GEN IV International Forum

Expertise | Collaboration | Excellence

ANNUAL REPORT 2025

www.gen-4.org

Foreword from the Chair

The Generation IV International Forum (GIF) 2025 Annual Report highlights the achievements and progress of research and development (R&D) collaborations for Generation IV (Gen IV) reactor systems.

The year 2025 was pivotal for GIF, following the considerable work undertaken by the negotiation teams over more than two years, which resulted in a new 2025 GIF Framework Agreement (FA). Signed at the end of 2024 by the United Kingdom and the United States, and on 29 January 2025 by Canada (pending ratification), France, Japan and Switzerland, the 2025 GIF FA entered into force on 1 March 2025. Korea joined the signatories later in 2025. There were also key milestones in 2025, aligned with the objectives set out in the strategic vision for my GIF Chairmanship: supporting the transition from R&D to industrial demonstration and deployment, and strengthening the relevance of GIF to industry.

The first major step was the endorsement by the GIF Policy Group and the launch for signature of the first Project Management Board (PMB) involving industrial partners. The path leading to the establishment of this PMB was long and rich in lessons learned, which will benefit future PMBs of this kind.

The second step was the organization of an industry roundtable during the Experts Group and Policy Group (EG/PG) meeting in Busan, Korea, in October. Thanks to the Korean teams and the strong involvement of the GIF Leadership Team, this roundtable brought together the entire value chain: utilities, vendors, supply chains and end-users. We were fortunate to welcome a representative of the Green Climate Fund among the panelists, who provided valuable insights into potential financing mechanisms. The success of this roundtable with Korean stakeholders encouraged Policy Group members to request the organization of an industry roundtable at every EG/PG meeting. This will offer a cross-cutting perspective on the nuclear value chain across GIF member countries and regions.

Finally, 2025 concluded with GIF participation in the World Nuclear Exhibition, in Paris. During this event, which gathered more than 36 000 participants from 80 countries, GIF – supported by France's Alternative Energies and Atomic Energy Commission (CEA) – hosted a workshop on "Accelerating the Deployment of Generation IV", welcoming more than 100 participants.

As we move through 2026, this must now be the year in which we meet our challenges and implement the actions that will enable GIF to achieve its objectives:

- Reforming the Senior Industry Advisory Panel (SIAP) and establishing a streamlined process to enable industry participation in GIF, will help strengthen the relevance of GIF to industry.
- Developing an inventory of assets, integrating fuel cycle considerations, sharing lessons learned from projects and reinforcing communication efforts, will help enhance GIF expertise and visibility.
- Organizing public sessions dedicated to the Young Generation – such as the one held during the EG/PG in Busan for the 10th anniversary of the Education and Training Working Group (ETWG) – and taking part in the 2026 International Youth Nuclear Congress, will be key avenues for supporting the development of the Gen IV talent pipeline.

The year 2026 will mark the 25th anniversary of GIF. To celebrate, we will host a series of events highlighting our achievements over the past 25 years, while also looking ahead to the future. The GIF biannual meetings in China in April 2026 and in Japan in October 2026 will provide ideal settings for these celebrations, with LinkedIn serving as the primary communication channel to share anniversary initiatives with our broader community.

Building on the successes of 2025, we are ready to make 2026 exceptional.

With best wishes,

Stéphane Sarrade
2025-2027 GIF Policy Group Chair





Table of contents

Foreword from the Chair **1**

Chapter 1. GIF membership, and research and development collaboration **6**

Chapter 2. GIF outlook and current initiatives **10**

Chapter 3. System summaries **11**

Gas-cooled fast reactor 11
Lead-cooled fast reactor 14
Molten salt reactor 19
Supercritical water-cooled reactor 26
Sodium-cooled fast reactor 31
Very high-temperature reactor 39

Chapter 4. Working group reports **48**

Advanced Manufacturing and Materials Engineering Working Group 48
Economic Modeling Working Group 51
Education and Training Working Group 53
Non-Electric and Cogeneration Applications Working Group 55
Proliferation Resistance and Physical Protection Working Group 57
Risk and Safety Working Group 59

Chapter 5. GIF Senior Industrial Advisory Panel (SIAP) report **60**

Summary of meeting themes and key outcomes 60
Response to SIAP Charge 2025 60
Industry perspective on GIF engagement and proposed changes 62

Appendix 1. Country reports 2025 ..... **63**

Australia 63
Canada 63
China 65
Euratom 65
France 66
Japan 67
Korea 68
South Africa 69
Switzerland 69
United Kingdom 70
United States 71

Appendix 2. List of abbreviations and acronyms **72**

List of figures

Figure 1-1: GIF Leadership at the 54th Experts and 60th Policy Group Meeting, October 2025, Busan, Korea 6

Figure 1-2: Structure of the GIF Technical Secretariat as of October 2025 7

Figure 1-3: Governance structure diagram 8

Figure 1-4: GIF Industry Roundtable at the 54th Experts and 60th Policy Group Meeting, October 2025, Busan, Korea 9

Figure GFR-1: HeFASTo reactor system concept 12

Figure LFR-1: GIF lead-cooled fast reactor reference systems 14

Figure LFR-2: EAGLES-300 roadmap 15

Figure LFR-3: 3D view of OTHELLO loop 16

Figure LFR-4: MicroURANUS conceptual design schematic 17

Figure MSR-1: Most studied MSR concepts, with some key developers 19

Figure MSR-2: Demonstration natural-circulation loop (DNCL) corrosion loop 24

Figure SCWR-1: KIT experiments on wall roughness effects on heat transfer 27

Figure SCWR- 2: Comparison of wall temperatures between RELAP5 simulations and experimental data – Panel a: Boundary condition; Panel b: Wall temperature 27

Figure SCRW-3: Comparison between CFD predictions and experimental data for a selected case by the Kline Database (CO_2) 28

Figure SCWR-4: Results of long-term supercritical-water corrosion tests on alloy 800H from JRC (A) and CNL (B) 28

Figure SCWR-5: Fracture surface of steel 310S specimen exposed to supercritical water at 500°C, showing intergranular crack initiation areas 29

Figure SCWR-6: Representative images and key results from the helium-ion implantation process on alloy 800H and steel 310S 29

Figure SFR-1: Water rig mesh and velocity vectors 35

Figure SFR-2: Effect of central hole off-centering on fuel temperature distribution 36

Figure SFR-3: Concept of FSIS-paired SMR 37

Figure VHTR-1: Cut-away view of the HTR-PM reactor building and schematic of power conversion system 39

Figure VHTR-2: Plans for CNNC's LWR+HTGR cogeneration plant in Lianyungang, Jiangsu 40

Figure VHTR-3: Example of the use of AI/ML methods to automate analysis of irradiated particle morphologies 41

Figure VHTR-4: The world's first high-temperature electrolyzer (HTE) system in multi-megawatt-scale at a renewable products refinery 43

Figure VHTR-5: Graphite inelastic response and failure 45

Figure VHTR-6: Nuclear island of HTR-PM demonstration 46

Figure AMME-1: GIF AMME WG members at TMS2025's Industry Panel 48

Figure AMME-2: Benchmark for DED fabrication 49
Figure EMWG-1: 2024 Special Gen IV Financing Workshop 51
Figure ETWG-1: ETWG meeting at the Fall 2025 Experts Group and Policy Group meeting 54
Figure ETWG-2: Announcement of ETWG 10-year webinar 54
Figure PRPPWG-1: In-person participants of the 35th PRPPWG Meeting 58

List of tables

Table LFR-1: Key design parameters of the GIF lead-cooled fast reactor reference systems 14
Table SCWR-1: Main operating conditions of proposed SCW-SMR designs 26
Table SFR-1: Typical design parameters for the Gen IV sodium-cooled fast reacto 31
Table ETWG-1: GIF webinars organized, presented and archived in 2025 53
Table NECA-1: Predicted cost and amount of hydrogen produced from select scenarios 56

1 GIF membership, and research and development collaboration

Introduction and context

The Generation IV International Forum (GIF) remains the only intergovernmental platform dedicated to the collaborative research and development (R&D) of Generation IV (Gen IV) nuclear energy systems. Its mission is to support and accelerate progress towards the deployment of six Gen IV systems[1] identified by GIF as the most promising technologies to meet the goals of improved sustainability, safety, economics and proliferation resistance. The systems also have the potential to be ready for deployment in the 2030s.

GIF provides a structured cooperation framework that enables participating countries to share knowledge, conduct coordinated R&D and develop harmonized approaches for advanced nuclear technologies. This framework creates new scientific knowledge, data and methodologies for ultimate demonstration and deployment. It captures invaluable experience (including from past and operating demonstrators) and drives analysis tailored to next-generation systems on key topics such as nuclear safety and security.

Global trends in 2025 confirm the relevance of GIF's work: energy security concerns, decarbonization goals and technological innovation have accelerated interest in advanced nuclear systems. As illustrated in the latest edition of the OECD Nuclear Energy Agency (NEA) Small Modular Reactor (SMR) dashboard, and as regularly reported by GIF members, demonstration units are operating, new projects are under construction, and private sector investment in SMRs and advanced modular reactors (AMRs) is surging, with a significant share directed towards Gen IV concepts. End-user interest and potential is also rising as major technology firms seek reliable, low-carbon energy (heat and electricity) for industrial applications and data centers.

Despite this encouraging momentum, technological, industrial and regulatory challenges remain in areas such as fuel and materials qualification, safety demonstrations, licensing, fuel cycle strategies and efficiency gains in construction. It is part of GIF's mission to address these challenges by leveraging decades

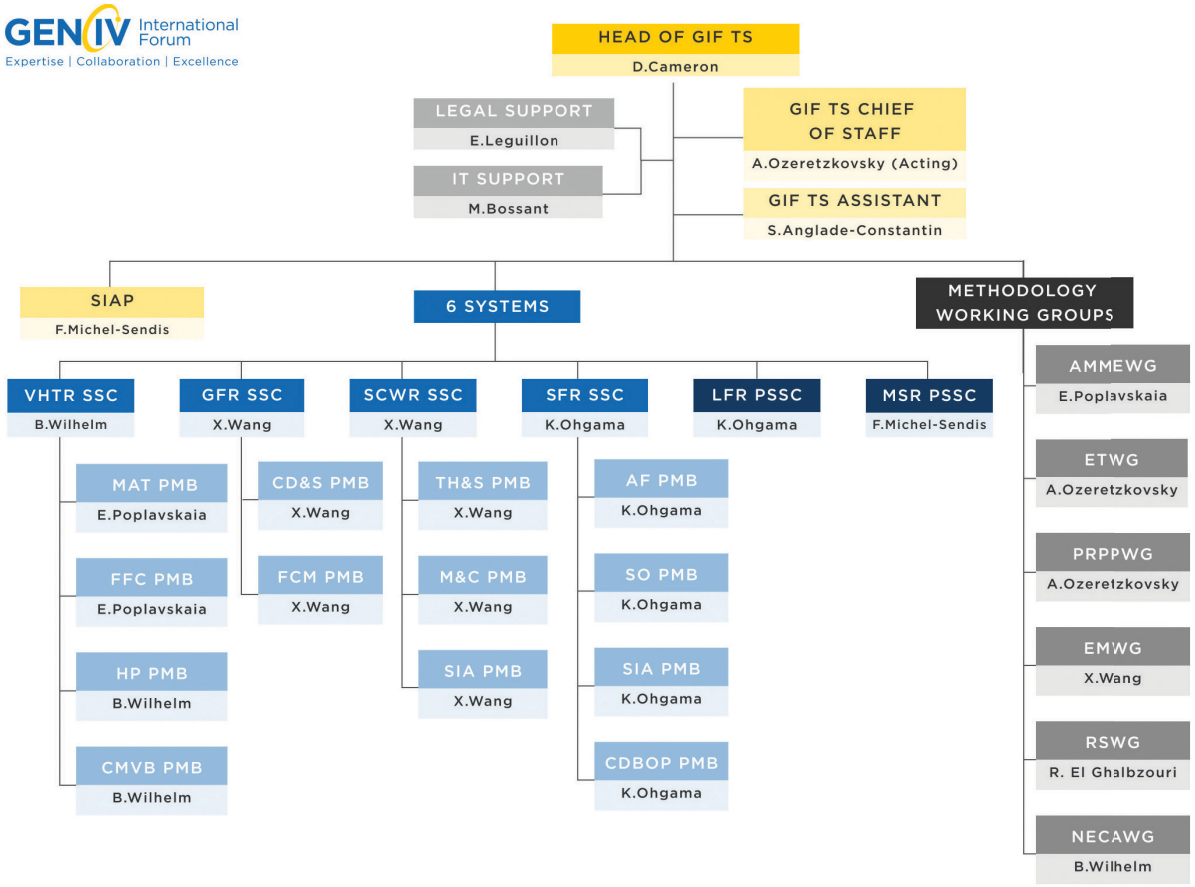
Figure 1-1: GIF Leadership at the 54th Experts and 60th Policy Group Meeting, October 2025, Busan, Korea



Left to right: Alexiei Ozeretzkovsky, GIF TS Chief of Staff; Michael Fütterer, GIF Technical Director; Daniel Brady, GIF Policy Director; Candice Boudet, GIF Chair's Chief of Staff; Stéphane Sarrade, GIF Chair; Jin-Young Cho, GIF Vice Chair for Education and Training; Diane Cameron, Head of the GIF TS; Nawaf Saleh, GIF Communications Director; Paul Nevitt, GIF Vice Chair for Market Issues and Industry Engagement; Hiroki Hayafune, GIF Vice Chair for Research and Infrastructure.

1. Sodium-cooled fast reactor (SFR), gas-cooled fast reactor (GFR), very high-temperature reactor (VHTR), lead-cooled fast reactor (LFR), molten salt reactor (MSR) and supercritical water-cooled reactor (SCWR).

Figure 1-2: Structure of the GIF Technical Secretariat as of October 2025



of accumulated knowledge and a broad research infrastructure, avoiding duplication and supporting coordinated approaches. With 38 countries having pledged to triple nuclear capacity by 2050, GIF's role as a knowledge and expertise hub and a coordination platform is more critical than ever.

Membership and governance updates

The year 2025 marked a significant milestone for GIF, with the entry into force of the 2025 *Framework Agreement for International Collaboration on Research and Development of Generation IV Nuclear Energy Systems* (referred to as the new 2025 GIF Framework Agreement, GIF FA) on 1 March, ensuring continuity of work, reinforcing governance and facilitating engagement with external stakeholders, including industry and private sector actors. The OECD Secretary-General is the depositary of the GIF FA.

Signatories under the new GIF FA include the United States and the United Kingdom (COP29, November 2024), Canada, France, Japan and Switzerland (signed at OECD headquarters in January 2025), and Korea (signed at OECD headquarters in September 2025). Euratom and China are expected to join in 2026, and Australia and South Africa are invited to become signatories in the coming years.

In January, Stéphane Sarrade, Director of Low-Carbon Energy Programs at France's Alternative Energies and Atomic Energy Commission (CEA), assumed the role of GIF Chair, succeeding Alice Caponiti (US Department of Energy). The Chair's priorities for 2025 to 2027 include accelerating the readiness of Gen IV systems for deployment, promoting integrated reactor-fuel cycle approaches, supporting applications of nuclear energy beyond electricity (heat, hydrogen, synthetic fuels), integrating new players such as start-ups, and strengthening links with international organizations (NEA, International Atomic Energy Agency [IAEA], International Energy Agency [IEA]) and SMR alliances.

The leadership team for 2025-2027 includes Daniel Brady (Canada) as Policy Director, Michael Fütterer (EU) as Technical Director and Nawaf Saleh (UK) as Communications and Marketing Director (Figure 1-1). The latter is a newly created role, reflecting GIF's commitment to increased visibility and outreach. Four vice chairs support strategic areas: Paul Nevitt (UK) for Market Issues and Industry Engagement, Hiroki Hayafune (Japan) for Research and Infrastructure, Jin-Young Cho (Korea) for Education and Training, and Janelle Eddins (US) for Regulatory Issues.

The NEA continues to provide technical secretariat services to the GIF technical bodies in charge of developing the different systems, to the methodology working groups and to the Senior Industry Advisory Panel (SIAP) (Figure 1-2).

More information on GIF governance and structure is available on the GIF public website (www.gen-4.org).

R&D highlights and key deliverables

In 2025, system steering committees (SSCs) and project management boards (PMBs) continued their planned activities and advanced experimental validation programs, updated their project plans, and initiated benchmarking exercises. Several projects are engaged with the private sector, and some upcoming projects are planned to include both public and private sector players, reflecting GIF's pivot towards supporting demonstration and deployment. Figure 1-3 shows the governance structure of GIF.

Among the highlights of 2025, the SFR Safety and Operation PMB significantly progressed in the area of advanced fuel modeling and common benchmark analysis based on experimental results from the reactors Phénix and EBR-II, while a new Thermal-Hydraulics Project Arrangement (SFR system) continued to be discussed, with interest from two private SFR developers to participate in the project once launched. The process used could be a blueprint for enhanced industry participation in other projects. The VHTR Materials PMB continued maintaining and enriching the Materials Handbook database, which is a repository of materials studies with properties data from more than 569 R&D reports by 11 participating countries. In 2025, this database was physically moved from Oak Ridge National Laboratory (ORNL) to Idaho National Laboratory (INL), to facilitate maintenance and security upgrades; it is expected back online in 2026. Under the VHTR SSC, GIF members carried out reactor physics benchmarks, scheduling a tri-structural isotropic (TRISO) fuel workshop for 2026. The SCWR SSC supported the organization of the 11th International Symposium on SCWR with the University of Pisa and the European Nuclear Society (ENS).

Cross-cutting working groups also delivered significant outputs. The Non-Electric and Cogeneration Applications (NECA) Working Group completed a techno-economic assessment of hydrogen production via high-temperature steam electrolysis using (very) high-temperature gas reactors (VHTR/HTGRs), published jointly with the NEA (GIF/NEA, 2025).

The Education and Training Working Group (ETWG) marked its 10th anniversary with a global panel on "Shaping the Future of Generation IV Nuclear Talents", which was streamed as a live webinar. The ETWG also conducted the third "Pitch Your Generation IV Research" competition focused on showcasing Gen IV related research by students and early career researchers. For the ninth consecutive year, the group continued its series of monthly webinars, with more than 110 publicly available recordings now on the GIF website.

The Advanced Manufacturing and Materials Engineering Working Group (AMME WG) expanded its qualification codes database and launched an international industry survey, while the Economic Modeling Working Group (EMWG) updated its Cost Estimating Guidelines and G4ECONS model, and began work on risk allocation for financial institutions.

