsibility for the nuclear research activities of JRC and the European Commission's Directorate-General for Research and Innovation (DG RTD).
- The Commissioner for Energy and Housing, Dan Jørgensen, who will have energy policy responsibilities. His mission letter from President von der

Leyen mentions explicitly that he "should support the acceleration of the development and deployment of Small Modular Reactors in Europe during the 2030s".[1]

The Draghi report on EU competitiveness was released in September 2024 and recommends supporting "new nuclear", i.e. SMR and AMR technologies.[2]

Euratom contributions to GIF

JRC and Euratom member state representatives proactively contribute to the six GIF systems in steering committees, projects, working groups and task forces. The contributions to GIF consist of:

- Indirect actions, which are projects co-funded by the European Commission's DG RTD. In September 2024, 16 new projects on SMRs were selected to be co-funded by Euratom.[3]
- Direct actions, which correspond to parts of the JRC research program. JRC mainly contributes to GIF along four dimensions:
  - coordination and management;
  - safety analysis;
  - production of experimental data in JRC research facilities on inactive structural materials required for codification, standardization and qualification;
  - characterization of active/irradiated fuels and compounds for reactor design, safety and performance analysis and for waste minimization.
- EU member state contributions from their national research programmes. European nuclear research consortia are in the process of designing, developing and constructing several demonstration reactors:
  - The ALLEGRO project, a GFR demonstration project to be constructed in Czechia, Hungary or the Slovak Republic with French CEA support.
  - The ALFRED project, an LFR demonstration project will be built in Pitesti, Romania. ALFRED comprises Italy's National Agency for New Technologies, Energy and the Environment (ENEA), Ansaldo Nucleare, and Romania's Nuclear Research Institute.
  - The MYRRHA research reactor project, a lead-bismuth cooled accelerator-driven fast neutron multi-purpose research reactor, is being developed. Belgium's SCK CEN research centre leads the project, which has many similarities with the LFR.
  - In Poland, NCBJ, in cooperation with JAEA of Japan, has recently issued the conceptual design of a new Polish high-temperature gas-cooled research reactor dubbed HTGR-POLA that will demonstrate the reactor and its use for different purposes.

Several private companies in different EU countries are developing Gen IV-related technologies for early deployment. For example, Newcleo is developing an LFR type SMR and Thorizon an MSR.

Initiatives and events

The JRC, as Euratom's GIF implementing agent, organised the 51st GIF Experts Group Meeting and 57th Policy Group Meeting in Brussels in May 2024. During this meeting, and for the first time, GIF engaged with the Sustainable Nuclear Energy Platform (SNETP) to explore potential ways of cooperation. The SNETP is a European research, development and innovation platform that aims to support and promote the safe, reliable and efficient operation of Generation II, III and IV civil nuclear systems. It gathers 114 members from industry, technical service organizations, and research.

On May 2024, the European SMR Industrial Alliance had its first General Assembly meeting to agree on the way forward and the strategic orientation, structure and next steps. On October 2024, the first batch of nine SMR projects that would constitute the Project-Working Groups were identified; three of these projects are Gen IV SMR projects (two LFRs and one MSR). Hence, there are synergies between GIF and the EU SMR Industrial Alliance that must be further explored by GIF, especially regarding industry involvement.

In conclusion

Nuclear energy and the development of conventional and advanced SMRs are currently experiencing a dynamic boost in Europe. One key to success is the smooth cooperation between R&D organizations and industry. The GIF Industry Forum in 2022 was a good start. The European SMR Industry Alliance has selected three Gen IV projects to work on, and GIF should seek to explore synergies. In this way, GIF will be in an outstanding position to concretely contribute to the future of nuclear energy.

1. European Commission (2024), Mission letter to Dan Jørgensen, https://commission.europa.eu/document/download/1c203799-0137-482e-bd18-4f6813535986_en?filename=Mission%20letter%20-%20JORGENSEN.pdf.

2. European Commission (2024), The Draghi report on EU competitiveness, https://commission.europa.eu/topics/eu-competitiveness/draghi-report_en.

3. European Commission (2024), Small Modular Reactors (LW-SMRs and AMRs): European Projects can be downloaded here: https://research-and-innovation.ec.europa.eu/document/download/74b352e3-cd1e-4b53-a341-7f495b64ec46_en?filename=ec_rtd_smr-projects.pdf.

France

Nuclear energy policy

Reaffirming his commitment to placing nuclear power at the heart of France's low-carbon energy mix, President Macron announced in December 2023 the creation of the Low Carbon Energy Program Agency. In his speech on the future of French research on 7 December 2023 he said: "Each agency [will have] to be [...] a strategist in its field, contributing to the definition of priority research themes, organizing scientific intelligence for all researchers in its area of expertise, interacting with international and European counterparts, and overseeing the development of research infrastructures."

Formally established in May 2024, the CEA leads the national Low Carbon Energy Agency. The agency covers the full range of decarbonized energy technologies, adopting an integrated approach to energy policy and energy technology issues:

- Energy production technologies, transport modes, storage, energy networks and an understanding of their operation.
- Mastery of the materials essential for energy development, with a focus on a circular economy (including knowledge or design of materials, geopolitics of materials, recycling, and substitution of critical materials).
- Understanding how technologies and solutions are adopted within a socio-technical system (in collaboration with approaches developed by the human and social sciences).