The Proliferation Resistance and Physical Protection Working Group (PRPPWG) finalized a report on siting for advanced modular reactors and microreactors, and completed a "safety, security and safeguards" (3S) interfaces case study in collaboration with the VHTR SSC and the Risk and Safety Working Group (RSWG). Importantly, this PRPPWG methodology attracted interest from private sector vendors seeking to incorporate GIF approaches in their

Figure 1-3: Governance structure diagram

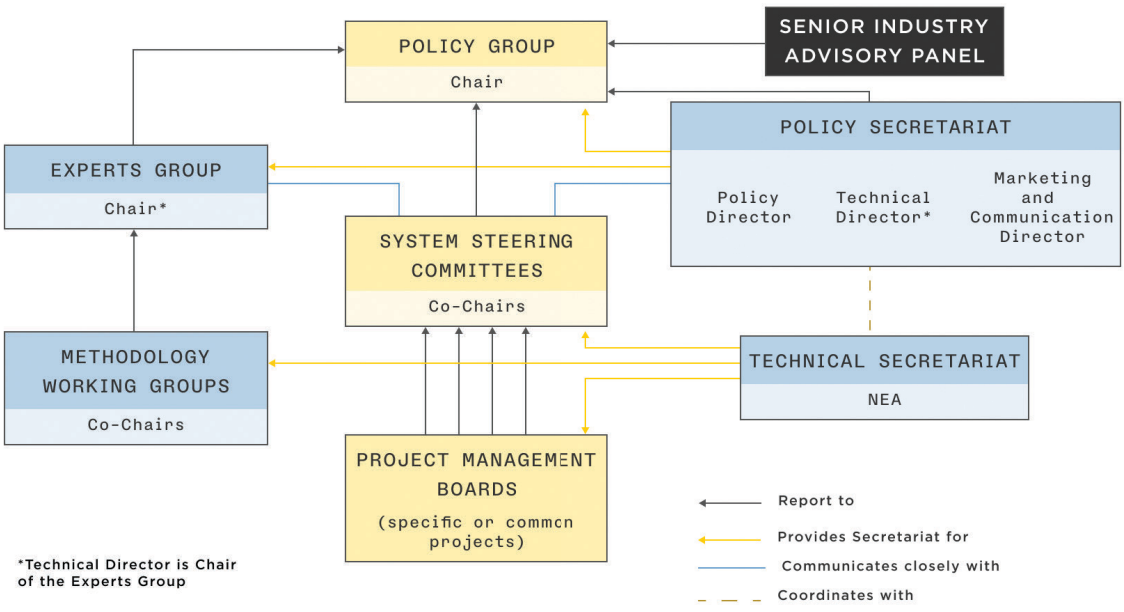


Figure 1-4: GIF Industry Roundtable at the 54th Experts and 60th Policy Group Meeting, October 2025, Busan, Korea



designs, which is a clear indication of GIF's potential in supporting stakeholders with the licensing and deploying of Gen IV systems.

GIF reinforced collaboration with international organizations through the 19th GIF-IAEA Interface Meeting in June, focusing on safety, safeguards, non-electric applications, workforce development and licensing. At the October 2025 Experts Group and Policy Group (EG/PG) meeting in Busan, plans to strengthen cooperation between GIF and the NEA, and to leverage synergies between the two organizations were proposed.

Industry engagement

GIF engagement with industry intensified in 2025. A public industry roundtable during the EG/PG meetings in Busan brought together Korean and international industry representatives alongside financial stakeholders, including the Green Climate Fund (Figure 1-4). These discussions explored pathways for cooperation to solve challenges on the way to demonstration and deployment. Such industry roundtables are now planned to become recurring meetings between GIF and industry, to capture the situations on different continents.

The LFR provisional SSC continued supporting the "GIF Talks with Industry" webinar series launched in 2024, successfully engaging with developers to accelerate deployment.

Across GIF, several working groups developed mechanisms to obtain early feedback from industry on draft reports and methodologies, inviting reviews that ensure outputs are informed by current experience and reflecting a shift towards a more interactive and collaborative engagement with industry stakeholders.

Looking ahead

Priorities for 2026 include strengthening partnerships for development and licensing, expanding benchmarking efforts and preparing for GIF's 25th anniversary in 2027. This will be the opportunity to showcase and reflect on GIF's achievements and to fully implement the new phase of collaboration among GIF members. GIF leadership will ensure that invaluable data, methodologies, tools and knowledge gathered by GIF over 25 years are put to good use for enabling Gen IV system deployment.

Reference

GIF/NEA (2025), *System Analysis: Hydrogen Production from Nuclear Energy*, Generation IV International Forum, Paris, www.gen-4.org/resources/reports/system-analysis-hydrogen-production-nuclear-energy-2025.



Diane Cameron
Head of the GIF Technical Secretariat



Daniel Brady
GIF Policy Director

2 GIF outlook and current initiatives

The year 2025 involved the transition to a fully-fledged new GIF Framework Agreement, including updates of our systems and projects plans. Let me thank all involved in the numerous and diverse activities summarized in this Annual Report for your ongoing commitment and added value to our cooperation.

GIF is focusing on efforts to accelerate the readiness of Gen IV systems for deployment, revisiting integrated reactor-fuel cycle approaches and supporting work that will enable Gen IV systems to contribute to de-fossilization via multiple energy carriers: electricity, heat, hydrogen or synthetic fuels. Today, GIF can capitalize on 25 years of data and knowledge. It has become the preferred time- and cost-saving partner for governments and industry, to help ensure the safe and efficient deployment of Gen IV nuclear energy systems.

Several Gen IV concepts have progressed to the licensing and demonstration phase, and there are opportunities for GIF to continue and actively contribute to this success, and to learn from demonstration projects in view of broader deployment. GIF plans to facilitate this by mapping its assets in the form of accumulated data, methods, knowledge, expertise and analyses. This will improve knowledge management and make the systems accessible to modern artificial intelligence (AI) tools for optimum valuation.

To allow deployment at scale, efforts need to be made to ensure coordinated and harmonized approaches to the safety and licensing of Gen IV designs being deployed internationally, including their SMR versions. GIF will continue playing a role in the ongoing global conversations on these key topics, and will further deepen the fruitful cooperation with the IAEA and the NEA.

GIF continues to develop innovative and impactful ways of engaging and integrating new public and private stakeholders, including start-ups, end users, supply-chain companies and financial institutions. A key initiative in this regard is the organization of biannual Regional Industry Round Tables held in conjunction with the EG/PG meetings. These round tables target key actors in the region hosting the EG/PG meeting. They are open to GIF members and non-members, fostering broad and inclusive dialogue. Key messages and outcomes are subsequently shared via the GIF LinkedIn channel to ensure wider dissemination and visibility. GIF held the 2025 Regional Industry Round Table in Korea. In 2026, more industry round tables will be organized in conjunction with the EG/PG meetings in China and Japan. Building on these regional engagements, GIF will convene its second Industry Forum in 2027, where the main outcomes of each Regional Industry Round Table will be presented.

GIF's role in enabling confidence in demonstration and deployment will further grow through initiatives on financing and risk mitigation (such as the EMWG), which are critical for attracting investment and reducing barriers to commercialization. GIF can also help regarding the public and private due diligence process, and with decision making. Several Gen IV reactors are capable of delivering the different low-carbon energy carriers needed to meet demand in future energy systems. Engagement with end users and financial institutions is a priority to ensure that Gen IV systems can be used globally to their full potential.

GIF will mark its 25th anniversary in 2026, and we will certainly celebrate our achievements. But more importantly, we will prepare for the future and, as simply and nimbly as possible, adapt our key priorities for the upcoming challenges.



Michael Fütterer
2025-2027 GIF Technical Director

3 System summaries

This chapter summarizes the 2025 accomplishments of GIF collaborations for the six reactor technologies identified in the 2002 GIF roadmap[1]: gas-cooled fast reactor (GFR), lead-cooled fast reactor (LFR), molten salt reactor (MSR), supercritical water-cooled reactor (SCWR), sodium-cooled fast reactor (SFR) and very high-temperature reactor (VHTR).

Gas-cooled fast reactor

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

1. GFR conceptual design and safety, with the EU Joint Research Centre (JRC) and French Alternative Energies and Atomic Energy Commission (CEA) as members.
2. GFR fuel, core materials and fuel cycle, with the JRC, CEA and Japan Kyoto University as members. France officially gave notice of its withdrawal from the Fuel and Core Materials project on 30 October 2025, effective 30 April 2026.

R&D collaboration activities pursued in the two GFR technical projects focus on the European Gas-cooled Fast Reactor Demonstrator, ALLEGRO. 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. It aims to achieve high thermal 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 of 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 to 1 500 Mwe (megawatt electric), 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.

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

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

- 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 TREASURE 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 Výzkumu (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-1) 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 electricity, high temperature heat supply for chemical industries and efficient hydrogen production.

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.

Figure GFR-1: HeFASTo reactor system concept



Source: UJZ (2025).

Collaborative research is being advanced under the TREASURE project, which is funded by Euratom's Horizon 2020 program. The project builds upon prior achievements, notably obtained through the SafeG project, to enhance the safety, reliability and operational flexibility of GFR systems, with a specific focus on the ALLEGRO demonstrator. 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, which is leading a task focused on the assessment of regulators and transmission system operators of the GFR technology and the ALLEGRO concept, looking, in particular, at areas that might be challenging in the current regulatory environment in Europe.

The project held its first plenary meeting at the Karlsruhe Institute of Technology (KIT) in 2025, showing promising progress in its first year. The major deliverables and dissemination of results will be shared with GIF and relevant stakeholders. Additional information is available on the websites of the SafeG project (www.safeg.eu), the ongoing TREASURE project (www.projecttreasure.eu) and the ALLEGRO reactor site (www.allegroreactor.eu).

There are various experimental facilities available to support the development of GFR technologies and analysis methods, which are explored below.

As a scaled-down model of the cooling circuits of a GFR reactor, a large-scale experimental facility known as S-ALLEGRO has been constructed in Pilsen, Czechia. This facility simulates thermal-hydraulic behavior and tests key components under realistic conditions, operating with helium at 850°C, 7 MPa pressure and a nominal flow rate of 0.5 kg/s. It includes a 1 MW electrical heater and has demonstrated the reliable performance of seals, circulators and heat exchangers. The feasibility and performance of the passive decay heat removal system, including the transient start-up phenomena, has been demonstrated within the SafeG project. Besides its continuing role in the TREASURE project, the facility is currently being used for a coordinated research project directed by the IAEA that aims to conduct thermal-hydraulic experiments and computational benchmarks for gas-cooled reactors.

The LVR-15 research reactor in Řež, Czechia, is used for irradiation experiments. Although it operates in a thermal spectrum, the high-temperature irradiation rig, which is being licensed to reach up to 800°C in a semi-fast-spectrum configuration, will enable representative material testing. This rig is inserted directly into the fuel zone, allowing for more accurate simulation of GFR conditions despite the limited availability of fast-spectrum reactors. Assembly began on a prototype irradiation rig for out-of-pile testing during the summer of 2025, simulating reactor thermo-hydraulic conditions with electrical heating instead of gamma heating. Certification with the regulatory body is underway, given the challenge of operating at 800°C inside a reactor environment at 40°C. First irradiation is expected by late 2026 or in 2027. The design uses tungsten heating elements, high-temperature insulation and a gas gap to achieve high sample temperatures while keeping heat flux to surrounding water within safe limits.

Concerning project advancements, the Fuel and Core Materials project published its final report on the research undertaken from 2018 to 2025, reporting on the testing of fuel and core materials for the ALLEGRO cores, and the development of numerical models and qualification procedures for the start-up cores. The suitability of the 15-15Ti cladding alloy under ALLEGRO conditions was confirmed through out-of-pile tests, and a qualification procedure outlining critical tasks for future fuel-related activities has been proposed. For the refractory core, SiC was investigated as a cladding material in high-temperature helium environments, with studies on irradiation effects and UO_2 fuel interaction confirming its suitability for ALLEGRO and broader GFR operating conditions. In parallel, the development of numerical models enabled the V4G4 consortium to apply fuel behavior simulations in the design process of the reactor core.

In summary, the present stage of advancement is characterized by a shift from fundamental research and prototype evaluation to facilitating the development of a full-scale, operational demonstration reactor. This marks a shift from basic R&D to application-driven development, with ALLEGRO serving as a critical milestone in the broader advancement of GFR technology.

Reference

UJZ (2025), "HeFASTo – Concept of Advanced Modular Reactor for the Future", www.ujv.cz/en/products-and-services-1/research-development/hefasto (accessed 1 April 2026).



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

Lead-cooled fast reactor

This section focuses on the main collaborative achievements under the GIF LFR provisional System Steering Committee (pSSC) to date. It also summarizes the highlights of the development of LFRs in GIF member countries and industrial entities, as shared within the GIF collaboration.

Main characteristics of the system

GIF has identified the LFR as a technology with high potential to meet the needs of both remote sites and central power stations, fulfilling GIF's four main goal areas: 1) sustainability; 2) economics; 3) safety and reliability; and 4) proliferation resistance and physical protection. In the technology evaluations of the 2002 Generation IV 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 proliferation resistance and physical protection. 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 two reference systems: 1) a large system rated at 600 MWe – the European Lead Fast Reactor (ELFR), intended for large-scale power generation; and 2) a small, transportable system of 10-100 MWe size – the US small secure transportable autonomous reactor (SSTAR), which features a very long core life (see Figure LFR-1 and Table LFR-1). The expected power conversion efficiency of LFR systems is at or above 42%. GIF LFR systems thus cover the full range of power levels, from small and intermediate, to large sizes. 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.

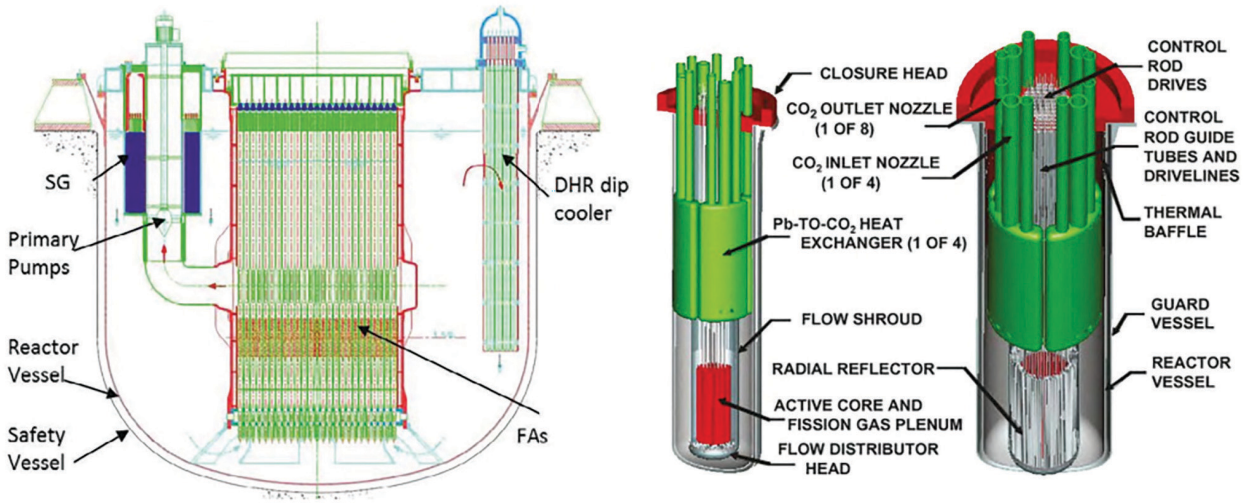
R&D objectives

The LFR System Research Plan is based on the use of molten lead as the reference coolant and lead-bismuth eutectic as an alternative for some designs. 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. Following the reformulation of the GIF LFR pSSC in 2012, the System Research Plan was completely revised.

Table LFR-1: Key design parameters of the GIF lead-cooled fast reactor reference systems

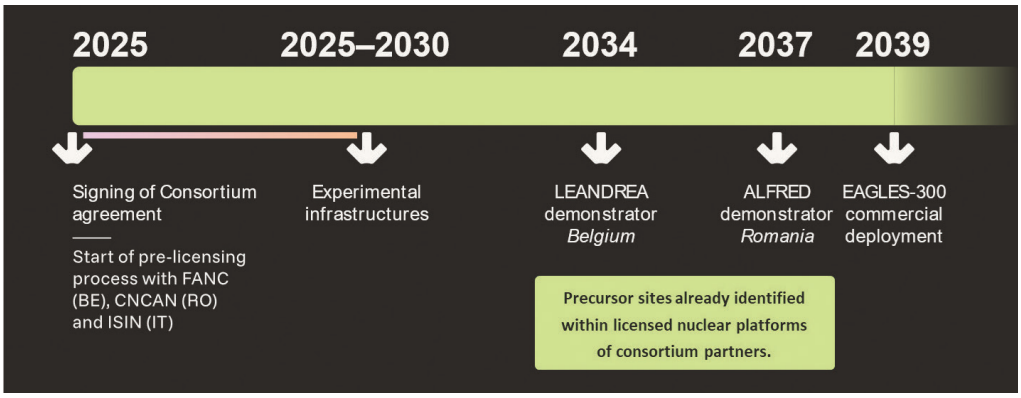
Parameters	ELFR	SSTAR
Core power [MWt]	1 500	45
Electrical power [MWe]	600	20
Primary system type	Pool	Pool
Core inlet T [°C]	400	420
Core outlet T [°C]	480	567
Secondary cycle	Superheated steam	Supercritical CO_2
Net efficiency [%]	42	44
Turbine inlet pressure [MPa]	18	20
Feed temperature [°C]	335	402
Turbine inlet temperature [°C]	450	553

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



Note: The European Lead Fast Reactor (left), and the SSTAR reactor (right).
Source: Alemberti et al. (2018).

Figure LFR-2: EAGLES-300 roadmap



Source: Courtesy of EAGLES.

Technical highlights – Provisional System Steering Committee activities

In 2025, the pSSC published the proceedings of the Global Symposium on Lead and Lead Alloy Cooled Nuclear Energy Science and Technology 2024 (GLANST2024). The pSSC also issued the *LFR System Safety Assessment* in 2020, *Proliferation Resistance and Physical Protection* white paper in 2021, and Safety Design Criteria (SDC) for Gen IV LFR in 2021. The IAEA and NEA Working Group on the Safety of Advanced Reactors provided comments on the SDC report in 2022, and the pSSC is currently working on revising the SDC.

Two meetings of the GIF LFR pSSC took place in 2025. The first meeting was hosted by the NEA in Paris, France, on 6-7 February, and the second was hosted by Blykalla in Stockholm, Sweden, on 10-11 September, with *newcleo*, Ansaldo Nucleare and Xi'an Jiaotong University (XJTU) invited. During these meetings, the LFR pSSC and invited experts exchanged information on the status of LFR development. Presentations were delivered on member activities with descriptions of their respective national LFR programs and information sharing with participants from the industry. The LFR pSSC also discussed cooperative activities, including the update of the LFR SDC and plans for webinars.

In 2024, the LFR pSSC launched the new GIF webinar series "GIF talks with industry" and held three webinars focusing on LFR development projects, inviting industry speakers to present. In 2025, three further webinars dedicated to key LFR technologies were organized: 1) *newcleo*'s materials strategy for Gen IV LFR research and development, with Dr. Francisco Garcia Ferré from *newcleo*; 2) The nitride fuel R&D program of Blykalla, with Prof. Janne Wallenius from Blykalla; and 3) EAGLES-300: European Advanced Gen IV Lead-cooled Energy System, with Dr. Michele Frignani from Ansaldo Nucleare. These webinars provided progress updates on key LFR technologies and the status of LFR development for each industry player. Industry needs, challenges and expectations from GIF activities were also discussed.

National LFR demonstration and development highlights

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

- **The development of an SMR LFR**. The Belgian Nuclear Research Centre (SCK CEN), Ansaldo Nucleare and National Agency for New Technologies (ENEA) (Italy), and RATEN-ICN (Romania) have launched the EAGLES consortium to speed up the industrial deployment of SMR LFR technology. The roadmap is based on two main milestones: 1) the design, construction and operation of LEANDREA in Mol (Belgium) by 2034, which is an LFR devoted to fuel qualification and irradiation purposes; and 2) the design, construction and operation of an LFR demonstrator in Romania, the "Advanced Lead Fast Reactor European Demonstrator" (ALFRED), by 2037. The commercial deployment of a 300 MWe SMR, named EAGLES-300, is also expected by 2039 (Figure LFR-2). To achieve this goal, a considerable R&D program is being implemented using synergies with the involved countries and leveraging the R&D infrastructure in operation or planned by ENEA (Brasimone), SCK CEN (Mol) and RATEN-ICN (Pitesti) (Khalil Youssef et al. 2025).
- **R&D activities for the construction of an LFR demonstrator in Sweden (Oskarshamn)**. SEALER (Swedish Advanced Lead Reactor) is designed for commercial power production in a highly compact format.
- **R&D activities carried out by *newcleo*, mainly in Italy and France, in collaboration with several EU organizations to develop the LFR-AS-30 and LFR-AS-200**. *newcleo* is investing up to EUR 100 million to build large-scale research infrastructure in collaboration with the ENEA Brasimone Research Centre (Italy). CORE1 and CORE2 with the CAPSULE facility are in operation to support corrosion and coolant chemistry investigation in lead, HUSTLE is in operation to support in-service inspection and repair (ISI&R) OTHELLO is under commissioning (Figure LFR-3), and PRECURSOR

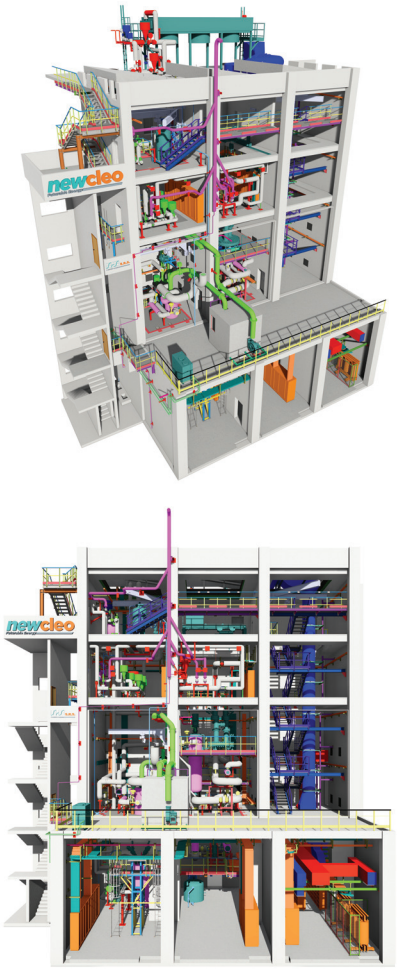
is under construction. newcleo is also working to set up a MOX fuel factory in France, fully funded by private investments, to complement its commercial LFR program (Gregori et al. 2025).

In parallel, several ongoing European collaborative projects (Euratom co-funded initiatives such as LESTO, CONNECT-NM, ANSELMUS, PASCAL and 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. These Euratom R&D projects are complemented by the R&D work conducted by the European Commission's Joint Research Centre (Cioli Puviani et al., 2025; Stefanini et al., 2025).

In Korea, R&D on LFR commenced in 1997, primarily led by universities, with the main objective of enabling the proliferation-resistant transmutation of spent nuclear fuels. Following the Fukushima Daiichi Nuclear Power Plant accident, the program using the medium-size PEACER reactor shifted focus towards developing an SMR without onsite refueling, evolving into the URANUS[1] design and later miniaturized into MicroURANUS® for maritime, as well as terrestrial uses. Subsequently, a start-up MicroURANUS Corporation emerged from a university-industry consortium, which then assumed the leadership for the commercialization of the micro LFR. The university-industry consortium, funded both privately and nationally, actively expands R&D activities by involving the Ulsan National Institute of Science and Technology, the Korean Advanced Institute of Science and Technology, Pusan National University, Chungnam National University and Seoul National University.

The conceptual design of MicroURANUS is being elaborated towards a standard design edition (Figure LFR-4). It has a 20-30 MWe power rating and uses lead-bismuth eutectic coolant. It has a minimum 40-year full-power service life out of the initial load of high-assay low-enriched uranium (HALEU) fuel (average enrichment 12.5%). The reactor is hermetically sealed against clandestine theft attempts, with additional security granted by radioactive polonium present in the coolant. Passive safety features practically eliminate severe accidents and minimize the size of the emergency planning zone. Assessments of scenarios such as steam generator tube ruptures at 350°C and/or reactor flooding with high-pressure water have shown immunity against steam explosion (Hwang, 2024) in contrast to SFR or MSR designs. Advanced alumina-forming austenitic stainless steels have been developed as cladding on proven structural materials for fuel rods and steam generator tubes, showing adequate resistance to corrosion, erosion and void swelling (Hwang, 2025).

Figure LFR-3: 3D view of OTHELLO loop



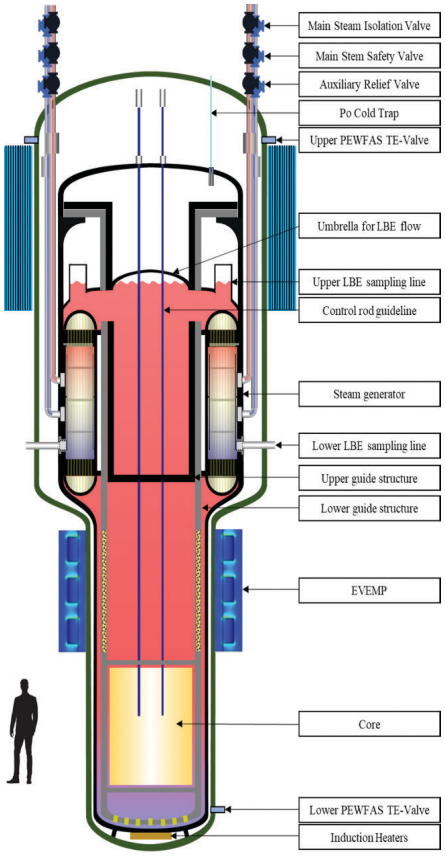
Source: Courtesy of newcleo.

The advanced pyro-electrochemical partitioning technology, PyroGreen®, is being developed to decontaminate all high-level waste streams from existing pyro-processing into intermediate-level waste storage with an institutional control period of 300 years. On the basis of MicroURANUS® and PyroGreen®, a cradle-to-grave service can be offered to universal applications for powering datacenters and maritime applications, as well as large-scale hydrogen production (Choi et al., 2025).

In the United States, work on LFR concepts and technology has been carried out since 1997. In addition to reactor design efforts, these activities have included work on lead corrosion/material compatibility and thermal-hydraulic testing at several organizations and laboratories, as well as the development and testing of advanced materials suitable for use in lead or lead-bismuth eutectic (LBE) environments. University-related activities include several projects sponsored by the US Department of Energy (DOE) under Nuclear Energy University Project (NEUP) funding.

1. Ubiquitous Robot Accident forgiving Nonproliferating Ultra-lasting Sustainer.

Figure LFR-4: MicroURANUS conceptual design schematic



Source: MicroURANUS.

Under the NEUP program, a project led by the Massachusetts Institute of Technology in the area of corrosion/irradiation testing in lead and lead-bismuth eutectic (Cairang et al., 2025; Zhang et al., 2025; Demir et al., 2025) was completed in 2025. The US DOE also approved funding for a Technology Commercialization Fund (TCF) project, which is supporting the adaptation of the fast reactor analysis software developed by national laboratories for industry needs. The "Enhancement of PyARC for Westinghouse LFR Design and Modeling" (Stauff et al., 2025; Park et al., 2025; Keisling et al., 2025) project by Argonne National Laboratory, with Westinghouse as an industry partner, was also completed in 2025. The First American Nuclear Company[2] was established in the United States in 2025 and is developing a loop-type LBE-cooled reactor.

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 Plan. 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. The 10 MW-grade CLEAR-M10 project targets the development of a small, compact LFR with inherent safety features, as well as ease of transportation and installation. The CLEAR-200 – a 200 MWt small modular lead-cooled reactor project – has been recently proposed to address a wider range of application demands, including substitution of fossil energy, power supply for computing centers, industrial steam supply and residential heating. In August 2021, an electric heated pool-type LBE-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 is being performed in CLEAR-M0.

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 the 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 China Institute of Atomic Energy (CIAE) and other industrial organizations, aims to build a 10 MWt subcritical experimental LBE-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 China, other organizations have started paying more attention to LFR development. For example, SPIC-SNERDI has proposed a long-life fully natural circulation small LBE-cooled reactor, LZU is developing an offshore stationary LFR, XJTU is developing the SARAX code for advanced reactor design and analysis, and SJTU is carrying out thermal-hydraulic experimental and numerical research, and multi-scale and multiphysics coupled analysis. In addition, the China National Nuclear Corporation (CNNC), China General Nuclear Power Group (CGN) and several universities, such as Harbin Engineering University and Zhejiang University, have been carrying out LFR-related R&D.



Mariano Tarantino
Chair of the LFR provisional System Steering Committee, with contributions from LFR members

2. https://fanuclear.com.

References

Alemberti, A. et al. (2018), "The Generation IV lead-cooled fast reactor activities", *Proceedings of the GIF Symposium 2018*, pp. 23-34, www.gen-4.org/gif/jcms/c_117863/2018-gif-symposium-proceedings.

Cairang, W. et al. (2025), "Simultaneous proton irradiation and dissolution corrosion of SS316L in liquid Pb-4Bi alloy", *Corrosion Science*, Vol. 253, Art. 113010.

Choi, J. W. et al. (2025), "Analysis of Residual Stress for Double-Walled Tubes Following Heat Treatment Process and Materials Behaviors", KPVP Conference, 19 November, Busan, Korea.

Cioli Puviani, P. et al. (2025), "A novel Ansys CFX-RELAP5 coupling tool for the transient thermal-hydraulic analysis of liquid metal systems", *Progress in Nuclear Energy*, Vol. 180, https://doi.org/10.1016/j.pnucene.2024.105590.

Demir, E. et al. (2025), "Behavior of Fe-based alloys in a liquid lead-bismuth environment under simultaneous proton irradiation and corrosion", *Acta Materialia*, Vol. 284, Art. 120578.

Gregori, G. et al. (2026), "Determination of Oxygen Activity Coefficient and Solubility in Lead Nuclear Coolant by Zirconia Solid Electrolyte", *The Journal of Chemical Thermodynamics*, Vol. 212, https://doi.org/10.1016/j.jct.2025.107568.

Hwang, I.S. (2025) "Micro Lead Fast Reactors with Cradle-to-Grave Services for Global Net-Zero", Invited, MIT-Oxford International Colloquium on Nuclear Engineering, 16 May 2025.

Hwang, I.S. and H.D. Chung (2024), "MicroURANUS Leveraged on Inert Coolant for Maritime Safety", GLANST-2024, September 30 - October 2, ENEA, Brasimone, Italy.

Khalil Youssef, G. et al. (2025), "Neutronic and thermal hydraulic analysis of ALFRED during Unprotected transients considering the reactor staged approach", Nuclear Engineering and Design, Vol. 444, https://doi.org/10.1016/j.nucengdes.2025.114412.

Kiesling, K.R. et al. (2025), "Depletion Benchmark Analysis on a Lead Fast Reactor Using PyARC/OpenMC", ANS Annual 2025.

Park, H. et al. (2025), "MC2-3 DPA Evaluation: Verification and PyARC Integration", ANS Winter 2025.

Stauff, N. et al. (2025), "Core Design and Performance of the Westinghouse Lead Fast Reactor with UO2 and MOX Configurations", *Nuclear Engineering and Design*, Vol. 442, Art. 114266.

Stefanini, P. et al. (2025), "Validation of a coupled STH and low-fidelity CFD approach using experimental data from NACIE-UP test facility", *Nuclear Engineering and Design*, Volume 444, https://doi.org/10.1016/j.nucengdes.2025.114353.

Zhang, M. et al. (2025), "Correlated chromium carbide dissociation and phase transformation in liquid lead-bismuth eutectic corroded T91 steel", *Corrosion Science*, Vol. 249, Art. 112851.

Molten salt reactor

The GIF molten salt reactor (MSR) system is organized by a memorandum of understanding instead of a system arrangement. With the renewal of the GIF Framework Agreement, the memorandum of understanding will also be renewed; however, this process could not be finalized in 2025. The mission of the MSR provisional System Steering Committee (pSSC) is to support international collaboration on the development of future nuclear energy concepts that can help meet the world's energy needs, while respecting the GIF targets. In 2025, two hybrid pSSC meetings were held: the 38th meeting took place at the Abilene Christian University in Texas, in the United States, with participants able to visit the building of the future Molten Salt Research Reactor (MSRR); and the 39th meeting was held at the Paul Scherrer Institute (PSI) in Switzerland. In 2025, cooperation within the GIF MSR system continued along three main axes: 1) salt behavior; 2) materials properties; and 3) system integration.

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). Liquid-fuel MSRs are a type of nuclear fission reactor in which a halide salt serves as 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 solid- and liquid-fueled MSRs have seen a resurgence in interest over the past two decades. Proposed designs with molten salt fluoride and chloride salt mixtures include both thermal and fast-spectrum systems, and there are also 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-1, which also highlights some prominent MSR developers.

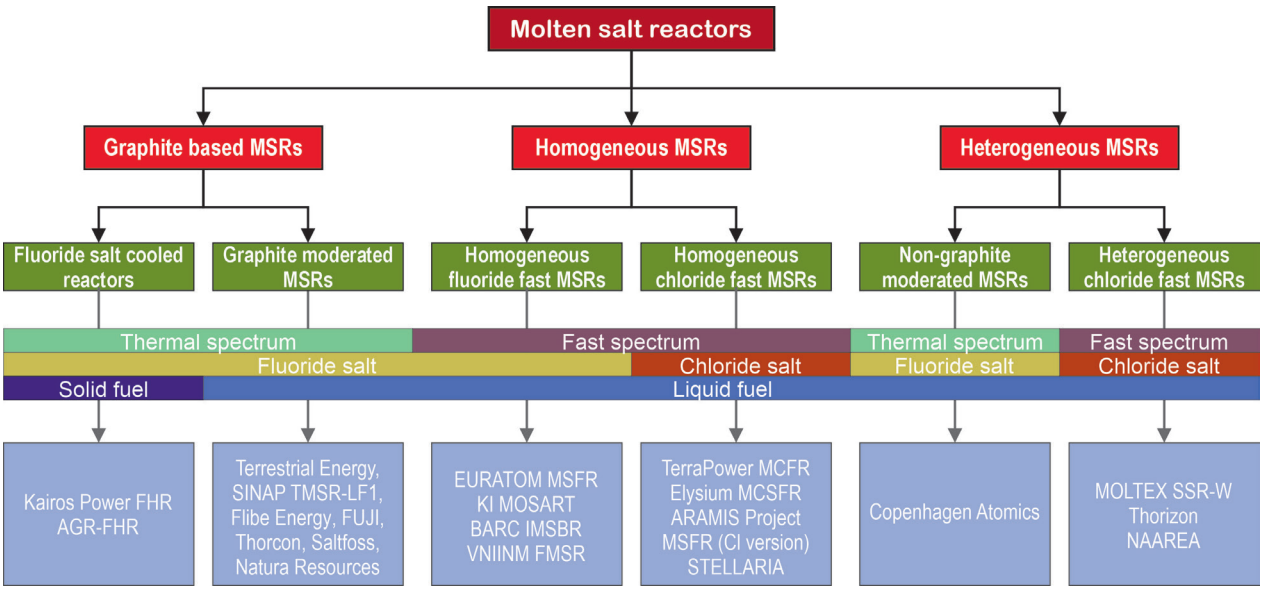
MSRs have several advantageous characteristics, ranging from high-temperature operation, which increases thermodynamic efficiency, to low-pressure operation, which reduces the driving force for radionuclide dispersal in the event of an accident. MSRs also tend to have strong negative reactivity feedback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

However, 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 they are trapped in claddings. Molten salts can also become highly corrosive if exposed to oxidative impurities. Overall, MSRs have substantial technology differences from both existing light water reactors (LWRs) and other advanced reactor concepts, necessitating different approaches to safety assessment, safeguards and operations.

R&D objectives

GIF's objective is to support collaboration on technology, data and analysis methods. While MSRs may be demonstrated in the next few years, their performance could be improved through the development

Figure MSR-1: Most studied MSR concepts, with some key developers



of better 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 and creep fatigue);
- demonstration of tritium management technologies;
- salt redox control technologies to master corrosion of 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-fueled reactors.

National MSR demonstration and development highlights

Euratom has significantly advanced its MSR ecosystem through coordinated projects, strengthened JRC leadership and growing industrial engagement. Research institutions, national laboratories and small and medium-sized enterprises (SMEs) collectively contribute to maturing MSR technologies, safety methodologies and supply-chain readiness.

At the industrial level, three main European SMEs focus on modular, safe and scalable MSR, with Thorizon emphasizing waste utilization, Saltfoss targeting ease of deployment via barge-mounted CMSRs, and Copenhagen Atomics leveraging thorium fuel and mass-manufacturing, for commercial and industrial energy solutions. All of these companies, together with France's Stellaria, are part of the European Industrial Alliance on Small Modular Reactors, which is a collaborative initiative created to accelerate development, demonstration and deployment of SMRs in Europe. In November 2025, Thorizon was reconfirmed as a Project Working Group under the Industrial Alliance.

At JRC, R&D efforts in 2025 included the development of methods to synthesize high-purity plutonium (III) chloride ($PuCl_3$) and uranium (III) chloride (UCl_3), and the validation of a method to synthesize molten salt mixtures from metallic precursors. A series of experiments was conducted to measure the thermophysical properties of the most important salt compositions for the chlorine-based fast-spectrum MSR. The focus was on salt mixtures of UCl_3 and $PuCl_3$ with sodium chloride (NaCl), and on systems containing a mix of fission products to investigate fuel behavior during reactor operation. JRC MSR R&D activities also expanded to safeguards and material testing.

The Joint Research Centre Molten Salt Database (JRCMSD) strengthened its role as Europe's reference database for molten salt properties. The 2025 update, developed collaboratively by JRC, CEA, Orano and TU Delft, focused on:

- thermophysical and thermochemical data consolidation;
- standardized data formats for safety assessments and reactor design;
- integration of new experimental datasets from European laboratories;
- improved validation workflows to support future licensing frameworks.

Within the framework of the Euratom Research and Training Programme, two MSR-related EU Horizon Europe projects are currently ongoing: the MIMOSA project and the ENDURANCE project.

MIMOSA focuses on developing a multi-recycling strategy for spent nuclear fuels from LWRs using molten salt technologies. 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 molten salt reactors (Cl MSRs);
- demonstrating key aspects of technical feasibility and performance for Cl MSRs, 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;
- developing pyrochemical processes to recycle plutonium and minor actinides;
- innovating methods for the removal, disposal, extraction and purification of fission products.

ENDURANCE 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 centers, 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. The ENDURANCE project aims to create a scientific roadmap for the future development and deployment of MSR technology in Europe, ensuring that MSRs can play a significant role in a sustainable and safe nuclear energy future. A specific task of the ENDURANCE project is to organize a worldwide round robin test on the thermophysical properties measurement of molten halide salts, extending beyond the EU. This initiative was communicated to the MSR GIF community during the last meeting and received a high level of interest.

Beyond European initiatives, substantial support continues for the development of MSRs across the continent through academic and national research institutions. At Politecnico di Milano, efforts are focused on modeling MSR dynamics, examining transient behavior, optimizing heat exchangers and studying multiphysics coupling. TU Delft contributes valuable experimental data on salt thermodynamics and redox control to the JRCMSD database, while also working to integrate viscosity and density information alongside structural studies conducted both on site at their test reactor and in collaborative environments. At NRG in the Netherlands, irradiation testing of MSR-relevant materials and salts is ongoing in the High Flux Reactor Petten, supporting research programs and industrial partners including Orano, Thorizon and Stellaria. Meanwhile, the Technical University of Denmark (DTU) is advancing computational fluid dynamics (CFD) and thermal-hydraulic modeling for molten salt systems, incorporating corrosion modeling and heat transfer studies to enhance system understanding and safety. This combined activity exemplifies strong institutional engagement, ensuring coordinated progress across Europe in MSR technologies.

At the close of 2025, it was officially announced that the first European Conference on Molten Salt Reactor Technology (EUROMOST) would be held from 26 to 29 May 2026 in Baden-Baden, Germany. Organized by the JRC, the conference will serve as a key platform for researchers, policy makers, funding organizations and industry leaders to discuss recent developments, share insights and explore collaborative opportunities in the field of MSRs, reflecting the EU's growing commitment to clean energy solutions and sustainable nuclear innovation. The conference is primarily a European event but is open to overseas partners for fruitful and collaborative discussions.