The activities of this agency also include the follow-up of the FRANCE 2030 call for SMRs alongside the existing Innovative Nuclear Program Agency.

In 2024, the Low Carbon Energy Agency counted 29 partners.

Nuclear Policy Council

The President of the French Republic convened the Nuclear Policy Council (CPN) on 26 February 2024 (the first two took place in 2023). The role of this council is to define and implement the major orientations of French nuclear policy. This meeting confirmed the cycle closure strategy and announced significant investments in the ORANO La Hague reprocessing plant.

The next council is planned to be held at the beginning of 2025.

National landscape

In terms of national policy, 2024 was a unique year as it saw the transition between three governments. In December 2024, François Bayrou was appointed Prime Minister and formed a new government, with Marc Ferracci as the Minister of Industry and Energy.

It was also a year of exceptional achievements, with 95% of electricity production derived from low-carbon sources, including 361 terawatt-hour (TWh) from nuclear energy. With a total of 536.5 TWh, France's electricity production reached its highest level of the past five years. This record-breaking production has enabled France to set a new milestone for net electricity exports in 2024. With 89 TWh of net exports, France surpassed its previous historical record set in 2002.

National support for innovation

Through the French Public Investment Bank for entrepreneurs, BPI France, France continues to support nuclear innovation via the France 2030 plan. France 2030 is investing a total of EUR 15 billion in emerging players, including EUR 3 billion for future technology start-ups and unicorns. As part of this plan, 11 start-ups focusing on various reactor designs (SFR, HTR, MSR, LFR, LWR, fusion) have been selected, representing EUR 129.8 million of BPI France investment.

Nine projects amongst the 11 winners of the call for SMRs asked for R&D support from the CEA. The High Commissioner for Atomic Energy (HCEA) was also tasked with reviewing all awarded projects in mid-2024. The 11 selected start-ups underwent evaluation by 36 experts, and the findings revealed that nuclear project leaders in France exhibit significant diversity, both in their technological choices – some of which are disruptive – and in their resources and progress with the Nuclear Safety Authority. The France 2030 project call has truly "opened an extraordinary idea box", encompassing innovations from thermal fission to nuclear fusion, with fuels such as plutonium, distinguishing France from the United States. These emerging players have demonstrated remarkable responsiveness and are attracting new talent. The state, in collaboration with the Nuclear Safety Authority and the CEA, continues to provide tailored support for these projects, addressing their specific maturity levels and needs.

R&D programs

Status of the French fast reactor program

The CEA is implementing its new fast reactor-related activities. It is focused on a strong R&D program dedicated to further progress on the fast reactor technology and the associated fuel cycle. Priority is still being given to SFR technology, which is considered as the most mature to comply with mean-term target (second half of the century).

Other concepts of fast-spectrum MSRs are being studied to identify the key feasibility issues, as well as their specific features and potential performances. The CEA, ORANO, EDF, Framatome and the CNRS have launched a four-year project supported by France 2030. Design studies, as well as material and corrosion investigations, are to be performed in parallel with an important R&D program dedicated to salt manufacturing and treatment processes.

Material test reactor: Jules Horowitz Reactor (JHR)

Since March 2020, the new development organization of the JHR required by the French government is fully operational and helping to secure the completion of the project, putting it on more robust tracks. One of the main outcomes of the new organization is to reassess some detailed design studies (ventilation, circuit and electricity) to freeze the 3D mock-up before starting the implementation of the components.

The Nuclear Policy Council reaffirmed its wish to continue and start the JHR as early as possible.

Status of new nuclear power plants

EPR of Flamanville

EDF loaded the 241 nuclear fuel assemblies into the Flamanville EPR reactor vessel in May 2024, following the decision by the French nuclear regulator (ASN) to authorise commissioning of the unit on 7 May. The EPR reached first criticality on 3 September, following the authorisation given by the ASN to launch the first nuclear reaction in a resolution of 2 September.

The EPR was successfully connected to the grid on 21 December 2024. It is expected to provide electricity for around two million people. The last French nuclear power plant to be commissioned was Civaux (Vienne) in 1997. The EPR is the 57th reactor in the French nuclear fleet.

EPR2 reactor program in France

EDF is engaged in the authorization procedures required for the launch of the construction of the first pair of EPR2 reactors at Penly in Normandy, as well as the administrative procedures for its completion and its link-up to the electricity grid. EDF started preparatory work on the Penly site mid-2024.

France has reaffirmed the central and strategic role of nuclear energy in achieving its major energy transformation. This ambition is reflected in massive investments in the construction of six new-generation EPR2 reactors and the launch of studies for eight more, as well as the extension of current reactors.

Japan

At the government's GX (Green Transformation) Implementation Council on 24 August 2022, Prime Minister, and council chair, Kishida Fumio expressed that making up for the delay in energy policies is a pressing issue in implementing the green transformation. Items requiring political decisions to expand the introduction of renewable energy were presented, including:

- drastically accelerating the development of power systems;
- speeding up the installation of fixed storage batteries;
- promoting offshore wind power and other electricity sources.

At the same time, items requiring future political decisions concerning nuclear power were also put forward, such as:

- combined efforts by the concerned parties to resume operations;
- on the basic premise of ensuring safety, maximum utilization of existing nuclear power plants, including the extension of their operation period;
- development and construction of next-generation advanced reactors with built-in new safety mechanisms.

On 10 February 2023, the cabinet approved a basic policy aimed at implementing a green transformation. The GX Implementation Council and councils at relevant ministries have been deliberating ways to simultaneously achieve decarbonization, stable energy supplies and economic growth.

The basic policy includes the following delineated points toward securing stable supplies of energy:

- promoting thorough energy efficiency improvement;
- making renewable energies the main power source;
- utilization of nuclear power, on the basic premise of gaining local understanding, materializing plans for building next-generation advanced reactors within the sites of existing nuclear power plants that have been determined to be decommissioned.

Developments based on the revised strategic roadmap for fast reactors, decided by the Inter-Ministerial Council for Nuclear Power on 23 December 2022, are ongoing:

- Third quarter 2023: Selection of a demonstration reactor concept and a core company.
- July 2023: The government selected a medium power pool-type SFR concept proposed by Mitsubishi FBR Systems as the design to be developed, with Mitsubishi Heavy Industries as the main manufacturer and constructor, and planned to enter operation in the 2040s.
- 2024-2028: Conceptual design and related R&D.
- 2028-: Decision to move to basic design and licensing application for the demonstration reactor.

Based on the lessons learned from the SFR demonstration reactor Monju, the development system in the conceptual design phase consolidated the engineering function into one core company so that the entire system was designed under a clear responsibility structure. However, the government (Fast Reactor Development Council/Strategy Working Group) continues to manage the overall project strategy. In addition, in July 2024 an R&D integration organisation was established at JAEA to take over R&D integration functions.

On 26 July 2023, the experimental fast reactor Joyo was granted a reactor modification license under the new regulatory standards. Modification and reinforcement of the facilities and buildings are ongoing. Joyo is scheduled to be restarted in the middle of Japanese fiscal year (JFY) 2026 and will be used for irradiation tests for fuels relating to the demonstration reactor, materials, etc., and for the demonstration of medical radioisotope production.

The HTGR demonstration reactor development project has also been ongoing based on the plan by Mitsubishi Heavy Industries as the core company of the project.

JAEA successfully completed a loss of forced cooling test during 100% reactor power operation (NEA project) in March 2024. This was a safety demonstration test using HTTR.

A demonstration project for hydrogen production using the existing HTTR is underway. It is planned to demonstrate hydrogen production using high-temperature heat from the HTTR by JFY 2028.

To accelerate R&D and related activities for the early deployment of HTGRs, JAEA and the UK's NNL signed a Collaboration Memorandum regarding the coated particle fuel project (Step 1) in April 2024. This followed the signature of a Collaboration Memorandum regarding the UK HTGR Demonstration Reactor programme (Phase B) in September 2023. JAEA and NNL are continuing their cooperation.

To further upgrade and internationally standardize Japan's HTGR technology developed through the construction and operation of HTTR, JAEA is collaborating with NCBJ in Poland on the basic design of an HTGR research reactor to be built at the NCBJ site.

Current fleet of LWRs

As of October 2024, 12 LWR units have been restarted, 5 units are certified, one unit is uncertified and 7 units are under examination based on new nuclear regulations. Onagawa Unit 2 has started generating and transmitting power and is scheduled to begin commercial operations in December 2024. This is the first time a BWR has been restarted since the Great East Japan Earthquake.

Discussions are underway to formulate the Seventh Basic Energy Plan, which will guide mid- to long-term energy policy in Japan. The plan is expected to be finalized by February 2025 with the main points to be compiled by the end of 2024. With the spread of AI and the expansion of the data centre market expected to increase electricity demand, one issue is how to balance decarbonization and the stable supply of electricity. There are also discussions about accelerating technological development to deal with negative emission technologies, such as the recycling and disposal of used solar panels, and the nuclear fuel cycle and final disposal of radioactive waste. Discussions are being held based on international trends, with the understanding that securing decarbonized energy and realizing the green transformation are issues that the world shares.

Korea

As of February 2024, there are 25 nuclear power plants (22 PWRs and 3 CANDUs) in operation in Korea, with a combined nuclear capacity that accounts for 17%, equivalent to 24 650 MWe, of the total national capacity. In 2023, these nuclear power plants generated 180 494 GWh of electricity, representing 30.6% of total domestic production. Shin-Hanul Unit 2 entered commercial operation on 5 April 2024, generating 1 400 MWe. Two PWRs, Shin-Kori units 5 & 6, are also currently being constructed.