In France, several MSR options are being considered, all using fast-spectrum and molten chloride: MSFR, ARAMIS, STELLARIUM, NAAREA and Thorizon. The associated R&D programs are multidisciplinary, covering:

- reactor system (i.e. neutronics, salt depletion, materials and components);
- reactor operation and safety (i.e. normal transients, accidental transients, start-up and draining);
- associated fuel cycle (i.e. salt behavior, corrosion, fission product management, salt polishing, salt synthesis [$PuCl_3$] and scenario studies), and the refueling and polishing strategy;
- multiphysics and chemistry modeling and simulation (neutronic/thermal-hydraulic simulations, coupling between salt depletion and thermochemical calculations, etc.).

Since 2022, CEA and the National Center for Scientific Research (CNRS), along with industrial partners Orano, Framatome and EDF, have actively contributed to the common French project Innovative System for Actinide Conversion (ISAC), supported by the France 2030 investment plan. One of the project's main objectives is to assess the feasibility of a fast chloride MSR for americium management. The project is divided into five work packages: conceptual design, scenario studies, active salt chemistry, material corrosion and irradiation, and experimental facilities. Around 14 Ph.D. students are funded within CEA and CNRS on various simulation and experimental activities. Some Ph.D. research has been completed, including those that have explored reactor design, operation and safety (Mascaron, 2024; Clot, 2024); neutron and thermal-hydraulic coupling (Sornay, 2024; Marjanovic, 2025); corrosion (Pellicot, 2024); and salt fuel cycle and property measurements (Brusq, 2025). The first specification of the ARAMIS-A concept was issued in 2023 (300 MWt, outlet fuel salt temperature up to 650°C), and its final conceptual design was delivered in 2025 with predesign studies of the main fuel loop components. Experimental studies on salt component synthesis ($PuCl_3$, americium (III) chloride [$AmCl_3$]) and full mixed salt were conducted in 2023 and 2024 (CEA, JRC), as well as experimental screenings of material corrosion in inactive chloride salts (NaCl-magnesium chloride [$MgCl_2$]) (CEA, CNRS). Chloride salt loops are under design and construction since 2023 at CEA and CNRS. The start of a first chloride loop with NaCl-$MgCl_2$ was achieved in 2025.

The following international MSR activities include French partners:

- ENDURANCE: A collaborative project involving CNRS, CEA and industrial partners such as NAAREA and Stellaria, aimed at advancing MSR technology in Europe;
- MIMOSA and MOSARWASTE: Further supporting MSR-related research and waste management solutions in collaboration with European partners;
- MSR System Safety Assessment by the GIF Risk and Safety Working Group;
- collaboration with US DOE on MSR safety initiatives (2026-2027);
- participation in the NEA/WPRS MSR Multiphysics Calculation Benchmarks, furthering efforts to standardize MSR modeling and simulations (a benchmark on the Molten Chloride Reactor Experiment [MCRE] is foreseen).

Finally, the French 2030 "Innovative Nuclear Power Plant" call has supported three start-ups based on MSR technology since 2023.

- Thorizon is developing an innovative MSR concept utilizing a core design based on an array of cartridges to address traditional challenges in MSR technology such as fuel management and material durability. Individual cartridges encapsulate the fuel, coolant (molten salt), pump and heat exchanger, making the core modular with the cartridges replaceable every five years. The design is supposed to be adaptable to various fuel types, with plans for demonstration in 2026 and deployment by 2032.

- Stellaria is developing a small nuclear reactor that will rely on natural convection cooling 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 as it is consumed, eliminating the need for pumps and fast-reactivity control systems. Stellaria's concept is housed in an underground vessel with four containment barriers, designed to keep radiation exposure below 1 mSv at the facility boundary. 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.
- NAAREA is developing a modular nuclear micro-generator that operates using high-temperature molten chloride salts in a closed fuel cycle, 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. However, the future of the company funding is uncertain.

In the United States, President Trump issued four executive orders on 23 May 2025 as part of the US administration's effort to quadruple US nuclear generating capacity by 2050, promote deployment of advanced nuclear technologies, build out nuclear fuel supply chains, expedite the licensing process and increase US nuclear exports.[1] There is an acceleration in the development and demonstration of advanced reactor systems, including both salt-cooled and salt-fueled.

The MSR development projects supported by the US DOE Office of Nuclear Energy (DOE-NE) continue to make progress and global interest in MSRs continues to grow. In May 2025, Kairos Power started nuclear construction on their TRISO-fueled Hermes test reactor at Oak Ridge, Tennessee,[2] which is supported through an Advanced Reactor Development Program (ARDP) Risk Reduction Award. Kairos Power also received an approved construction permit from the Nuclear Regulatory Commission (NRC) for their Hermes 2 reactor, which will deliver up to 50 MWe to the TVA (Tennessee Valley Authority) grid that powers Google data centers in Tennessee and Alabama.[3] Natura Resources,[4] partnered with Abilene Christian University (ACU), was recently accepted into the DOE Reactor Pilot Program,[5] with plans to build the MSR-1 as a university research reactor at ACU. Terrestrial Energy was also accepted into DOE's Reactor Pilot Program and the Fuel Line Pilot Program[6] to demonstrate its Integrated Molten Salt Reactor (IMSR).[7] Terrestrial will use LEU fuel salt at the first reactor site, which is soon to be announced. The MSR Research Program under DOE-NE is reducing technical, regulatory and operational risks for these emerging designs. Several US national laboratories are involved and provide the missing thermal properties data of molten salts, which are collected in the Molten Salt Thermal Properties Databases–Thermochemical (MSTDB-TC) and Thermophysical (MSTDB-TP). Professor Ted Bessman, from the University of South Carolina, organized a workshop on Effect of Oxygen, Hydrogen, and Moisture on Molten Salt Behavior on 3-4 June 2025,[8] with the following topics covered:

- challenges and best practices for the measurement of oxygen, hydrogen and moisture content in salts;
- current understanding of the effects on thermochemical and thermophysical properties;
- modeling and measuring influence on redox state;
- modeled and observed effects on corrosion behavior.

The updated version of MSTDB-TC Ver 4.0 has been released and is available for public use.[9] The databases both increase the amount of information within the databases and increase confidence in the validity of the data.

US national laboratories are developing sensors to monitor MSR off-gas, expand the MELCOR code for MSR accident scenarios and mechanistic source term, and develop simulation scenarios for MSR safety to support design, development and licensing of commercial MSR technology. The annual program review took place in April 2025, and the presentations are available on the MSR website.[10]

1. www.energy.gov/ne/articles/9-key-takeaways-president-trumps-executive-orders-nuclear-energy.
2. https://kairospower.com/external_updates/kairos-power-begins-nuclear-construction-of-hermes-demonstration-reactor.
3. https://kairospower.com/external_updates/kairos-power-begins-nuclear-construction-of-hermes-demonstration-reactor.
4. www.naturaresources.com.
5. www.energy.gov/ne/us-department-energy-reactor-pilot-program.
6. www.energy.gov/ne/energy-department-fuel-line-pilot-program
7. www.terrestrialenergy.com.
8. https://gacenterusc.org/mstdb-workshop.
9. https://gacenterusc.org/mstdb-tc.
10. https://gain.inl.gov/doe-molten-salt-reactor-program.

The Nuclear Energy University Program (NEUP), established by DOE-NE in 2009, plays an important role in advancing nuclear energy research and education, helping to educate and train the next generation of nuclear energy professionals through various opportunities. The Integrated Research Program (IRP) is one of the funding opportunities available to universities providing R&D solutions most directly relevant to the near term, significant needs of the DOE-NE R&D programs. There are two ongoing projects that support molten salt and MSR research. The first involves the Massachusetts Institute of Technology (MIT) and its university partners, who are developing a general-purpose loop at the MIT research reactor, where salt flowing through the loop is irradiated by neutrons from the reactor. The neutrons interact with the salt to create various radionuclides in the salt, including tritium, helium and noble metal fission products, depending on the salt being irradiated. The loop creates conditions similar to those in the primary coolant circuit of MSRs and fluoride-cooled high-temperature reactors (FHRs), allowing experimenters to: 1) understand salt behavior in a reactor; 2) test redox control and other chemistry control systems designed to minimize corrosion; 3) test salt cleanup systems; 4) test instrumentation systems and other equipment for salt reactors; and 5) collect data to validate models of radionuclide transport in salt systems.[11]

The second IRP project is at the University of California (UC), Berkeley,[12] which involves improving the understanding of the role of impurities and fission products on the operational performance of MSRs, as well as potential impacts on accident scenarios. A key target is to contribute to the development of MSRs solving real world issues. For this reason, UC Berkely is working closely with two MSR developers representing two different MSR categories: TerraPower Molten Chloride Fast Reactor (MCFR) is the selected case study for liquid-fuel MSR, while Kairos Power's FHR is the case study for a solid fuel system.

TerraPower has received a GAIN (gateway for accelerated innovation in nuclear) award[13] and is partnering with Argonne National Laboratory (ANL) to generate nuclear quality assurance (NQA)-1 qualifiable and traceable thermophysical property data of NaCl-potassium chloride (KCl)-UCl_3 salt for beginning-of-life (BoL) and simulated end-of-life (EoL) ternary fuel salts. ANL has proven expertise in molten salt thermophysical measurement under NQA-1 standards. These results will directly inform reactor and component design, thermal-hydraulic modeling, safety margins and licensing strategies.

The National Reactor Innovation Center's (NRIC) Molten Salt Thermophysical Examination Capability (MSTEC), located at Idaho National Laboratory, is finalizing the commissioning of a combined set of hot cells and glove boxes to focus on high-temperature molten salt chemistry. MSTEC will be among the world's first facilities capable of examining irradiated molten salt, supporting MSR research and pyro-processing spent nuclear fuel. The hot cell's argon atmosphere supports research with irradiated and non-irradiated chlorides, fluorides, beryllium and actinides.[14] ORNL's engineering-scale chloride salt pumped test loop was employed for sensor performance validation testing in August 2025, with Raman spectroscopy and portable Laser Induced Breakdown Spectroscopy tested (Felmy et al., 2025; Andrews et al., 2025).

The annual MSR workshop, organized by ORNL, was held in person in Knoxville, Tennessee, in November 2025 with 325 participants.[15]

Canadian Nuclear Laboratories (CNL) is leading a pan-Canadian initiative to develop a national framework that will accelerate the deployment of microreactors for off-grid applications in remote communities. Building on the *Small Modular Reactor (SMR) Roadmap and Action Plan* (Canadian Small Modular Reactor Roadmap Steering Committee, 2018; Canada's SMR Action Plan, 2026), this effort addresses the unique challenges of off-grid deployment and identifies gaps in Canada's current nuclear ecosystem. Eighteen organizations from across Canada, involving 65 participants that included representatives from various Government of Canada agencies, the Province of Ontario, municipalities, Indigenous organizations, utilities, SMR vendors, industry associations and academia, contributed to the development of the framework.

CNL's Canadian Nuclear Research Initiative (CNRI) program expanded this year to include fusion-based R&D. CNRI helps to accelerate the deployment of new innovations, including SMR and other advanced reactor designs, next-generation on-grid reactors and fusion technologies, by connecting reactor vendors with the funding, facilities and expertise within Canada's national nuclear laboratories.

Through Atomic Energy of Canada Limited's Federal Nuclear Science & Technology (FNST) Work Plan, CNL supports the collective interests of 15 federal departments and agencies in areas such as health, energy, nuclear safety and the environment. Under FNST programs, CNL is developing modeling and experimental molten salt capabilities. R&D efforts in

11. https://neup.inl.gov/content/uploads/14/2024/07/IRP-20-22026_TechnicalAbstract_2020CFASummaryAbstract20-22026.pdf.

12. https://neup.inl.gov/content/uploads/14/2024/07/IRP-22-28329_TechnicalAbstract_2022CFASummaryAbstractIRP-22-28329.pdf.

13. https://gain.inl.gov/thermophysical-property-measurements-of-nacl-kcl-ucl3.

14. https://nric.inl.gov/mstec.

15. https://events.ornl.gov/msrworkshop2025.

2025 included the development of custom crucibles and encapsulation methods for high-temperature differential scanning calorimetry measurements of high-volatility fuel salts. These crucibles and associated experimental protocols address the limitations of commercial crucibles for measuring melting point, heat of fusion and specific heat capacity at temperatures above 600°C. Progress was also achieved in measuring oxygen concentrations in molten salts using inert gas fusion analysis. This capability will enable evaluation of the purification methods required to control corrosion and allow quantification of the impact of oxygen content on thermophysical and safety-related properties such as melting point. Following corrosion experiments conducted in a natural-circulation corrosion loop made of SS 316L exposed to eutectic KCl-lithium chloride (LiCl) salt, the characterization of metal coupons and salt samples is ongoing, along with analysis of components retrieved from the hot leg and cold leg of the corrosion loop (Figure MSR-2).

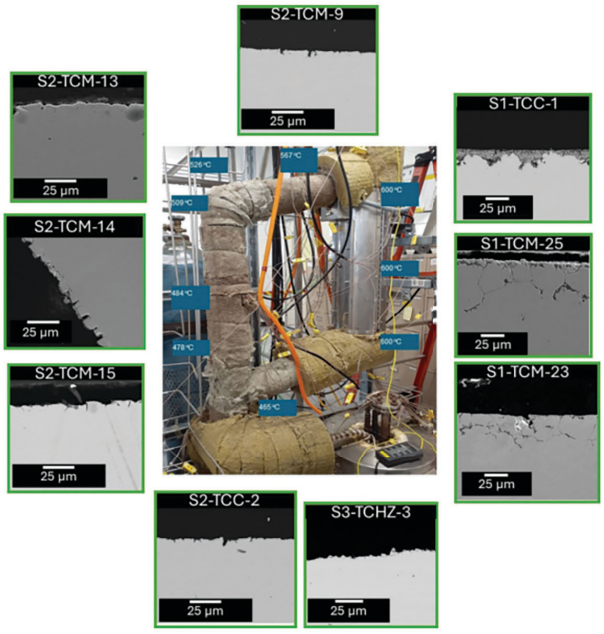
In Switzerland, MSR research is centralized at PSI, which cooperates with the universities ETH Zurich and EPFL Lausanne. The long-term aim of MSR research in Switzerland is safety and fuel cycle sustainability, without a particular focus on specific MSR concepts. This research relies on national and international projects, and student education.

A Ph.D. project financed by the Swiss National Science Foundation focusing on transmutation performance evaluation in many reactors was ongoing in 2025. Switzerland, represented by ETH Zurich and PSI, participate as a third country in the ongoing EU project ENDURANCE. Within this project, the TRACE/PARCS code system, which was modified in 2015 at PSI for MSR application, was checked and updated. As a result, the transient analysis of MSRE and MSFR could be replicated. The PSI in-house tools EQL0D and GEMS (with Heracles database) are being coupled to simulate salt speciation during burnup.

In 2025, Swissnuclear, the association of Swiss nuclear power plant operators, awarded a Ph.D. grant to a PSI student for the systematic analysis of one or two MSR concepts, with the aim that the student will apply all the simulation tools so far developed or modified at PSI.

In 2025, collaboration between PSI and Copenhagen Atomics continued, focusing on preparing documentation for licensing. The Copenhagen Atomics Onion Core critical experiments are planned to be carried out in collaboration with the Hotlab department at PSI.

Figure MSR-2: Demonstration natural-circulation loop (DNCL) corrosion loop



Source: Canadian Nuclear Laboratory.



Jiří Křepel
Chair of the MSR provisional SSC
with contributions from MSR members

References

Andrews, H.B. et al. (2025), *Analysis of Off-Gas Streams from Small- and Large-Scale Sparging Salt Vessels using Laser-Induced Breakdown Spectroscopy*, Oak Ridge National Laboratory, https://gain.inl.gov/content/uploads/4/2025/10/ORNL-TM-2025-4115.pdf.

Brusq, A. (2025), "Développement de techniques de mesure de propriétés thermophysiques de mélanges de chlorures fondus" [Development of measurement techniques for thermophysical properties of molten chloride mixtures], PhD Thesis, Université de Toulouse.

Canada's SMR Action Plan (2026), Homepage, https://smractionplan.ca (accessed 2 April 2026).

Canadian Small Modular Reactor Roadmap Steering Committee (2018), *A Call to Action: A Canadian Roadmap for Small Modular Reactors*, Ottawa, Ontario, Canada, https://smrroadmap.ca/wp-content/uploads/2018/11/SMRroadmap_EN_nov6_Web-1.pdf.

Clot, L. (2025), "Studies and optimisation of molten salt burner reactors: from calculation scheme to fuel cycle simulations", PhD Thesis, Université Grenoble Alpes.

Felmy, H.M. et al. (2025), *Demonstration of Optical Spectroscopic Flow Cell Design for Molten Salt Reactor Off-Gas Streams*, Pacific Northwest National Laboratory, https://gain.inl.gov/content/uploads/4/2025/10/PNNL-38277.pdf.

IAEA (2023), "Status of molten salt reactor technology", *Technical reports series*, no. 489, International Atomic Energy Agency, https://www-pub.iaea.org/MTCD/Publications/PDF/STI-DOC-010-489_web.pdf.

Marjanovic, D. (2025), "Neutronic modelling for molten Salt reactor design studies", PhD Thesis, Université Aix-Marseille.

Mascaron, M. (2024), "Multicriteria analysis of operating margins for a molten salt reactor", PhD Thesis, Université Grenoble Alpes

Pellicot, L. (2024), "Understanding the corrosion mechanisms of alumina-forming alloys in molten chlorides salts: Application to the molten salt reactor", PhD Thesis, Sorbonne Université.

Sornay, T. (2024), "Calculation tools and methodology for the multiphysics and multicriteria study of SMR-type molten-salt reactors", PhD Thesis, Université Grenoble Alpes.

Supercritical water-cooled reactor

In 2025, GIF members Canada, China, Euratom and Japan contributed to the System Arrangement (SA) for collaboration on supercritical water-cooled reactor (SCWR) R&D in three technical projects established for GIF collaborations:

1. SCWR system integration and assessment (provisional);
2. SCWR thermal hydraulics and safety, with Canada, China and Euratom;
3. SCWR materials and chemistry, with Canada, China and Euratom.

Main characteristics of the system

The SCWR is a high-temperature, high-pressure water-cooled nuclear reactor concept that operates above the thermodynamic critical point of water (374°C and 22.1 MPa). By circulating coolant in a single supercritical phase, the SCWR enables direct heat transfer to a high-efficiency power conversion system, using decades of accumulated industrial experience from both light water reactors and supercritical fossil-fired power plants.

SCWR technology represents an evolution of current light water reactor (LWR) systems, maintaining the same coolant, many familiar operational principles and a large portion of the industrial supply chain, while achieving significantly improved thermal efficiency (targeting 44-48%). This evolutionary continuity reduces the technological gap towards deployment and increases compatibility with existing infrastructure, standards and regulatory knowledge.

Two main design lines are under development: 1) pressure-vessel concepts (Japan, Euratom, China); and 2) pressure-tube concepts, pioneered by Canada. Despite differences in core arrangement and structural configuration, both approaches share similar operating pressures and temperatures, steam cycle options, neutron spectrum flexibility, and common R&D challenges related to materials performance, corrosion and stress corrosion cracking, water chemistry control, fuel qualification, thermal hydraulics and safety integration. These shared challenges make the SCWR a strong candidate for internationally coordinated development.