The Korean government continues to prioritize nuclear energy, as confirmed by its announced new policy to strengthen the country's nuclear strategy in 2023. Korea also plans to expand R&D and industry based on "national strategic technologies", with next-generation nuclear systems selected as one such technology. In early 2024, the government announced a strategy to encourage public-private partnerships for next-generation reactors. This would enable the private sector to develop its own SMR models based on government-secured technologies and to respond quickly to market needs. This approach is expected to form a new value chain in the nuclear industry through public-private partnership projects. In particular, the government will propose a technology development model in which the Korean government and private companies cooperate to accelerate the demonstration of MSR and HTGRs.

There is increasing interest in the utilization of high-temperature heat from HTGRs across various industries. The Alliance for Nuclear Heat Utilization in Korea was established in August 2023 and comprises 13 organizations involved with the supply of domestic process heat.

As many private companies have an interest in MSR technology development, the government has established an MSR development agency, and KAERI is actively collaborating with several leading Korean companies with the aim of realizing MSR technology in the near future.

Russia

Two topics being successfully implemented in the Russian Federation strongly affect the future of nuclear energy in the horizon of the 21st century. These are the closed nuclear fuel cycle and SMRs.

Creating a two-component nuclear power and the closing of the nuclear fuel cycle is Russia's strategic line. The Russian concept of two-component energetics is based on the integration of traditional thermal neutron reactors and next-generation fast reactors, as well as the establishment of a unified and balanced closed nuclear fuel cycle.

The construction of the BREST-OD-300 lead-cooled pilot industrial reactor is underway on the territory of the Siberian Chemical Combine (Seversk city). The first stage of the reactor vessel installation has been completed and the production of components for fuel was launched in 2024. Tests of the prototype main circulation pump unit are being conducted and a pilot demonstration energy complex is being created, which includes the module for fabrication/refabrication of dense mixed uranium-plutonium fuel and the module for reprocessing spent nuclear fuel. Comprehensive testing of equipment on depleted uranium was completed and commissioning of the main technological equipment was finished by September 2024.

In February 2024, JSC Rosenergoatom received the status of operating organization for the SMR in Yakutia, and the technical design of the RITM-200N reactor unit was approved. Commissioning is scheduled for 2028.

In May 2024, the floating nuclear power plant Akademik Lomonosov marked four years since its commissioning.

In May 2024, the contract was signed for the construction of an SMR in Uzbekistan. This is Rosatom's first export contract for the construction of a small nuclear power plant.

Rosatom is responsible for ensuring the transportation of goods along the Northern Sea Route. In 2024, the volume of shipments was around 40 million tons. Currently, at the Baltic Shipyard, mooring trials of the nuclear-powered icebreaker *Yakutia* have begun, and the reactor containment block has been loaded onto the nuclear-powered icebreaker *Chukotka*.

Work on foreign projects is proceeding according to schedule, with more than 20 power units currently under construction abroad simultaneously. The Belarusian Nuclear Power Plant has been transferred to commercial operation. The construction of nuclear power plants in Bangladesh, Egypt, Hungary, Iran and Turkey is being carried out as planned. In particular, nuclear fuel has been delivered to the Rooppur Nuclear Power Plant (Bangladesh), and the first concrete has been poured for the fourth power unit at the El Dabaa Nuclear Power Plant (Egypt).

South Africa

The concurrence under Section 34 of the Electricity Regulation Act of 2006, issued to the Department of Mineral Resources and Energy by the National Energy Regulator in August 2023, was withdrawn in August 2024. While the concurrence allowed the department to proceed with the procurement of a nuclear build programme to the extent of 2 500 MW at a pace and scale that the country can afford, it was withdrawn to allow proper processes and transparency in the implementation of the programme.

Eskom submitted a license application and a safety case report for long-term operation to the National Nuclear Regulator (NNR) in July 2022 to allow for the continuous operation of the Koeberg Nuclear Power Plant for an additional 20 years. On 15 July 2024, the NNR granted Eskom the requested license extension for Koeberg Unit 1, with the decision for Unit 2 expected in November 2025. Thus far, the replacement of steam generators on Unit 2 and a major plant refurbishment are in progress.

The National Radioactive Waste Disposal Institute is undertaking a feasibility study for the establishment of the Centralised Interim Storage Facility. Once completed, and a shovel readiness status is obtained, procurement for the facility will commence.

The South African Nuclear Energy Corporation is forging ahead with the development of the Multi-Purpose Research Reactor Project to complement the current Research Reactor, which is now almost 60 years old. The project is now shovel ready and request for proposals will be issued next year.

Switzerland

Molten salt reactors

A PhD project on transmutation and fuel cycle simulations began in August 2024, supported by the Swiss National Science Foundation. Switzerland joined the EU ENDURANCE project in October, focusing on MSR safety and sustainability.

In June 2024, PSI signed a large-scale experimental collaboration agreement with Danish MSR developer Copenhagen Atomics. The project aims to license and conduct the Copenhagen Atomics Molten Salt Experiment to advance MSR technology. Pending approval from Swiss licensing authorities as a low-risk facility under the Swiss Nuclear Energy Ordinance, this pioneering experiment will be conducted at PSI's purpose-built nuclear test facility. The project is expected to provide critical data for the further development of MSR technology.