Importantly, SCWR technology is also being investigated in SMR configurations (Table SCWR-1), positioning it as one of the most immediate and pragmatic options for future nuclear deployment, particularly where rapid decarbonization, industrial heat applications and scalable construction strategies are required. The combination of evolutionary design, higher efficiency, simplified plant architecture and SMR scalability strengthen the SCWR's prospect as a near-term Gen IV solution for large-scale low-carbon power generation.

In 2025, the SCWR SA completed several reports under the Joint European Canadian Chinese – Small Modular Reactor Technology (ECC-SMART) project. The most relevant highlights achieved during this period are detailed below.

Table SCWR-1: Main operating conditions of proposed SCW-SMR designs



Parameters	Canadian SCW-SMR[1]	CSR-150[2]	ECC-SMART[3]
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).

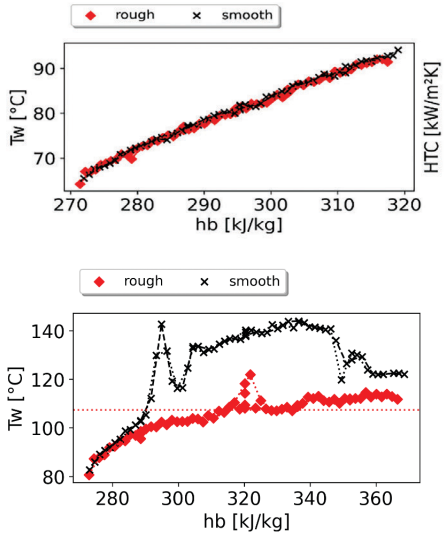
Technical highlights – Thermal-hydraulics and safety project

Recent efforts in thermal-hydraulics modeling have focused on extending the existing theory of water-cooled reactor systems by exploiting the analogies between subcritical and supercritical regimes. Research groups at the University of Pisa (UNIPI, Italy), CNL and the Chinese Academy of Sciences (CAS) continue to refine correlations and stability criteria to improve the prediction of heat transfer deterioration, buoyancy effects and density-wave oscillations under supercritical conditions. After several decades of computational fluid dynamics (CFD) investigations on fuel assemblies exposed to supercritical water, results obtained by different institutions are converging into consistent observations and recommendations. Furthermore, a manuscript entitled "A state-of-the-art review of the supercritical water-cooled, part I economics, thermal hydraulics, and safety & licensing", which summarizes the latest developments in economics, thermal hydraulics, and safety and licensing, has been completed and submitted to a special issue of *Nuclear Engineering and Design* (Nava Dominguez, Azih, et al. 2025).

In Canada, CNL conducted a frequency domain stability analysis of two parallel channels using experimental data from Nuclear Power Institute of China (NPIC). The goal is to gain a better understanding of the potential instabilities that may be triggered in reactors where a significant change in coolant density occurs in the core.

CNL and the University of Wisconsin-Madison are working together on critical heat flux (CHF) near the critical point, which can occur during the ramp up and shut down of SCWRs. Water properties vary significantly near the critical point, affecting thermal-hydraulics behavior, and understanding heat transfer is essential for supporting the conceptualization of SCWRs.

Figure SCWR-1: KIT experiments on wall roughness effects on heat transfer



Source: Wiltschko and Cheng, 2025; Wiltschko et al., 2025.

Regarding experimental activities, the KIT (Germany) experimental campaigns continue to investigate heat transfer to supercritical fluids, comparing smooth and rough wall conditions. The experiments have shown, for example, that with sufficient wall roughness, heat transfer deterioration could be delayed or disappear (Figure SCWR-1) (Wiltschko and Cheng, 2025; Wiltschko et al., 2025).

The University of Sheffield (UK) has released a new revision of the direct numerical simulation (DNS) code CHAPSim, which now incorporates the capability to simulate supercritical-water flows in horizontal configurations, allowing for more accurate study of asymmetrical heat transfer behavior and gravitational effects.

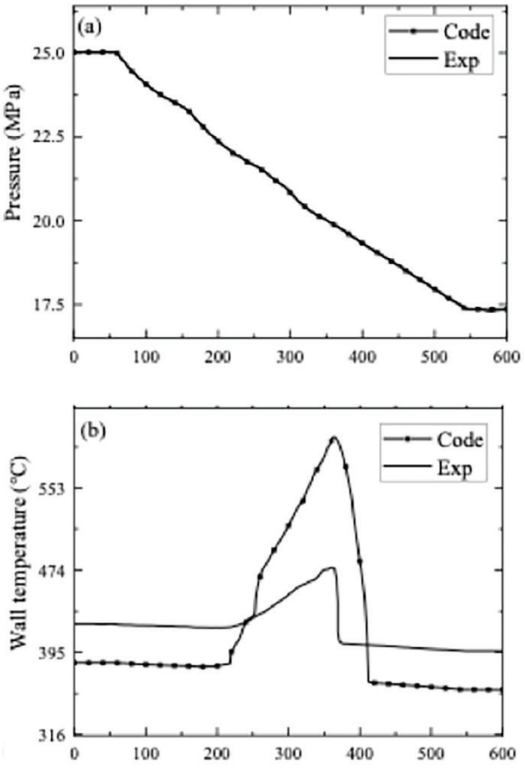
In parallel, XJTU (China) is upgrading and validating RELAP5 to enhance its supercritical capabilities, providing improved system-level modeling tools for transient analysis and safety assessments of SCWR concepts. The modifications to RELAP5 were developed with reference to the pseudo-boiling phenomenon in supercritical water and are grounded in the pseudo-two-phase theory of supercritical water. The updates to RELAP5 encompass one set of heat transfer coefficient logic for wall surfaces, as well as heat transfer models for both the high-pressure subcritical region and the supercritical region. The revised version of RELAP5 was validated through computational simulation of a hypothetical blowdown case and was further benchmarked against trans-critical transient experimental data from SJTU's 2×2 rod bundle tests (Li et al., 2017). The findings indicate that while the modified code is capable of modeling trans-critical processes, its predictive accuracy still requires enhancement through the development of more appropriate models (Figure SCWR-2).

The University of Wisconsin-Madison (United States) is conducting tests on 2×2 rod bundle configurations to quantify the effects of non-uniform axial heat flux distributions in supercritical water, providing essential data for validating subchannel codes and CFD models.

Research at NPIC has advanced the understanding of natural-circulation flow stability under supercritical conditions, which is crucial for assessing passive cooling strategies and start-up transients. Additionally, CAS is performing targeted experimental work to explore the integration of supercritical CO_2 cycles, assessing thermal-hydraulic coupling and potential improvements in overall plant efficiency.

In Europe, SURO and Centrum Výzkumu Řež, (CVŘEZ, Czechia) are jointly coordinating an international thermal-hydraulics benchmark focused on the start-up and shutdown transients of a supercritical-water loop (SCWL). This work aims to harmonize validation data sets and improve cross-code comparability (Ruscak et al., 2025).

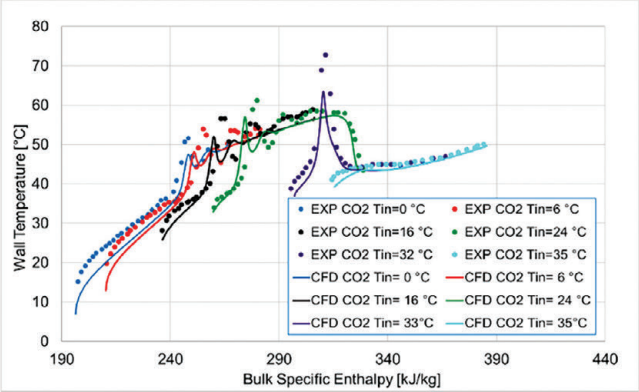
Figure SCWR-2: Comparison of wall temperatures between RELAP5 simulations and experimental data – Panel a: Boundary condition; Panel b: Wall temperature



Source: Wu Pan et al., 2025, XJTU Internal Report.

UNIPI (Italy) continues to work on fluid-to-fluid scaling methodologies, trying to propose a rationale to find equivalent operating and boundary conditions between different fluids at supercritical pressure. This is also the topic of a benchmark proposed in the frame of an IAEA CRP on supercritical water-cooled reactors. UNIPI is also comparing CFD predictions for pressure drops in supercritical water-cooled bundles, finding good match with available experimental data and correlations (Figure SCWR-3) (Kassem et al., 2025).

Figure SCRW-3: Comparison between CFD predictions and experimental data for a selected case by the Kline Database (CO_2)



Source: Kassem, S. et al. (2025).

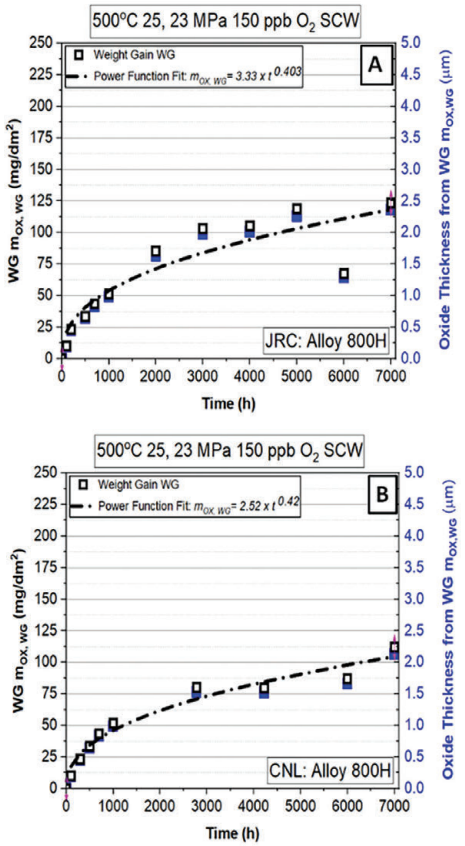
In the framework of the EU's ECC-SMART project, the Budapest University of Technology and Economics (BME) has performed a multi-scale safety and design assessment of the SCW-SMR concept. At the system level, analyses using the APROS code validated the feasibility of natural circulation and passive-heat removal during a long-term station blackout (SBO) and established safety margins for "large break loss of coolant accident" (LBLOCA) transients (Varju and Aszódi, 2025a; 2025b). These macro-scale findings are complemented by detailed CFD studies on fuel assembly sub-channels, which optimized heat transfer by evaluating the impact of wrapped wire spacers (Kiss and Adorján, 2025; Kiss and Kiss, 2025). Together, these contributions provide a comprehensive validation of the reactor's thermal-hydraulic performance, ranging from local core cooling efficiency to overall plant safety.

Technical highlights – Materials and chemistry project

Significant progress has been achieved in the evaluation of materials under supercritical water conditions. The corrosion behavior of approximately 700 specimens has been completed in the ECC-SMART project, enabling inter-laboratory comparison and the application of advanced analytical techniques to assess oxide morphology, internal oxidation, chromium depletion, and the correlation between descaling mass loss and net weight gain, which remains essential for long-term life prediction and material qualification (Khumsa-Ang et al., 2025).

The down-selection of candidate fuel cladding alloys continued with focused attention on alloy 800H, 310S and alumina-forming austenitic (AFA) alloys. Long-term exposures reaching up to 7 000 hours have produced consistent kinetic datasets (Figure SCWR-4), supporting both experimental observation and model-based predictions. Oxide growth modeling efforts were extended and improved, with current simulations predicting, for example, an end-of-life oxide thickness of approximately 27 micrometers (µm) at 550°C for alloy 800H, depending on environmental assumptions and exposure history.

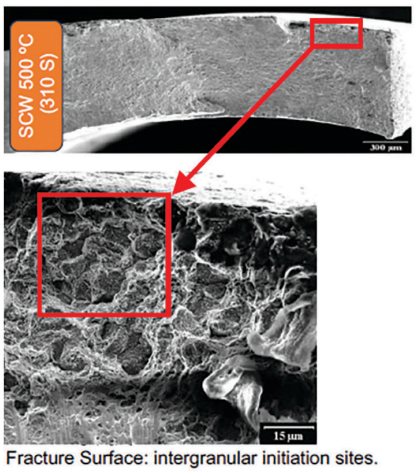
Figure SCWR-4: Results of long-term supercritical-water corrosion tests on alloy 800H from JRC (A) and CNL (B)



Source: ECC-SMART Deliverable D2.3, "Report Summarising the Results of the Out-of-Pile Corrosion Tests".

Mechanical performance evaluation has progressed through tensile testing at selected temperatures, as well as slow strain-rate tensile tests (SSRT) performed in supercritical water at 380°C and 500°C (Figure SCWR-5), with complementary reference tests in air at the same temperatures, supporting the definition of operational limits and informing structural integrity assessments. Figure SCWR-5 shows the fracture surface of the 310S candidate alloy under SSRT conditions. Oxidation studies were conducted on materials neutron-irradiated in the CVŘEZ facility up to 0.3 dpa, showing irradiation-induced changes in mechanical properties; however, no significant differences were observed in the oxide-layer characteristics compared with non-irradiated conditions.

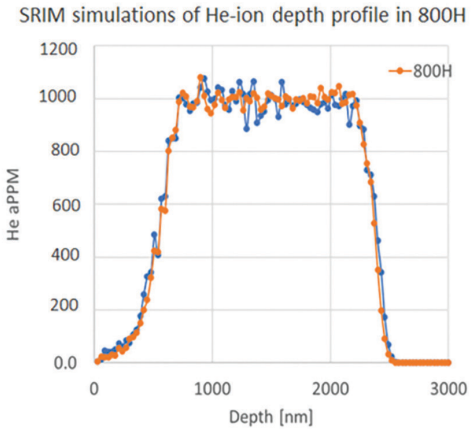
Figure SCWR-5: Fracture surface of steel 310S specimen exposed to supercritical water at 500°C, showing intergranular crack initiation areas

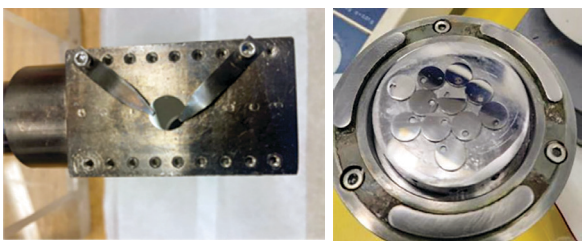


Source: ECC-SMART Deliverable D2.3, "Report Summarising the Results of the Out-of-Pile Corrosion Tests".

Further work performed by CNL includes SCW oxidation for 500 hours on helium-ion-implanted specimens of alloy 800H and 310S – conducted at room temperature and 450°C with implantation levels of 100, 500 and 1 000 appm – to investigate helium-induced effects relevant to fast-spectrum options (Figure SCWR-6). Additionally, a 500-hour SCW oxidation of welded specimens has been completed, with microstructural analysis currently underway to assess weld metal behavior and heat-affected zone susceptibility.

Figure SCWR-6: Representative images and key results from the helium-ion implantation process on alloy 800H and steel 310S





Source: Canadian Nuclear Laboratory.

Finally, preparations are in progress to initiate corrosion-product transport studies using refreshed-flow supercritical-water autoclaves with dedicated inserts, enabling investigation of dissolution, precipitation and downstream deposition mechanisms. Parallel feasibility studies are evaluating the potential to use the same SCW infrastructure for supercritical CO_2 testing to support future synergies with advanced Brayton-cycle reactor concepts.

Safety and licensing highlights and lessons learned (ECC-SMART)

The ECC-SMART project developed a comprehensive safety framework for the SCW-SMR concept by reviewing international safety principles (IAEA, Western European Nuclear Regulators' Association [WENRA], GIF) and relevant national regulatory approaches. From this analysis, the project identified the most important generic and design-specific safety criteria applicable to the conceptual reactor design, together with the key principles guiding its further development.

The safety-related features of the SCW-SMR were assessed by combining literature on SCWR, SMR and boiling water reactor (BWR) technologies with the technical findings from the project. Expert judgement on material, thermal-hydraulic and neutronic behavior was consolidated through a structured PIRT-type analysis, which highlighted the main phenomena, uncertainties and knowledge gaps influencing the safety demonstration of the concept.

A pre-licensing study established a methodology to relate safety requirements to the challenges specific to supercritical water technology. It clarified which safety aspects are already reasonably supported, which require additional research, and which may call for design adjustments. The study also outlined the codes and standards relevant for conceptual design, the analytical tools needed for safety assessment, and the experimental programs required to qualify materials and validate modeling approaches.

Complementary guidelines were developed to define the evidence needed at each development stage of the technology, including material property evaluation, applicability of analytical tools and the regulatory landscape that could shape potential licensing pathways in different countries. In addition, the Risk and Safety Working Group is in the process of developing Safety Design Criteria for fast neutron SCWR.

Lessons learned and recommendations

A key lesson from the SCWR system activities is the need for tighter integration between conceptual design activities and safety-related research. Early coordination among designers, analysts and experimental teams improves the identification of critical phenomena, accelerates the resolution of knowledge gaps and strengthens the overall safety case. The structured PIRT-based approach proved particularly valuable and should be retained in future international collaborations.

Challenges and strategic needs

The shift from large LWRs to non-water-cooled SMRs has disrupted the visibility and continuity of SCWR development. Classification frameworks that label certain SMR concepts as "advanced" have, in practice, sidelined water-cooled Gen IV options. To transition towards an industrial deployment pathway and to preserve momentum built over decades of international collaboration, the SCWR community is working to establish a robust and sustained support framework.



Alberto Sáez Maderuelo
Acting Chair of the SCWR SSC, with contributions from SCWR members

References

Kassem, S., A. Pucciarelli and W. Ambrosini (2025), "Modelling the influence of surface roughness on heat transfer at supercritical pressure", 11th International Symposium on Supercritical Water-Cooled Reactors (ISSCWR-11), Pisa, Italy, 3-5 February 2025, www.torrossa.com/en/resources/an/5914784.

Khumsa-Ang, K., et al. (2025), "A state-of-the-art review of R&D for the super critical water-cooled reactor technology - Part II Materials and Chemistry", submitted to *Nuclear Engineering and Design*.

Kiss, A. and L. Adorján (2025), "Comparison of CFD analysis results of horizontal flow in SCW-SMR fuel assembly with and without wrapped wire spacers", 11th International Symposium on Supercritical Water-Cooled Reactors (ISSCWR-11), Pisa, Italy, 3-5 February 2025, www.torrossa.com/fr/resources/an/5914843.

Kiss, A. and B. Kiss (2025), "Validation of CFD models of horizontal and vertical upward water flow in straight tubes under supercritical conditions", 11th International Symposium on Supercritical Water-Cooled Reactors (ISSCWR-11), Pisa, Italy, 3-5 February 2025.

Li, H. et al. (2017), "Experimental investigation on transient heat transfer in 2×2 bundle during depressurization from supercritical pressure", *Annals of Nuclear Energy*, Vol. 109, pp. 237-248, https://doi.org/10.1016/j.anucene.2017.05.023.

Nava Dominguez, A., C. Azih et al. (2025), "A state-of-the-art review of the supercritical water-cooled reactor technology part I economics, thermal-hydraulics, and safety and licensing", manuscript submitted for publication in Social Science Research Network, https://doi.org/10.2139/ssrn.5433539.

Nava Dominguez, A., X. Huang, X. et al. (2025), "Progress on a preconceptual supercritical water-cooled small modular reactor", *ASME Journal of Nuclear Engineering and Radiation Science*, Vol. 11(3), https://doi.org/10.1115/1.4068326.

Ruscak Musa, A. et al. (2025), "Introduction of benchmark specifications for supercritical water loop", 11th International Symposium on Supercritical Water-Cooled Reactors (ISSCWR-11), Pisa, Italy, 3-5 February 2025, https://digital.casalini.it/9791256081332.

Schulenberg, T. and I. Otic (2022), "Concept of a Small Modular SCWR With Horizontal Fuel Assemblies", *ASME Journal of Nuclear Engineering and Radiation Science*, Vol. 8(3): 031104.