Sodium fast reactors

Research continued under the Euratom ESFR-SIMPLE project, with PSI studying neutronics, thermal hydraulics and fuel behavior for various core designs, including U-Pu-Zr and MOX-fuelled cores. A 360 MWt ESFR-SMR model was developed with detailed design, neutronics and thermal-hydraulic simulations. Base-irradiation and transient behavior of metallic U-Pu-Zr fuel for the 3 600 MWt core were analyzed, producing benchmarks for European models. Additionally, a compact printed-circuit steam generator was designed, with ongoing simulations of protected station blackout events.

Liquid metal-cooled reactors

PSI's research on lead-cooled systems examines the volatilization of polonium and fission products in liquid metals, with studies under the Euratom projects PATRICIA and PASCAL. A key finding shows that cesium and iodine form CsI in lead-bismuth eutectic, enhancing volatilization. Under the ANSELMUS project, two PhD students and a postdoctoral student are investigating how impurities and fission products, such as xenon and krypton, affect evaporation and fuel-pin failure detection in the ALFRED reactor.

Very high-temperature reactor

Material research progressed with the completion of a project on SiC composite analysis, with findings submitted to the VHTR Materials Handbook. Another project on irradiation creep in nickel models identified key diffusion properties and is expected to conclude by January 2025. Research on additive manufacturing is ongoing and seeks to optimize printing parameters through real-time process monitoring.

Politics and regulation

In August, the Swiss government rejected the "Electricity for All" initiative, which had been launched by some political parties to challenge the ban on new nuclear power plants, but expressed conditional support for lifting the ban on new nuclear power plant construction. The Swiss Federal Office of Energy published a report on the state of nuclear energy, prepared by researchers from PSI, ETH Zurich, and EPFL Lausanne.

Nuclear operations and waste management

In November 2024, Swiss National Cooperative for the Disposal of Radioactive Waste submitted a general license application for a deep geological repository, detailing the location and infrastructure for radioactive waste disposal. In December, Axpo announced that the Beznau nuclear power plant would continue operations until 2032 (Unit 2) and 2033 (Unit 1), with decommissioning to follow.

United Kingdom

The UK government's report *Civil Nuclear: Roadmap to 2050* aims to deploy up to 24 GW of nuclear power by 2050, supporting growth in nuclear fission, UK fuel production and investment in new projects. In 2023, electricity generation fell by 10% due to increased imports and lower demand, with low-carbon sources generating 176.5 TWh. Nuclear power, despite outages, produced 40.6 TWh. Advanced nuclear technologies, including SMRs, are crucial for energy security, clean power and job creation, and can also help decarbonise energy-intensive industries, aiding in achieving net zero.

Great British Nuclear (GBN)

The UK government is committed to using new nuclear power stations, such as Sizewell C and SMRs, to achieve energy security, clean power and create skilled jobs. GBN, established in 2023, is leading the nuclear programme, including an SMR technology selection process that has shortlisted four companies for further negotiations. Bidders will be invited to enter negotiations with GBN.

Siting

A new national policy statement is being developed to guide new nuclear projects. The policy will consider the significant changes in the nuclear landscape, including the potential for deployment of advanced nuclear technologies such as SMRs.

New nuclear financing

The UK government has implemented funding models to reduce investment risks and attract financing for high-cost advanced nuclear technologies projects. Key mechanisms include the "contract for difference" and "regulated asset base", which provide investor certainty. The government is also reviewing feedback from an alternative route to market consultation to develop additional revenue support policies for new nuclear technologies.

Advanced modular reactors

The AMR Research, Development and Demonstration programme aims to demonstrate HTGR technology by the early 2030s to support net zero by 2050. The program includes developing advanced modular HTGR technologies and coated particle fuel, with several contracts awarded for preliminary front-end engineering design (pre-FEED) studies. Phase B focuses on developing FEED+ projects, enabling R&D, and achieving technical maturity by 2025. Match-funded grants have been awarded to support these efforts, and regulatory engagement is ongoing to ensure successful delivery and risk reduction.

Nuclear fuel

The UK is working with international partners to reduce reliance on Russian nuclear fuel and is investing over GBP 35 million, matched by industry, to develop domestic nuclear fuel production. Additionally, GBP 16 million has been awarded to the NNL for coated particle fuel development.

To support AMRs, the government announced up to GBP 300 million for a domestic HALEU supply chain, with GBP 196 million allocated to Urenco for HALEU enrichment capabilities, aiming for operations by 2031. The remaining funds will support HALEU deconversion facilities and related infrastructure.

Future Nuclear Enabling Fund

The Future Nuclear Enabling Fund allocated up to GBP 120 million to support new nuclear development by reducing project risks and encouraging future investments. Three companies, Holtec Britain, GE-Hitachi and Cavendish Nuclear, received grants totalling up to GBP 67 million. This funding aims to accelerate advanced nuclear business development and help advanced nuclear designs enter UK regulation.

Nuclear regulation

The Generic Design Assessment is a three-step process by the ONR and the Environment Agency to ensure nuclear power plant designs meet safety, security and environmental standards. The Rolls-Royce SMR design completed Step 2 in July 2024, marking significant progress. Holtec International's SMR design began Step 1 in October 2023 and is now entering Step 2. A new early regulatory engagement framework was launched in March 2024 to facilitate early discussions for deploying nuclear reactor technology in Great Britain.

United States

Nuclear energy continues to be a vital part of the energy development strategy, with DOE continuing to advance new and innovative advanced reactors from the conceptual and development stages into the commercial energy sector.

Securing a domestic nuclear fuel cycle

DOE is working to grow the US nuclear fuel supply chain by selecting multiple companies to participate in low-enriched uranium[4] and high-assay low-enriched uranium[5] capacity building programs. The USD 3.4 billion effort will allow the awardees to bid on future task orders to produce, store and deconvert material that can be fabricated into fuel for current and future reactors.

Newly signed bill will boost nuclear reactor deployment

The ADVANCE Act directs the NRC to reduce certain licensing application fees and authorizes increased NRC staffing to expedite the review process. It also introduces prize competitions to incentivize deployment, directs the NRC to develop guidance to license and regulate microreactor designs within 18 months, and enables the cleanup and reuse of brownfield sites, including retired or retiring coal plants.

US technology companies invest in nuclear power for data centers

Amazon, Google and Microsoft recently made announcements on nuclear power investments to run their data centers. Google signed a deal with Kairos Power to build seven small reactors to supply electricity to its data centers. Microsoft has plans to pay Constellation Energy to restart a reactor at Three Mile Island that was shut down in 2019. Amazon has plans to would build a hyperscale data center and directly connect it to another nuclear plant in Pennsylvania, as well as to work with Dominion Energy to explore putting an SMR near its existing North Anna nuclear power station in Virginia. Amazon is also investing in X-energy for its early development work and collaborating with utility Energy Northwest in central Washington to put four X-energy reactors there.

Reactor companies hit licensing milestones

In September 2024, the NRC approved construction of the Molten Salt Research Reactor facility on the Abilene Christian University campus, marking the first research reactor project approved by the NRC in decades. In November, the NRC approved the construction of two additional Hermes test reactors being developed by Kairos Power.

Advanced Reactor Demonstration Program

The two major US demonstration projects, Natrium by TerraPower and Xe-100 by X Energy, continue to progress well. The construction permit application for Natrium has been accepted for review by the NRC, with review completion expected in December 2026. X-energy plans to submit its application in 2025. The five risk reduction projects – 1) Hermes by Kairos Power; 2) eVinci™ by Westinghouse; 3) BWXT Advanced Nuclear Reactor by BWXT Advanced Technologies; 4) SMR-300 by Holtec Government Services; and 5) Molten Chloride Reactor Experiment (MCRE) by Southern Company Services – are progressing well towards development of their technologies. Kairos Power started construction activities on one of the first advanced reactors in the United States. Additionally, Kairos Power completed molten salt testing on the company's first engineering test unit. Finally, Kairos Power broke ground on a new facility that will produce a specialized "FLiBe" molten salt coolant for its Hermes reactor. Holtec Government Services announced an increased power rating of its SMR design from 160 MWe to 300 MWe and plans to build its first two SMR-300 reactor units at the Palisades site in Michigan by 2030. Southern Company Services completed the preliminary design of MCRE and the final design of the fuel salt synthesis line to be established at INL.

Construction on the National Reactor Innovation Center (NRIC) Demonstration and Operation of Microreactor Experiments (DOME) test bed at INL continues and is expected to be completed as soon as 2026. DOE awarded a total of USD 5 M to Radiant Industries and Westinghouse to progress their microreactor designs for potential testing in DOME. Westinghouse submitted a preliminary safety design report to DOE to ensure safe operations during testing.

Advanced Reactor Concepts-20 (ARC-20)

ARC-20 projects are progressing well in their designs and could have significant impact on the energy market in the mid-2030s or later. These projects are: ARC-100 by Advanced Reactor Concepts Clean Energy, Fast Modular Reactor Conceptual Design by General Atomics, and Horizontal Compact High Temperature Gas Reactor by Massachusetts Institute of Technology.

Microreactor applications, research, validation and evaluation

MARVEL submitted a preliminary documented safety analysis to DOE for review in July 2024 and is completing fabrication of the guard vessel. The fabrication of the reactivity control system is in progress.

4. www.energy.gov/ne/domestic-low-enriched-uranium-supply-chain.
5. www.energy.gov/ne/haleu-availability-program.