Varju, T. and A. Aszódi (2025a), "Investigation of the passive heat removal from the SCW-SMR reactor core in the event of a long-term station blackout", *Nuclear Engineering and Design*, Vol. 444, Art. 114349, https://doi.org/10.1016/j.nucengdes.2025.114349.

Varju, T. and A. Aszódi (2025b), "Parameter analysis of the cold-leg LBLOCA initiating event of the SCW-SMR reactor concept", article under review, *Nuclear Engineering and Design*.

Wiltschko, F. and X. Cheng (2025a), "Experimental investigation of heat transfer to supercritical pressure fluid in tubes with rough inner surface", *ASME Journal of Heat and Mass Transfer*, Vol. 147(5), https://doi.org/10.1115/1.4067608.

Wiltschko, F., I. Otic and X. Cheng (2025b), "Prediction of the heat transfer to supercritical pressure fluid at rough surface", 11th International Symposium on Supercritical Water-Cooled Reactors (ISSCWR-11), Pisa, Italy, 3-5 February 2025, www.torrossa.com/en/resources/an/5914786.

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. Four technical projects have been established for GIF collaborations:

1. SFR system integration and assessment;
2. SFR safety and operations;
3. SFR advanced fuels;
4. SFR component design and balance of plant.

Main characteristics of the system

The SFR system uses liquid sodium as the reactor coolant, allowing high-power density with low coolant volume fraction. Because of the advantageous thermophysical properties of sodium (high boiling point, suitable heat capacity and very 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 in the framework of the Gen IV System Arrangement. Plant sizes ranging from small modular systems to large monolithic reactors are being considered.

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

Reactor parameters	Reference value
Core outlet temperature	500-550 °C (often close to 550 °C)
Pressure	~1 atmosphere
Power rating	30-5 000 MWt (10-2 000 MWe)
Fuel	Oxide, metal alloy and others
Cladding	Ferritic-martensitic, oxide dispersion-strengthened (ODS) and others
Average burnup	150 GWD/MTHM (Gigawatt-days per metric tonne heavy metal)
Breeding ratio	0.5-1.30

Three general classes of SFR design concepts have been identified for Gen IV SFR research collaboration: 1) loop configuration; 2) pool configuration; and 3) SMRs. Within this structure, several design tracks that vary in size, key features (e.g. fuel type) and safety approaches have been identified, with pre-conceptual design contributions by Gen IV SFR members. These are the Chinese SFR (CFR1200, China), the European SFR (ESFR, Euratom), the Japanese SFR (JSFR, Japan), Korea's advanced liquid metal reactor (KALIMER, Korea) and the US 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.

Industry engagement and near-term demonstrations

The SFR System Steering Committee (SFR SSC) hosted a panel session for SFR demonstrations at the Gen IV Small Reactors International Conference (G4SR-4) in October 2022 in Toronto, inviting 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, with some follow-up discussions with GIF subsequently taking place. 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 is now awaiting formal signature.

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, as well as the construction and commissioning 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), targeting a much lower cost per MWe compared to CFR-600. Based on metal-fuel and pyro-processing technologies, China is developing integral fast reactor systems with a capacity of 1 000-1 200 MWe (CNNC, 2024). CIAE, the designer of the project, has completed the preliminary design of the reactor, and the pilot equipment for pyro-processing and metal-fuel fabrication has been established, with samples of fuel pin and structure material produced, and awaiting irradiation test in the CFR-600.

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)[1] to further improve the European sodium fast reactor (ESFR) concept, which is a large pool-type SFR developed by 25 European partners within

1. https://esfr-smart.eu.

the Euratom CP-ESFR project (2009-2013). The ESFR-SIMPLE project aims to improve the safety of the European SFR through innovative monitoring, power level flexibility and experimental research (ESFR-SIMPLE, 2026). Current R&D activities include advanced designs, system optimization, use of AI for monitoring, SMR flexibility enhancement for grid requirements, advanced components for passive safety, and measurements on high porosity MOX fuels. In addition, the Sustainable Nuclear Energy Technology Platform (SNETP), through the European Sustainable Nuclear Industrial Initiative (ESNII),[2] supports Fast Reactor R&D coordination activities (SNETP, 2026).

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) (BPI France, 2022). Currently, 11 projects have been selected, with two led by new companies, HEXANA and OTRERA, to develop new reactors based on SFR technology. Beyond this, France's Nuclear Policy Council (CPN) marked a new strategic milestone for the future of nuclear energy in France by asking the major players (CEA, EDF, Orano and Framatome) to develop a joint strategy towards fuel cycle closure, including fast neutron reactors and associated facilities, by the end of 2025 (Sfen, 2025). The roadmap must specify technological choices, schedule, industrial organization and investment requirements.

In Japan, based on the Strategic Roadmap for Fast Reactor Development revised in 2022, the Fast Reactor Cycle System Project Management Office was established in JAEA in July 2024 and has initiated a conceptual design of the demonstration SFR until 2028. It is cooperating with Mitsubishi Heavy Industry, which was chosen as the core company for design, manufacturing and construction. Major design options are under investigation such as a fuel type (MOX or Metal), a seismic isolation system (2-dimensional isolation or 3-dimensional isolation), a containment concept (steel plate reinforced concrete structure or steel containment) and a spent fuel storage system (in-vessel storage or ex-vessel storage). Designs will be finalized in 2026.

In Korea, following the decision to put the Prototype Gen IV Sodium-cooled Fast Reactor (PGSFR) Program on hold, the SFR-based SMR SALUS-100 (Small, Advanced, Long-cycled and Ultimate Safe) finished its basic design in 2024. SALUS-100 is a pool-type SFR with an electric output of 100 MWe, operating on a 20-year refueling cycle utilizing metal fuel. It uses 10-U-Zr metal fuel. The values of U-235 enrichments are 9.0, 12.7 and 19.0 wt% for inner core fuels in the 0-3rd row, middle core fuels in 4-5th row and outer core fuels in 6th row, respectively. The design went through the IAEA Technical Safety Review (TSR): Design Safety service, and the final report was published in February 2025 (IAEA, 2025). In July 2025, the first public-private cooperative SFR project was launched with the aim of continuing the SALUS design up to licensing-ready level. KAERI is partnering with Hyundai Engineering & Construction (HDEC) and Korea Electric Power Corporation Engineering & Construction (KEPCO E&C) to develop an SFR for the specific market in Korea. Based on Korean SFR history and experience, the design and safety assessment will be expedited, resulting in a competitive and safe SFR-type SMR. The Preliminary Safety Analysis Report (PSAR) is expected to be ready in the early 2030s. Regulation in Korea is also moving forward and trying to align with industry. The Nuclear Safety and Security Commission (NSSC) has started to establish a roadmap for the licensing of non-LWR reactors and related works similar to that of the Licensing Modernization Project in the United States. By the mid-2030s, not only SFRs but also other Gen IV reactors, namely HTGR and MSR, are expected to be starting deployment.

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 Nuclear Regulatory Commission completed its final safety evaluation in December 2025 for the application submitted by TerraPower to build Kemmerer Power Station Unit 1 (Natrium design) in Kemmerer, Wyoming. The evaluation concludes that there are no safety aspects that would preclude issuing the construction permit (NRC, 2025). Natrium is a compact 840 MWt pool-type SFR that uses a molten salt energy storage system that enables the plant to vary its supply of energy to the grid by up to 500 MWe net for over 5.5 hours. The project is funded by a public-private partnership through the US DOE Advanced Reactor Demonstration Program (TerraPower, 2026). In addition, two other US SFR companies, Oklo and ARC Clean Technology (ARC, 2025), also have commercialization efforts underway. Both designs are based on metal alloy fuel and sodium coolant, and have the potential for recycling. In September 2025, Oklo held a groundbreaking ceremony at Idaho National Laboratory for its Aurora powerhouse SFR (Oklo, 2025a). It also had the Nuclear Safety Design Agreement for its fuel fabrication facility approved by US DOE in November 2025 (Oklo, 2025b).

2. https://snetp.eu/esnii.

Technical highlights – System integration and assessment project

Euratom has been conducting research to propose innovative mitigation features that enhance core-catcher integrity. As a first step, past core-catcher designs were reviewed. Based on this analysis, several innovative concepts were identified and new mitigation features were proposed that can be experimentally investigated. These measures aim to strengthen the beneficial "pool effect" that occurs when a corium jet impinges on the core catcher, which is a phenomenon observed in previous experiments and known to significantly slow down core-catcher ablation. From the perspective of preventing ablation, it is essential to consider both the behavior during corium jet formation and the long-term cooling phase after corium relocation to the core catcher. To reduce ablation during jet formation, the introduction of pods located directly beneath the transfer tubes has been proposed. The inclination, shape and surface roughness of the upper face of these pods are of primary interest as they govern the onset and intensity of the pool effect. Representative experimental tests are therefore planned to assess these parameters. Experiments are being conducted at the LAMETA laboratory to confirm which pod design provides the most effective protection. The introduction of pods may also affect long-term corium cooling by altering natural convection patterns, modifying heat transfer or promoting preferential crust formation. To investigate these effects, dedicated experiments are planned at KIT to evaluate the influence of cavity-type features. These tests will use a eutectic nitrate salt mixture of potassium nitrate (KNO_3) and sodium nitrate ($NaNO_3$), with a melting point of 220°C, serving both as a simulant melt and as a simulant material for the core-catcher bottom plate.

The CEA has designed ATRIUM, a 400 MWt SFR based on the CADOR (Core with Adding Doppler effect) concept, which enhances negative reactivity through the Doppler effect by loading moderator materials into the core. ATRIUM adopts Na/gas heat exchangers, ex-vessel passive decay heat removal systems (DHRS) and a tank with phase change material, which accomplishes the function of final heat sink. The CEA conducted a preliminary safety analysis by employing the CATHARE code for representative events such as unprotected loss of flow (ULOF), unprotected loss of heat sink (ULOHS), unprotected transient over power (UTOP) and station blackout (SBO), confirming that no fuel damage occurred in any of these cases. For instance, in case of UTOP analysis, an event with reactivity insertion (USD 4) to simulate the insertion of an sCO_2 gas bubble, which corresponds to a reactivity insertion of USD 3.3 within 80 milliseconds, was calculated. The simulation showed that the reactor returned to a steady state within 50 seconds due to the significant Doppler effect.

The JAEA has been developing its Advanced Reactor Knowledge and AI-aided Design Integration Approach (ARKADIA) through the whole plant life-cycle to build a capability of sophisticated optimization of entire plant design with state-of-the-art multi-scale simulations and accumulated knowledge on experiments, plant design, operation and decommissioning, to reduce the time and cost needed for design. ARKADIA consists of three major systems: 1) enhanced and AI-aided optimization system (ESA); 2) virtual plant life system (VLS); and knowledge management system (KMS). ARKADIA was applied to examples such as the optimization of reactor vessel wall thickness to thermal transient and seismic loads in manual shutdown, and the optimization of containment vessel volume regarding economy and safety factors. JAEA will continue to develop the ARKADIA system and expand its application to various design optimization cases.

KAERI contributed to the evaluation of uncertainty on physics parameters for a TRU metal-fuel core. In this study, values of uncertainty of multiplication factors of a design target core in transport-depletion calculations were evaluated by a nuclear data-driven (random sampling) approach and a bias trending approach. In the nuclear data-driven approach, values of uncertainty of multiplication factors at BOC (beginning of cycle) and EOC (end of cycle) were around 2 590 and 2 410 pcm,[3] respectively. These were evaluated by transport-depletion calculations using 250 sets of randomly sampled libraries. The analysis also shows that the impact of fission yield perturbation is negligible. In the bias trending approach, the uncertainty of the design core was evaluated based on the correlation between biases – defined as differences between measured values from critical experiments and corresponding analytical results – and coefficients, which quantify the similarity between each critical experiment and the design target core. In this analysis, values of uncertainty of the design target core at BOC and EOC based on the bias trend approach were 1 080 and 1 190 pcm, respectively. The uncertainty at EOC increases because most similarity coefficients are lower at EOC than at BOC. As a future plan, KAERI is planning to extend this approach to decay heat and radioactive source terms.

Technical highlights – Safety and operations project

The CIAE has been studying a 280 MWt loop-type SFR with a 0.5 GWh molten salt thermal energy storage (MSTES) system. As a part of this study, the CIAE conducted a preliminary safety analysis for an unintentional withdrawal of a control rod (CR) with a loss of off-site power and a single failure: a failure to open the damper of an air heat exchanger. When the increasing core power due to the withdrawal of the CR exceeded the neutron flux limit, a reactor scram was triggered within two seconds. It was confirmed that maximum cladding and coolant temperature in this scenario satisfied the criteria for allowable consequences.

3. Measure of reactivity by 0.001% ("Percent Mille" or "pour cent mille").

Euratom examined the effect of adding neutron absorber material to the ESFR-SMART core as a means to mitigate severe accidents. This should prevent the formation of a large, melted fuel pool, stop cyclic re-criticalities and avoid power excursions. Two main scenarios – passive shutdown rod insertion and dropping of boron materials from upper neutron shielding into a degraded core – were identified. The viability of the passive shutdown rod was studied with SIMMER-III. The results show that the passive shutdown rod insertion before the power peak, within 30 seconds after a ULOF onset, avoids a power excursion and the core melt down, even if only one rod is inserted. However, the analysis indicates that even the insertion of all 12 safety rods is not sufficient to avoid the core melt down 50 seconds after an ULOF onset. The assessments of the boron materials fall down from shielding concept evaluated with MCNP indicate that the proposed absorber structure has the potential to provide a mitigation provision in severe accident conditions.

Euratom conducted a benchmark exercise with fuel performance codes on nominal and transient conditions such as UTOP and ULOF scenarios for ESFR, Superphénix (SPX) and CAPRA fuel designs to evaluate MOX pin behavior during transients to guide design by using six codes: FRED (PSI), GERMINAL (CEA), OFFBEAT (EPFL), TRANSURANUS (ENEA), SIM-SFR (KIT) and FEMAXI (KIT). The pin behavior predicted by six codes will be compared for both types of transients.

France's CEA is improving SIRENa, a computer-based tool for reactor designer use and operator training, which was developed in 2010-2012. SIRENa, used in training courses by the CEA, provides a real-time simulation of reactor startup-shutdown, and normal and accidental operations. It is a "full-scale" training tool based on the Super-Phénix Power Plant and has a graphical user interface such as panels of reactor control, simulator control and loops control. CEA is planning to update SIRENa based on the French calculation code CATHARE-3 (Code for Analysis of Thermal-hydraulics during Accident and for Reactor safety Evaluation), allowing it to have enlarged capabilities, such as high-fidelity models and upgraded visualization tools, and with the possibility of being extended to other reactor designs.

The CEA has also been preparing SAIGA (Severe Accident In-pile experiments for Generation IV reactors and Astrid project) tests to study the efficiency of the Corium Transfer Tube (TT) in the SFR core in the case of ULOF. The test is a multi-assembly test consisting of two fuel bundles with different powers and one TT in the Impulse Graphite Reactor (IGR). This project is being implemented by NNC-RK (Kazakhstan) under specifications and support from CEA. All components for the test, such as sodium loop, and instrumentations, such as thermocouples, optical fibers, void sensos, Compton emission neutron detectors, fission chambers and dynamic pressure sensors, will be supplied to NNC for assembly and commissioning. Alongside the experiment preparation, safety analyses and administrative process will continue until the performance of the test, which has been postponed to 2027.

Japan's JAEA has been investigating post-buckling behavior under severe earthquake conditions, developing an effective evaluation methodology for measures to improve structural robustness in order to provide more realistic fragility data of vessels for seismic Probabilistic Risk Assessment analysis. The seismic failure of the components was based on the design limits, i.e. buckling for the reactor vessel. However, recent studies have shown that failure would more likely be caused by crack penetration due to cyclic fatigue. The present analysis, with a detailed three-dimensional structural analysis code FINAS/STAR using only a horizontal seismic wave, showed the axial compaction buckling of the reactor vessel. The fragility (median value) obtained from cumulative fatigue damage fraction based on the analysis in the present study is 1.1 times larger than the conventional value of fragility obtained using the design limit of buckling. The realistic consideration of post-buckling behavior is regarded as the measure for improving resilience. Using fragility, the effectiveness of the measures for improving resilience can be evaluated by quantifying the reduction of seismic core damage frequency. The seismic fragility evaluation method in this study can consider fatigue damage from both a main earthquake and afterquakes.

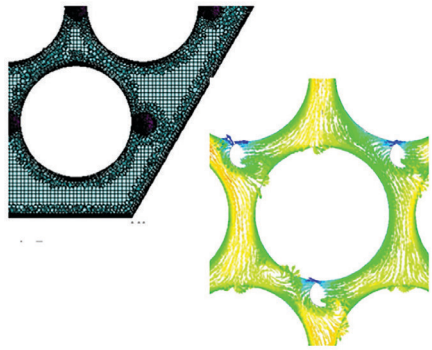
JAEA has also investigated an initiating phase of core disruptive accident (CDA) in a ULOF for a small-size SFR with MOX fuel with negative void reactivity coefficients by conducting sensitivity studies with the SAS4A code in order to examine the reactor safety characteristics during the CDA. The base-case analysis showed that the event progression is slow and mild as there is no significant positive reactivity insertion, and the total reactivity maintains a subcritical state during the initiating phase. The sensitivity studies indicate that the generation of mechanical energy during the initiating phase is less likely to occur compared to a large SFR. The studies confirm that validation of the cladding motion model is essential work for the future, because the cladding relocates significantly before the fuel relocation during the CDA, and its positive reactivity affects the event progression.

In Korea, KAERI has improved the numerical model for the system code MARS-LMR, which was developed to analyze two-train DHRS tests of LOHS simulation in the STELLA-2 facility (a large-scale sodium integral effect test facility). The improvements include a heat loss model added to the hot pool, more hydraulic losses on the DHRS loops (Na sides), and a detailed model for the helical-coil sodium-to-air heat exchanger (AHX) and finned-tube sodium-to-air heat exchanger (FHX) shell sides including air ducts. The new model has shown better transient results in terms of core temperature and flows, particularly in the early stages; however, it underpredicted after 1 400 seconds owing to a declining natural-circulation flow. KAERI has identified further model improvement possibilities such as additional discretization in the cold pool for higher spatial resolution and heat loss models through the sodium-to-sodium decay heat exchangers (DHXs) and DHRS loops.

The UK's National Nuclear Laboratory (UKNNL) has been working on the FAITH (Fuel Assemblies Incorporating Thermal Hydraulics) project, with the

ultimate aim of designing and building a modular sodium test facility for thermal-hydraulics analysis. Under this project, two test rigs were planned to be designed and constructed to represent a fast reactor fuel assembly for thermal-hydraulic model validation, specifically for CFD calculations (Figure SFR-1). The first rig, an isothermal water-based facility with the initial test section based on a PRISM fast reactor wire-wrapped tube bundle, was designed and installed during the first phase of project in 2019-2021, and has been continuing to operate and generate results. Concerning the sodium-based rig for a future phase, rig scaling (e.g. dimensionless groups such as Reynolds number), instrumentation and challenges such as the specific requirements for sodium rig operation were examined among stakeholders. Case studies were also performed for the test section, with both water and sodium as the working fluids. The sodium cases are essentially "blind" calculations for any future CFD validation for a sodium system, should the project attract future funding.

Figure SFR-1: Water rig mesh and velocity vectors



Source: Ward (2020).

Technical highlights – Advanced fuels project

CIAE has conducted ion irradiation experiments on oxide dispersion-strengthened (ODS) alloys and ODS tubes. ODS alloy samples were irradiated by Fe ion beams at high temperature up to 100 dpa for studying the irradiation stability of Y-Ti-O nano enhanced phase. Crystallographic structures of nano-oxide particles in the irradiated samples were characterized, and the evolution of particle size, distribution and composition of nano-oxides were statistically analyzed. The effect of ion irradiation on mechanical properties of ODS tubes were observed by nanoindentation and other technical means. The data of irradiation swelling and nano hardness before and after irradiation were compared to analyze the influence of dislocation density, nano-oxide particles and number of holes in heavy-ion irradiated ODS tubes. These data contribute to elucidating the mechanism of irradiation swelling.

CEA has conducted a study to quantify the uncertainties in the SFR MOX fuel melting margin evaluation (Dupont et al., 2024). The important parameters are geometrical defects on fuel pellet (Figure SFR-2), irradiation conditions and fuel behavior laws. CEA assessed melting probability by three different approaches: 1) analytical method; 2) Monte Carlo simulation; and 3) FORM/SORM reliability method. The melting probability of 1.9×10^{-6} was obtained using the Monte Carlo simulation with millions of calculations. The SORM method provided values close to the Monte Carlo results while reducing the number of calculations (about 500). Therefore, it can be recommended as a method for melting probability analysis.

CEA has also investigated hardness changes and their mechanisms during the manufacturing of an Fe-14Cr ODS cladding tube by analyzing hardness and microstructural indicators from samples taken at each production stage (Salliot et al., 2024). The measured microstructural indicators included the volume fraction of nano-oxides, grain size, crystallographic texture, geometrically necessary dislocation (GND) density by Electron Backscatter Diffraction (EBSD), and statistically stored dislocation (SSD) by X-ray diffraction (XRD). These new insights show that the sole factor contributing to hardness reduction during heat treatment is the SSD density, as the GND density remains stable during this process.

CEA has studied the effect of phase transformation on the grain growth of nano-oxide particles in ferritic/martensitic (F/M) ODS steels (Spartacus et al., 2024). Martensitic steels are characterized by a more isotropic grain structure than ferritic ODS steels, but they exhibit lower corrosion resistance and poorer manufacturability. Therefore, CEA attempted to monitor the time-dependent change in the average radius of nano-oxides by performing continuous in-situ Small Angle X-ray Scattering (SAXS) measurements during heat treatment. The observed average radius of nano-oxides in Fe-9Cr (F/M) after phase transformation was larger than that in Fe-14Cr (ferritic) ODS steel. It was also confirmed that the average radius in Fe-9Cr before transformation was similar to that observed in Fe-14Cr. This study experimentally demonstrated that phase transformation affects the growth of nano-oxide particles.

JAEA has measured the chemical diffusion coefficients of oxygen by controlling the oxygen/metal ratio (O/M) of fast reactor MOX during manufacturing. The reduction of MOX is diffusion-controlled, which enables the measurement of the oxygen chemical diffusion coefficient $D_o^{\sim}$. JAEA has conducted thermogravimetric analysis (TGA) of 30% plutonium (Pu)-MOX samples with various initial O/M ratios in isothermal conditions at 1 773 K, 1 873 K and 1 923 K under a flow of gas with controlled oxidation potential (Ar/4.5% H_2+ H_2O), extending into a range of non-stoichiometry (from 2.000 to 1.948) that had never been studied before. JAEA plans to investigate the evolution of the O/M ratio throughout the entire sintering heat treatment process, including cooling, and to develop a model to predict the final O/M ratio of MOX from the geometry and sintering conditions.

To understand the effects of fission products (FPs) on properties of irradiated MOX fuel, JAEA has conducted a systematic study on properties such as thermal conductivity, thermal expansion, oxygen

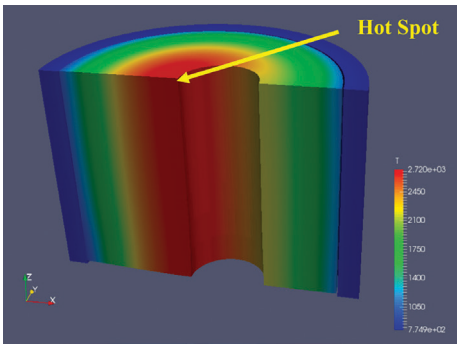
potential and mechanical properties of MOX fuel doped with simulated FP with high fission yields such as Zr, Nd, Ce, Ba, La and Sm.[4] Measurements were conducted on samples containing 10% of each respective FP oxide. The obtained data enhanced the reliability and accuracy of existing property models. JAEA will continue these measurements and plans to investigate the effects of FPs on the O/M ratio as a future study.

KAERI has been developing an SFR-based innovative long fuel cycle core concept with an electrical output of 100 MWe, SALUS-100, which is a spin-off design from its PGSFR concept. It will employ its FC92 cladding and Cr barrier to prevent fuel cladding chemical interaction (FCCI) for SALUS's U-10Zr fuels. To ensure fuel rod integrity, KAERI conducted a preliminary performance evaluation and confirmed that the design criteria are satisfied under normal operating conditions in terms of maximum fuel centerline temperature, cladding strain (less than 1%) and cumulative damage fraction (CDF) (less than 0.05).

In order to mitigate FCCI, KAERI has been studying the Cr barrier coating technology for the inner surface of cladding tubes by employing pulse-reverse current electroplating with hexavalent chromium (Cr^{6+}). To address environmental concerns and the toxicity of Cr^{6+}, it initiated the development of a trivalent chromium (Cr^{3+}) plating process, which involves a more complex solution formulation and is more challenging to control cracks within the chromium coating. KAERI has successfully developed a precipitate-free solution through various trials and is currently optimizing the plating process parameters using Hull-cell tests.

KAERI has also been developing a liner crucible and a coated crucible to improve the yield of the nuclear fuel manufacturing process by using the new $NdYO_3$ (neodymium-yttrium) material. Prototype crucibles with a diameter of 30 mm and a capacity of 20~30 cm^3 were manufactured employing slip-casting at 1 500 to 1 600°C using powders with a molar ratio of Nd_2O_3 and Y_2O_3, varying from 6:4 to 3:7 based on the test results of the previous year. The characterization results showed that dense sintered bodies were obtained with almost no pores at 1 550°C and 1 600°C in 50/50 to 40/60 molar ratio compositions. Prototypes of $NdYO_3$ plasma-coated graphite crucibles were also manufactured with Nd/Y molar ratios of 50/50, 45/55 and 40/60. SEM analysis results revealed a good continuous, crack-free coating layer with its deposited thickness within the range of 250±30 µm. A reaction test of this coated crucible with U-10Zr-5RE melt at 1 470°C for 10 minutes was conducted. An Energy Dispersive X-ray Spectroscopy (EDS) analysis of a sample of the test showed no RE (rare earth) penetration into the graphite crucible, with the coating layer remaining intact.

Figure SFR-2: Effect of central hole off-centering on fuel temperature distribution



Source: Dupont et al. (2024).

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

CEA is working on ultrasound methods for inspecting complex structures (such as nuclear reactors), because ultrasound can propagate through both liquids and steel elements to be inspected. Leaky Lamb waves have been extensively researched to detect damages in plate-shaped structures, which are waves that reemit bulk waves towards the surrounding fluid. An imaging method based on the time reversal of Lamb waves has been applied in preliminary work to detect the edge of a single immersed plate and a machined notch. In this study, the frequency domain topological energy method is applied to a set of two parallel immersed plates to succeed in accurately localizing defects represented by the edges of the plates. The Fast Topological Imaging Method (FTIM), which allows for faster computations with less data storage, is applied to the case of Lamb waves in a set of parallel plates. Lamb modes can be used to improve analysis of the images obtained. An original methodology is proposed based on spots (maxima) analysis for interpreting the results of this topological energy and identifying the edges of the two plates. In addition, it was shown that the choice of mode according to its attenuation allows different inspections to be carried out: a low attenuation mode allows the first plate to be probed, while a high attenuation mode allows the second plate to be probed. A moderately attenuated mode allows both plates to be seen. This process could be similarly applied to other scattering defects in ultrasound non-destructive testing of plates.

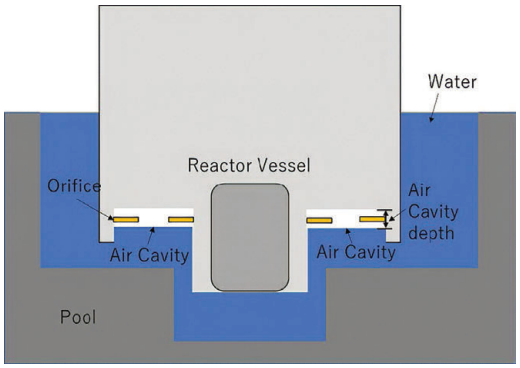
Within the framework of the dismantling of SFRs in France (Phénix, SPX and Rapsodie), several processes are under investigation regarding sodium cleaning and disposal. One is based on the implementation of the sodium-water reaction, in a controlled and progressive way, to remove residual sodium, mainly from the cold traps in the sodium purification systems. This system contains, after draining, residual sodium and trapped impurities such as sodium oxide (Na_2O), and sodium hydride (NaH) with traces of tritium (NaT). The hydrolysis of these various chemical

4. Zr (zirconium), Nd (neodymium), Ce (cerium), Ba (barium), La (lanthanum) and Sm (samarium).

species leads to the production of a liquid effluent, mainly composed of an aqueous solution of sodium hydroxide, and a gaseous effluent, mainly composed of nitrogen (inert gas), hydrogen and steam. The tritium is distributed among these effluents. Within the gaseous effluent, it is expected to be released only in the form of HT. However, according to some experimental data gathered from tritiated sodium hydrolysis operations, a non-negligible amount of tritium is released in the off-gas as HTO (up to more than 90% of the tritium found in the gaseous effluent). Given that HTO is 10 000 times more radiotoxic than HT, precise knowledge of the mechanisms governing the phase distribution of tritium is necessary to estimate the tritium distribution. The process needs to be designed to optimize the treatment of the off-gas before its release into the environment. In order to develop a numerical model able to predict the chemical composition of each effluent, a phenomenological description of the hydrolysis of residual sodium performed in active cleaning vessel conditions has been proposed. To validate some of the hypotheses made in this phenomenological description, a series of experiments has been performed in a laboratory-scale hydrolysis process designed at CEA Cadarache during Chassery's Ph.D. thesis (Chassery et al., 2015). The experimental device consists of a two-liter cylindrical glass reactor into which small quantities of sodium containing tritium were hydrolyzed by water injected drop by drop. The thesis presents the different experimental techniques implemented in tests and their qualification to ensure the quality of experimental results.

CEA investigated the mixing process of sodium-water reaction in the small-scale configuration of 1-4 g sodium pellets with excess water in a closed vessel, using time-resolved video, optical, pressure and temperature acquisition. The results show that sodium vaporization is involved in the reaction and generated in great quantity during a runaway. However, it appears from temperature measurements that the boiling temperature is not at all or only locally reached in the sodium before runaway. It is therefore possible that reactant mixing occurs in the gas phase if an intensification of sodium vaporization takes place as a fast local transient. The possibility of reactant mixing in liquid phase is not contradicted by these results but was not identified from the available videos and data.

Figure SFR-3: Concept of FSIS-paired SMR



Source: Mori et al. (2023).

JAEA has investigated the Floating Seismic Isolation System (FSIS), which is a unique seismic isolation technology designed to enhance the site availability of SMRs (Figure SFR-3, Mori et al., 2023). FSIS achieves three-dimensional seismic isolation by equipping air cavities and orifices at the bottom of a floating structure, which is installed in a man-made pool. The FSIS extends the vertical natural period of the floating structure by reducing bulk modulus, which contributes to suppressing the pressure wave propagation, through air cavities. Additionally, orifices embedded in the FSIS cavities throttle airflow provide a damping effect that reduces seismic response peaks at the structure's natural frequency. The JAEA is also conducting vibration tests to understand the seismic isolation effect of a floating seismic isolation building with air cavities and orifices by vertical seismic motion.

KAERI has been developing a plate-type ultrasonic waveguide sensor array for viewing under sodium. In 2025, performance tests were conducted on several specimens containing adjacent slit defects of various widths, depths and gap distances in silicone oil at a high temperature of 150oC. The widths and depths of slits, and the gaps between adjacent slits in the specimens, were all in the range of 0.5-2.0 mm. The results showed that all adjacent slits were successfully detected and distinguished using the prototype waveguide sensor array under high-temperature conditions. Even in the specimen containing two slits that were each 0.5 mm wide and separated by a 0.5 mm gap, both defects were well detected and resolved. The slit and gap dimensions observed in the C-scan images showed good agreement with the actual dimensions. However, unwanted ghost images, caused by the ultrasonic beam width and the structural characteristics of the sensor array, were also observed. Therefore, KAERI is planning to conduct a follow-up study to eliminate these ghost images.

KAERI has been studying the applicability of induction bending to the P91 pipes of the SFR. Traditionally, the piping system has been manufactured by welding straight pipes and elbow pipes, but this method results in a large number of weld joints. Such weld joints are prone to sodium leakage due to the high probability of manufacturing defects, residual stresses and stress corrosion cracking. Unlike the conventional method, applying induction bending, which manufactures straight pipes and curved pipes as an integral body, can enhance the integrity of the piping by minimizing the number of welds. The first attempt to fabricate an induction-bent pipe with a large diameter-to-thickness ratio D/t (outer diameter 559 mm, thickness 12.7 mm, D/t = 44) for the SFR was successfully conducted. Post-fabrication inspections, including visual examination and magnetic particle testing, confirmed that all dimensional requirements such as thickness, ovality, bend radius, bend angle and wall buckling complied with ASME Sec. III, Div. 1. Using specimens taken from the manufactured pipe, tensile tests (room temperature, 350°C and 550°C), impact tests and hardness tests were conducted, and it was confirmed that all tests

met the specified ASME requirements. These results confirm the applicability of induction bending to P91 piping in SFRs, contributing to weld reduction, enhanced safety and improved economics. KAERI is planning to conduct further studies on the high-temperature fatigue and creep properties of P91 bent pipes manufactured by induction bending.



Yoshitaka Chikazawa
Chair of the SFR SSC,
with contributions from SFR members

References

ARC (2025), Homepage, ARC Clean Technology, www.arc-cleantech.com (accessed 3 April 2026).

Bangor University (2023), "Learning from the past, to power up the future - ARUP, NNL and Bangor University collaborate on AMR knowledge capture project", www.bangor.ac.uk/news/2023-07-19-learning-from-the-past-to-power-up-the-future-arup-nnl-and-bangor-university.

BPI France (2022), "Appel à projets « Réacteurs nucléaires innovants »" [Call for Proposals: Innovative Nuclear Reactors], www.bpifrance.fr/nos-appels-a-projets-concours/appel-a-projets-reacteurs-nucleaires-innovants.

Chassery, A. et al. (2015), "Experimental study of the tritium distribution in the effluents resulting from the sodium hydrolysis." *Fusion Science and Technology*, Tenth International Conference on Tritium Science and Technology, 67 (2), pp. 300-303.

CNNC (2024), "The Integrated Fast Reactor Innovation Alliance was officially established" (In Chinese), China National Nuclear Corporati, www.cnnc.com.cn/cnnc/xwzx65/ttyw01/1459312/index.html.

Dupont, V. et al. (2024), "Thermal design criteria computation using various statistical approaches – application to a SFR fuel element", *Nuclear Engineering and Design*, Vol. 428, Art. 113520, https://doi.org/10.1016/j.nucengdes.2024.113520.

ESFR-SIMPLE (2026), Homepage, http://esfr-simple.eu (accessed 3 April 2026).

IAEA (2025), *Technical Safety Review NSNI/TSR/DS/2024/002F (Restricted)*, International Atomic Energy Agency.

Mori. T. et. al. (2023). "Experiment of Floating Seismic Isolation System," ASME 2023 Pressure Vessels & Piping Conference, 16-21 July 2023, Atlanta, GA, USA, PVP2023-102224.

NRC (2025), "NRC Completes Safety Review of Construction Permit Application for Kemmerer Power Station in Wyoming", Nuclear Regulatory Commission, www.nrc.gov/sites/default/files/cdn/doc-collection-news/2025/25-063.pdf.

Oklo (2025a), "Oklo Breaks Ground on First Aurora Powerhouse", https://oklo.com/newsroom/news-details/2025/Oklo-Breaks-Ground-on-First-Aurora-Powerhouse/default.aspx.

Oklo (2025b), "Oklo Announces U.S. Department of Energy Approval for Nuclear Safety Design Agreement of Aurora Fuel Fabrication Faciltiy", https://oklo.com/newsroom/news-details/2025/Oklo-Announces-U-S--Department-of-Energy-Approval-for-Nuclear-Safety-Design-Agreement-of-Aurora-Fuel-Fabrication-Facility/default.aspx.

Salliot, F. et al. (2024), "On dislocation hardening in a new manufacturing route of Ferritic ODS Fe-14Cr cladding tube", *Materials*, Vol. 17(5): 1146, https://doi.org/10.3390/ma17051146.

Sfen (2025), "EPR2, back end of the future, cycle closure... the nuclear policy council speeds up", Sfen in Engligh, https://sfeninenglish.org/epr2-fuel-cycle-nuclear-energy-france.

SNETP (2026), Homepage, The Sustainable Nuclear Energy Technology Platform, https://snetp.eu (accessed 3 April 2026).

Spartacus, G. et al. (2024), "Precipitation kinetics of ferritic/martensitic oxide dispersion strengthened steels: Influence of the matrix phase transformation", *Acta Materialia*, Vol. 280, Art. 120328. https://doi.org/10.1016/j.actamat.2024.120328.

TerraPower (2026), "Frequently Asked Questions", www.terrapower.com/faq (accessed 3 April 2026).

Ward C, (2020), "CFD Analysis of Sodium Rig", FNC 61303-50892R, December 2020.

WNN (2021), "Chinese fast reactor begins high-power operation", *World Nuclear News*, 19 February, www.world-nuclear-news.org/Articles/Chinese-fast-reactor-begins-high-power-operation.

WNN (2020), "China starts building second CFR-600 fast reactor", *World Nuclear News*, 29 December, https://world-nuclear-news.org/Articles/China-starts-building-second-CFR-600-fast-reactor.

Very high-temperature reactor

With a new FA in 2025, the System Arrangement (SA) for Gen IV international R&D collaboration on the very high-temperature reactor (VHTR) is renewing signatories. The current signatories are France, Japan, Switzerland and the United Kingdom, but Australia, Canada, China, Euratom, Korea and the United States are expected to sign shortly. The VHTR System Research Plan outlines four active projects with the following members and observers (the observers are temporary while awaiting signature of FA and SA by their respective countries):

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

VHTRs contribute to GIF's goals, as high core outlet temperatures enable high efficiencies for power conversion and hydrogen production, as well as cogeneration of high steam qualities (superheated or supercritical), and can be used as an energy carrier and/or as feedstock for chemical reactions. 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.