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Appendix 2. List of abbreviations and acronyms

3S	Safety, security and safeguards
ADS	Accelerator-driven system
AFA	Alumina-forming austenitic
AI	Artificial intelligence
ALFRED	Advanced Lead Fast Reactor European Demonstration Project
ALLEGRO	European Gas Fast Reactor Demonstrator Project
AMME WG	Advanced Manufacturing and Materials Engineering Working Group
AMR	Advanced modular reactor
ANL	Argonne National Laboratory (United States)
ANSTO	Australian Nuclear Science and Technology Organization
ANTSER	Advanced Nuclear Technology Cost Reduction Strategies and Systematic Economic Review
BREST-OD-300	Russian acronym for 300 MW passive safe pilot demonstration fast neutron reactor
CEA	Alternative Energies and Atomic Energy Commission (France)
CFD	Computational fluid dynamics
CIAE	China Institute of Atomic Energy
CLEAR	China Lead-based Reactor
CMVB	Computational methods validation and benchmarks
CNL	Canadian Nuclear Laboratories
CNNC	China National Nuclear Corporation
CNRI	Canadian Nuclear Research Initiative
CNRS	National Center for Scientific Research (France)
CNSC	Canadian Nuclear Safety Commission
CVR	Centrum výzkumu Řež (Czechia)
DOE	Department of Energy (United States)
DNS	Direct numerical simulation
ECC-SMART	European Canadian Chinese – Small Modular Reactor Technology project
EMWG	Economic Modelling Working Group
ENEA	National Agency for New Technologies (Italy)
ESFR	European sodium fast reactor
ESFR-SIMPLE	European sodium fast reactor – Safe, simple, and flexible
ESNII	European Sustainable Nuclear Industry Initiative
ETWG	Education and Training Working Group
EU	European Union
FA	Framework Agreement
FCCI	Fuel cladding chemical interaction

Gen IV	Generation IV
GFR	Gas-cooled fast reactor
GIF	Generation IV International Forum
GW	Gigawatt
GWe	Gigawatt electrical
GWt	Gigawatt thermal
HALEU	High-assay low-enriched uranium
HTGR	High-temperature gas-cooled reactor
HTR	High-temperature reactor
HTR-PM	High-Temperature Reactor – Pebble-Bed Module
HTSE	High-temperature steam electrolysis
HTTR	High-temperature test reactor
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
INET	Institute of Nuclear and New Energy Technology (China)
INL	Idaho National Laboratory (United States)
ISAC	Innovative System for Actinide Conversion (France)
JAEA	Japan Atomic Energy Agency
JRC	Joint Research Centre (Euratom)
JSFR	Japanese sodium-cooled fast reactor
KAERI	Korea Atomic Energy Research Institute
KIT	Karlsruhe Institute of Technology
LFR	Lead-cooled fast reactor
LWR	Light water reactor
MMR	Micro Modular Reactor (Canada)
MOX	Mixed oxide (fuel)
MCRE	Molten Chloride Reactor Experiment (United States)
MSR	Molten salt reactor
MW	Megawatt
MWe	Megawatt electrical
MWt	Megawatt thermal
MPa	Megapascal
MSFR	Molten salt fast reactor (Euratom)
NCBJ	National Centre for Nuclear Research (Poland)
NEA	Nuclear Energy Agency
NECA	Non-Electric and Cogeneration Applications
NNL	National Nuclear Laboratory (United Kingdom)
NPIC	Nuclear Power Institute of China
NRC	Nuclear Regulatory Commission (United States)
NSTF	Natural Convection Shutdown Heat Removal Test Facility
NRCan	Natural Resources Canada (Canada)
ODS	Oxide dispersion-strengthened

ONR	Office for Nuclear Regulation (United Kingdom)
OPG	Ontario Power Generation
ORNL	Oak Ridge National Laboratory (ORNL)
PMB	Project management board
PNNL	Pacific Northwest National Laboratory
PR	Proliferation resistance
PRPPWG	Proliferation Resistance and Physical Protection Working Group
PP	Physical protection
PSI	Paul Scherrer Institute (Switzerland)
pSSC	Provisional System Steering Committee
PWR	Pressurized water reactor
R&D	Research and development
RSWG	Risk and Safety Working Group
SCWR	Supercritical water-cooled reactor
SCW-SMR	Supercritical water-cooled small modular reactor
SCK CEN	Belgian Nuclear Research Centre
SDC	Safety design criteria
SDG	Safety design guidelines
SFR	Sodium-cooled fast reactor
SIAP	Senior Industry Advisory Panel
SiC	Silicon carbide
SMR	Small modular reactor
SOEC	Solid oxide electrolyzer cell
SNETP	Sustainable Nuclear Energy Technology Platform
SSC	System Steering Committee
STELLA-2	Large-scale Sodium Integral Effect Test Facility (Korea)
SWR	Sodium-water reaction
TMSR	Thorium molten salt reactor (China)
TRISO	Tri-structural isotropic (nuclear fuel)
UCO	Uranium oxycarbide (fuel)
UJV	Ustav Jaderneho Vyzkumu group (Czechia)
UN	Uranium nitride (fuel)
VHTR	Very high-temperature reactor
VUJE	Nuclear Power Plant Research Institute (Slovak Republic)
WGNT	Working Group on New Technology (NEA)
WNA	World Nuclear Association
ZrC	Zirconium carbide

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Appendix 3. Selection of GIF publications (2024)

Ammirabile, L. et al. (2024), *Safety, Security, and Safeguards (3S) Interface Identification and Characterisation in Generation IV Advanced Modular Reactors: A Generation IV Internation Forum Case Study*, International Conference on Small Modular Reactors and their Applications, 21-24 October 2024, Vienna, Austria.

Bourg, S., Y. Lee and J. Krepel (2024), "Generation IV international forum", in T. J. Dolan, *Global Progress on Molten Salt Reactors*, 2nd Edition.

GIF (2024), *Safety Design Guidelines on Structures, Systems and Components for Generation IV Sodium-cooled Fast Reactor Systems*, GIF/RSWG/2023/002, Generation IV International Forum, Paris, www.gen-4.org/resources/reports/safety-design-guidelines-structures-systems-and-components-generation-iv-sodium.

Kalivodova, J. et al. (2024), *Structural Materials Testing in Media*, SafeG project deliverable D2.5, 2024, available at www.safeg.eu/fileadmin/user_upload/SafeG_D2.5_Structural_materials_testing_in_media_web.pdf.

Nguyen, F. (2024), *GIF Proliferation Resistance and Physical Protection (PR&PP) Working Group Activities on Generation IV Nuclear Energy Systems*, International Conference on the Nuclear Fuel Cycle (GLOBAL 2024), 6-10 October, 2024, Tokyo, Japan, paper 2M-03-01.

Paviet, P. (2024), *Generation IV International Forum – Knowledge Management and Knowledge Preservation: An Initiative from the Education and Training Working Group*, Paper #44164, ANS National Meeting, 16-19 June 2024, Las Vegas.

Renda, G. (2024), *GIF Proliferation Resistance and Physical Protection (PR&PP) Working Group Overview and Activities*, IAEA Interregional Workshop on Safety, Security and Safeguards by Design in Small Modular Reactors, 4-8 November 2024, Oak Ridge, Tennessee.

van der Ende, B., (2024), *Generation IV International Forum Case Study of 3S Interfaces for a VHTR System*, IAEA Interregional Workshop on Safety, Security and Safeguards by Design in Small Modular Reactors, 4-8 November 2024, Oak Ridge, Tennessee.

Balbaud-Célérier, F. and C. Cabet (Coordinators) (2024), *Materials and Processes for Nuclear Energy Today and in the Future*, Wiley, https://doi.org/10.1002/9781394325870.

GIF contributions to this book include:

- Chapter 4. Structural Materials for Sodium Cooled Fast Reactors (pages 145-168), Hayato Yamashita, Tai Asayama.
- Chapter 5. Materials and Processes for Heavy Liquid Metal Cooled Reactors (Pages: 169-196), Serguei Gavrilov.
- Chapter 6. Materials and Processes for Molten Salts Reactors (pages 197-223), Céline Cabet, Yann De Carlan, Laure Martinelli.
- Chapter 8. Advanced Materials: Ceramics and Composite Materials (pages 261-277), James Braun.
- Chapter 9. Advanced Materials: Oxide-Dispersion Strengthened Steels (pages 279-297) Satoshi Ohtsuka, Takashi Tanno, Yasuhide Yano, Takeji Kaito.
- Chapter 10. Materials Discovery (pages 299-336), Andrea Jokisaari, Cheng Sun, Jian Gan.

THE GENERATION IV INTERNATIONAL FORUM

Established in 2001, the Generation IV International Forum (GIF) was created as a co-operative international endeavour seeking to develop the research necessary to test the feasibility and performance of fourth generation nuclear systems and make them available for industrial deployment by 2030. The GIF brings together 13 countries (Argentina, Australia, Brazil, Canada, the People's Republic of China, France, Japan, Korea, the Russian Federation, South Africa, Switzerland, the United Kingdom and the United States), as well as Euratom – representing the 27 European Union members and the United Kingdom – to co-ordinate research and development on these systems. The GIF has selected six reactor technologies for further research and development: 1) the gas-cooled fast reactor; 2) the lead-cooled fast reactor; 3) the molten salt reactor; 4) the sodium-cooled fast reactor; 5) the supercritical water-cooled reactor; and 6) the very high-temperature reactor.

NUCLEAR ENERGY AGENCY

The OECD Nuclear Energy Agency (NEA) was established on 1 February 1958. Current NEA membership consists of 34 countries: Argentina, Australia, Austria, Belgium, Bulgaria, Canada, Czechia, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Luxembourg, Mexico, the Netherlands, Norway, Poland, Portugal, Korea, Romania, Russia (suspended), the Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Türkiye, the United Kingdom and the United States. The European Commission and the International Atomic Energy Agency also take part in the work of the Agency.

The mission of the NEA is:

- to assist its member countries in maintaining and further developing, through international co-operation, the scientific, technological and legal bases required for a safe, environmentally sound and economical use of nuclear energy for peaceful purposes;
- to provide authoritative assessments and to forge common understandings on key issues as input to government decisions on nuclear energy policy and to broader OECD analyses in areas such as energy and the sustainable development of low-carbon economies.

Specific areas of competence of the NEA include the safety and regulation of nuclear activities, radioactive waste management and decommissioning, radiological protection, nuclear science, economic and technical analyses of the nuclear fuel cycle, nuclear law and liability, and public information. The NEA Data Bank provides nuclear data and computer program services for participating countries.

The Nuclear Energy Agency serves as Technical Secretariat to GIF.

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