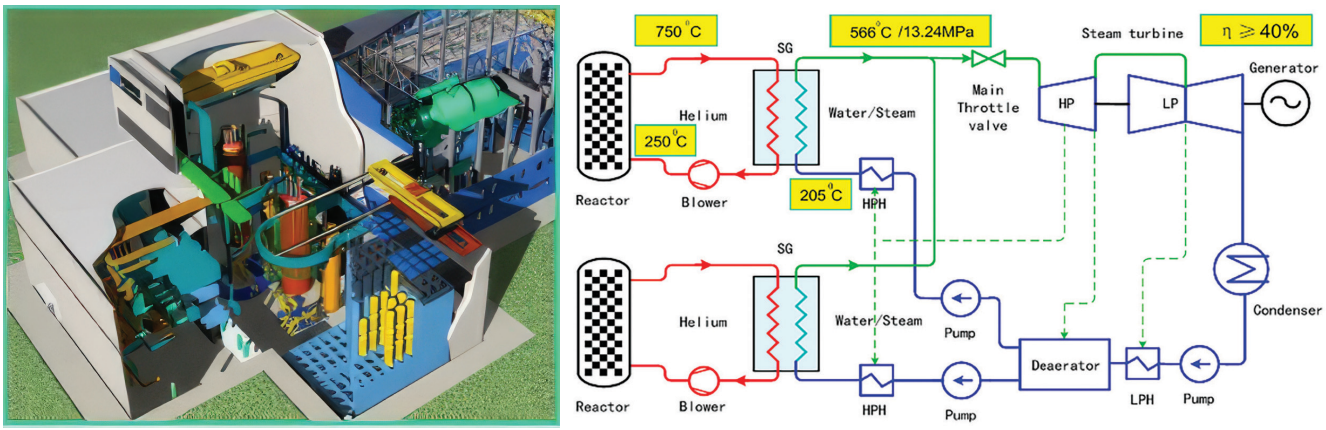
In terms of GIF VHTR SSC collaboration activities in 2025, the GIF Risk and Safety Working Group (RSWG) and the Proliferation Resistance and Physical Protection Working Group (PRPPWG) are working on a joint study on Safety, Security and Safeguards by Design ("3S"). This joint study utilizes a generic pebble-bed HTGR model developed by the US DOE. (A high temperature gas-cooled reactor [HTGR] is a near-term version of the VHTR with more accessible operating temperatures up to 950°C avoiding the need for completely new structural materials.) Hosted by the Education and Training Working Group, past VHTR SSC Chair Gerhard Strydom presented a webinar in 2025 entitled "Overview and update of the VHTR Activities" (GIF, 2025).

Main characteristics of the system

The operational envelope of HTGRs can be adapted to specific end-user needs, and there is a significant near-term market 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 thermal gigawatt days per metric ton of heavy metal [GWtd/tHM]), high efficiency and modular construction are all advantages favoring commercial HTGR deployment.

The HTGR standard fuel form is based on UO_2 TRISO-coated particles (UO_2 kernel, buffer/inner pyrocarbon/silicon carbide/outer pyrocarbon coatings) embedded in a graphite matrix, which is then formed either into 6 cm diameter pebbles or cylindrical compacts of various geometries embedded in hexagonal fuel blocks. This fuel form exhibits confirmed temperature tolerance up to 1 600°C in accident situations, with sufficient safety margin. Recent research has shown that safety performance may be further enhanced through using uranium oxycarbide (UCO) as the fuel kernel, and potentially other modifications such as zirconium carbide (ZrC) instead of silicon carbide (SiC), or the replacement of the graphite matrix material with SiC. These options are subject to ongoing R&D.

Figure VHTR-1: Cut-away view of the HTR-PM reactor building and schematic of power conversion system



Source: Image courtesy of Tsinghua University/INET.

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 carried out internationally on TRISO and graphite waste processing, in particular to reduce waste volumes that would be expensive to store.

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) (Figure VHTR-1) entered commercial operation in late 2023. A demonstration utilizing heat from this reactor was connected to a local heating grid in March 2024 (WNN, 2024). Since then, the project has achieved additional milestones, including a 100-hour continuous operation test, delivery of district heating to the local community, completion of the first maintenance outage and restart thereafter.

Significant progress has also been made on follow-on commercial concepts, including HTR-PM600, HTR-PM600S and HTR-PM1000, which have targeted the cogeneration of steam and electricity, and (for the largest concept) fossil plant replacement applications, as well as exploring avenues for cost reduction. China National Nuclear Corporation (CNNC) plans to build two 1 208 MWe (net) Hualong One units and one 660 MWe HTGR unit at the site in Lianyungang, Jiangsu province (Figure VHTR-2) (WNN, 2025).

Japan's High-Temperature Engineering Test Reactor (HTTR) was restarted in 2021 after a decade of shutdown following the Great East Japan Earthquake in 2011. Building on the earlier simulated loss-of-coolant/forced-cooling tests, Japan's current emphasis is the HTTR heat application test, which aims to establish a safety design for coupling an HTGR with a hydrogen production plant, specifically for the delivery of process steam for steam-methane reforming. These activities support Japan's longer-term plans for an HTGR demonstration reactor for hydrogen production and industrial heat applications in the 2030s.

The UK continues HTGR-relevant R&D and collaboration, including coated particle fuel development with JAEA and ongoing technical contributions across VHTR materials areas. However, the UK's government-backed AMR (HTGR-focused) demonstration program ended in December 2025, with no further UK government funding expected, and the UK is moving towards a pathway for privately led advanced nuclear technologies.

France's HTGR activity remains part of the broader France 2030 SMR/advanced reactor landscape, under which the French government is supporting multiple start-ups with diverse reactor concepts, with CEA guiding R&D developments. Jimmy Energy is working on a 15 MWt prismatic HTGR microreactor designed to operate at high temperatures, and Blue Capsule is advancing a compact 150 MWt TRISO-fueled HTGR with sodium as a heat carrier to provide industrial heat at 700°C.

Figure VHTR-2: Plans for CNNC's LWR+HTGR cogeneration plant in Lianyungang, Jiangsu



Source: Nuclear Engineering International (2025).

Poland's HTGR-POLA program (30 MW) has completed its basic design, and the intention now is to demonstrate multiple cogeneration applications. In addition, JAEA has noted ongoing involvement in Poland's basic design work, explicitly positioning HTGR-POLA to demonstrate the replacement of fossil-based steam in chemical plants with HTGR-supplied heat.

Canada's Micro Modular Reactor (MMR) demonstration at the Chalk River campus continues to be positioned as a demonstration for remote and industrial applications, targeting operation in the 2030s. A key development is that Nano Nuclear Energy purchased the MMR (KRONOS) reactor intellectual property (IP) and associated demonstration projects from discontinued Ultra Safe Nuclear Corporation (USNC). In parallel, Canada is advancing enabling conditions for microreactor deployment through a National Microreactor Framework and has launched an AECL/CNL Request for Expression of Interest (RFEOI) to gauge market interest in licensing historic small reactor concepts for commercialization.

The US DOE continues to support several advanced reactor test and demonstration activities relevant to HTGRs and microreactors. DOE-supported efforts include X-energy's plan to deploy Xe-100 units at Dow's facility in Texas, plus the continued development of microreactor demonstrations planned for INL's NRIC-DOME (Demonstration of Microreactor Experiments) test bed. DOE reported that most front-end engineering design (FEED) work was completed with USNC for DOME, and that a new FEED effort with Antares has been initiated. In August 2025, X-energy, Amazon, Korea Hydro & Nuclear Power and Doosan Enerbility signed a strategic collaboration agreement to accelerate Xe-100 deployment, alongside plans for Maryland-based test capabilities, including a full-scale helium test facility (HTF), an experimental test facility (XTF) and a full-scale plant control room simulator. In August, DOE also announced a new pathway for DOE-authorized test reactors via the Nuclear Reactor Pilot Program (NRPP), selecting 10 companies, including Radiant Industries (HTGR) and Valar Atomics (HTGR). DOE also highlighted HALEU/fuel enablement actions, including the Fuel Line Pilot Program (June 2025) to accelerate fuel fabrication for new test reactors.

Technical highlights – Fuel and fuel cycle project

The VHTR Fuel and Fuel Cycle (FFC) Project Management Board (PMB) meeting was held on 14-15 October 2025 in Busan, Korea. The PMB welcomed the UK representative as a new member of the VHTR FFC Project Arrangement (PA), and the representative from Canada as an observer, as they were in the process of becoming a member. Canada became an official member in mid-December 2025.

The FFC project is intended to provide the demonstrated solutions for VHTR fuel (design, fabrication and qualification) and 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 ZrC coating for enhanced burnup capability, minimized fission product release and increased resistance to core heat-up accidents (above 1600°C). Such higher fuel performance would enable a core with higher power density and thus smaller volume, helping to cut costs.

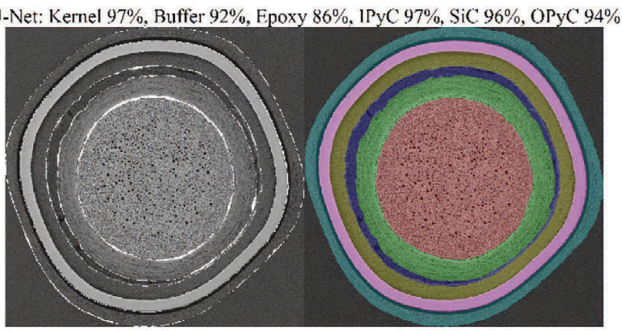
Fuel characterization work, post-irradiation examinations (PIE), high-temperature safety testing, fission product release evaluation, and the measurement of chemical and thermomechanical material properties in representative conditions will continue to feed a fuel performance database. Further development 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, previous national and international projects have confirmed the potential for deep-burn of plutonium and minor actinides in a VHTR, as well as the use of thorium-based fuels. These options continue to be considered as a longer-term evolution towards closed and symbiotic fuel cycles.

2025 highlights

Several members are performing PIE and safety testing of irradiated TRISO fuel. The United States has continued the examination of compacts and coated particles from the AGR-5/6/7 fuel qualification irradiation experiments. Currently the image analysis (Figure VHTR-3) is in progress to process hundreds of individual particle cross sections using AI/machine learning methods to automate the analysis of particle morphologies for assessment of buffer and IPyC fracture behavior, coating layer separation and high-temperature kernel migration behavior.

Figure VHTR-3: Example of the use of AI/ML methods to automate analysis of irradiated particle morphologies



Note: The colors on the right image show the regions identified by the model as the various components of the particle (kernel, buffer, coating layers, etc.). The data at the top of the image represent the Intersection of Union values, a metric indicating the accuracy of the model in identifying the various regions in the image.

Source: Cai et al. (2026).

China has performed deconsolidation and burnup analysis on pebbles discharged from the HTR-10 reactor. A microanalysis of fuel particles from HTR-10 pebbles and from pebbles previously irradiated in the HFR-EU1 experiment was completed, and the final summary report is in progress. High-temperature heating tests of HTR-10 fuel were conducted by JRC Karlsruhe, measuring the fractional release of fission products such as Cs-134, Cs-137 and Kr-85 at temperatures up to 1 780°C.

The development of new post-irradiation fuel heating test capabilities is in progress in China and the United States. The new KÜFA furnace has been installed and calibration completed; the first fuel was heated at 1 620°C for 150 hours, and Cs release was measured using several cold plates. The United States has continued to develop the Air Moisture Ingress Experiment (AMIX) 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 April 2026. AGR-3/4 PIE and heating tests have been completed, with current efforts focused on data analysis to refine fission product transport parameters for graphite and fuel matrix; the final PIE report will be prepared in 2026.

Japan's JAEA conducted air oxidation tests at temperatures up to 1 400°C using irradiated HTTR fuel compacts, sharing the results afterwards. The conditions for the oxidation test were established based on the HTTR accident analysis results and SiC layer failure rate; the oxidation test was measured using the acid leaching method. The results confirmed that the fuel maintained its integrity and there was no significant increase in SiC layer failure rate. In the future, JAEA will share the results of the inspections examining the effects of air oxidation.

The development of advanced TRISO fuel particles is being pursued by several PMB members. Korea launched a new basic research project on nuclear fuel for advanced microreactors in January 2025, focusing on lab-scale UCO kernel fabrication technology by internal gelation and the establishment of related equipment and processes. KAERI has made progress in internal sol-gel process development, preliminary experiments for UCO kernel fabrication, and optimization of carbon dispersion and heat treatment conditions for zirconium-cobalt (ZrCO) formation. Research also includes the microstructure analysis of matrix graphite powder and the achievement of target particle sizes through jet milling. China has already manufactured approximately 1.36 million fuel elements with 8.5% enrichment for HTR-PM, and construction of a new manufacturing line with larger capacity is underway.

France's CEA is planning to share the results of the earlier PYCASSO irradiation tests in the HFR Petten among PMB members for further collaboration activities and is transferring PYCASSO particles to Oxford University and Canadian Nuclear Laboratories for post-irradiation examination.

Technical highlights – Hydrogen production project

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

In 2025, the Hydrogen Production PMB approved a new Project Plan, formalizing research collaboration details until 2028 and including additional focus on the hybrid-sulphur hydrogen production process and research related to generalized hydrogen production coupling technologies. Research has continued to focus on scaling high-temperature steam electrolysis (HTSE) and advancing stack efficiency, materials research and pilot-scale demonstrations. New tasks were also added to the Project Plan to address emerging priorities, including research activities on ceramic proton exchange membranes, CO_2 co-electrolysis and market assessments for end-user engagement.

Canada's CNL expanded research on HTSE and CO_2 co-electrolysis for hydrogen and syngas production, including the preparation and testing of solid-oxide electrolysis cells (SOEC). In 2025, CNL developed in-house capabilities for fabricating and characterizing both oxygen and proton-conducting SOECs, with a focus on optimizing performance through material and component testing. The ongoing pilot demonstration in Canada to assess the feasibility of producing synthetic diesel from biomass-derived hydrogen using clean electricity was advanced, with infrastructure and policy considerations being addressed. CNL is also exploring co-electrolysis to produce synthetic gas in partnership with industry and is moving forward with a kilowatt-scale demonstrator.

In China, research details were shared on scaling up the hybrid-sulphur (HyS) process, and progress has continued to develop an Iodine-Sulphur/HyS demonstration plan under the leadership of Institute of Nuclear and New Energy Technology (INET) at Tsinghua University. Recent milestones include the successful operation of the integrated lab-scale facility and the development of prototype components for sulfuric and hydriodic acid decomposition. Safety analyses have also been conducted to address hydrogen leakage concerns, with strategies proposed to mitigate risks. As a provisional member of the HP PMB, INET has been an active and productive partner in advancing hydrogen production research collaboration.

In 2025, Euratom completed three very relevant nuclear hydrogen production and energy system integration projects: NPHyCo, TANDEM, and GEMINI 4.0. Public information from these projects has been shared with the VHTR HP PMB and with the NECA WG:

Figure VHTR-4: The world's first high-temperature electrolyzer (HTE) system in multi-megawatt-scale at a renewable products refinery



Source: Technology | HySelect.

1. NPHyCo (www.nphyco.org): This project assumed a large LWR as the power source for large-scale bulk hydrogen production using alkaline electrolysis. It assessed the feasibility of producing hydrogen near an existing nuclear power plant, as well as the added value of such a project. Potential locations for a pilot project were identified.
2. TANDEM (https://tandemproject.eu): The focus of this project was the integration of LW SMR in future hybrid energy systems (Vaglio-Gaudard et al., 2026).
3. GEMINI 4.0 (https://gemini-initiative.com/gemini-4-0): This project successfully demonstrated the safety and feasibility of HTRs for the cogeneration of process heat and electricity for industrial applications. It builds on the experience and knowledge of the previous GEMINI+ project and involves partners from Europe, Japan and Korea. Specifically for H_2 production, flowsheets to couple a conventional HTGR with HTSE were developed and completed with a techno-economic analysis.

In Europe, there is also a significant body of research related to hydrogen production organized in part through the Clean Hydrogen Partnerships, which aims to support research and innovation activities to make hydrogen generation from renewable energy sources competitive. Activity in Europe includes the CONVEY project, which aims to establish a hydrogen ecosystem in Northern Jutland, Denmark; the HySelect project, which focuses on solar-powered hybrid thermochemical cycles for efficient water splitting (HySelect, 2026); and the MULTIPLHY project (Figure VHTR-4), which involves the installation of a high-temperature electrolyzer at a biofuels refinery in Rotterdam, demonstrating the EU's capacities in SOEC technology. The EU's updated hydrogen strategy calls for improved enforcement of legislation, infrastructure development and public funding to foster early adoption and to reduce risk for first movers in the hydrogen sector.

CEA has achieved progress in HTSE technology, which is demonstrated by its success in experimental testing and the development of HTSE cells and systems, with efforts to harmonize testing protocols. The CEA is focused on scaling up HTSE processes and enhancing the durability of new cell generations. The CEA collaborates internationally to accelerate test protocols and methodologies.

JAEA has continued to demonstrate leadership in hydrogen production with its HTTR, and efforts in Japan are underway to establish safe coupling technology between HTGRs and hydrogen production facilities using steam-methane reforming, with a target to achieve this by 2030. Compared to more advanced hydrogen production technologies, steam methane reforming is not free of CO_2 emissions,

but it is a relatively simple and proven way to integrate nuclear steam into the process, thus saving about 30% of the natural gas input and related emissions. An HTGR demonstration reactor development project is also being developed and supported by METI in Japan, with Mitsubishi Heavy Industries selected as the core company for development. The project is advancing to basic and detailed design, followed by safety reviews and construction, with operation expected in the late 2030s.

In Korea, a nuclear-powered low-temperature electrolysis demonstration project is beginning in Ulsan, which aims to establish a 10 MW hydrogen plant by 2028 to support the Uljin Nuclear Hydrogen National Industrial Complex. SOEC systems are also being developed in the kilowatt-scale. KAERI has expanded experiments with its helium loop to demonstrate high-temperature steam electrolysis as part of an institutional research project starting in 2027.

In 2025, the United Kingdom officially became a full member of the HP PMB after transitioning from observer status. The UK is also actively engaging end users to explore the integration of nuclear energy into industrial processes. The UK is expected to publish an updated H_2 strategy to fast-track hydrogen development. The first Hydrogen Allocation Round is progressing, with projects expected to become operational by 2028, supported by government and private investment. While no specific nuclear projects are currently part of the hydrogen funding, there is potential for nuclear-enabled hydrogen.

The United States is progressing with integrating nuclear energy systems for hydrogen production, primarily through the Light Water Reactor Sustainability Program and the DOE's Integrated Energy Systems Program, which has advanced nuclear e-fuels catalyst screening and performance verification. Testing capabilities that support research on high-temperature hydrogen production include the DETAIL Dynamic Energy Transport and Integration Laboratory, and the Energy Technology Proving Ground.

The HP PMB continues to engage observers from GIF member countries that are pursuing hydrogen-related research. In 2025, the HP PMB engaged researchers from Switzerland to share ongoing activities on hydrogen production being pursued through the ETH Zurich and PSI's Energy System Integration (ESI) platform.

Finally, VHTR HP PMB members have supported analysis led by the NECA Working Group within GIF to evaluate the technical and economic viability of coupling Gen IV systems with HTSE.

Technical highlights – Materials project

The VHTR Materials Project Arrangement (MPA) continues working within the new GIF FA that entered into force on 1 March 2025. The third amendment of the MPA became effective on 3 January 2024. Materials PMB members have been focusing on further updating the new Project Plan 2024-2028. At the 33rd Materials PMB meeting, held on 8-10 September 2025 in Busan, Korea, the last revision of the Project Plan was reviewed and the next actions for its completion were identified.

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. The Generation IV Materials Handbook, which is a comprehensive materials database, is utilized for sharing R&D contributions by all signatories. The database efficiently stores and manages materials data, facilitates international R&D coordination, and supports modeling to predict lifetime damage assessment. It contains a variety of data for structural materials such as metals, graphite, ceramics and composites. The Materials Handbook is intended to support modeling to predict damage lifetime assessment and contains a variety of data for structural materials such as metals, graphite, ceramics and composites that involve various activities including materials selection, component design, stress analysis and code development. More information on the database is available at www.gen-4.org/resources/gif-tools-and-databases/generation-iv-materials-handbook).

By the end of 2025, the Materials Handbook had received over 560 technical reports and numerous materials test records. A total of 561 technical reports, including 22 multi-signatory high-level deliverables and 539 individual signatory reports have been uploaded, as well as over 40 000 supporting items of data. The high-quality data and remarkable expertise of the database is increasingly attracting attention from industry representatives, and, as a result, the previously agreed-upon process for gaining access to the new Materials Handbook, including the definition of third party, was discussed in-depth at the September PMB, with a new process agreed to by the Materials PMB. The Materials Handbook is in the process of being moved from Oak Ridge National Lab to Idaho National Lab.

In 2025, the Materials project's research focus remained on near- and medium-term projects, with an 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.

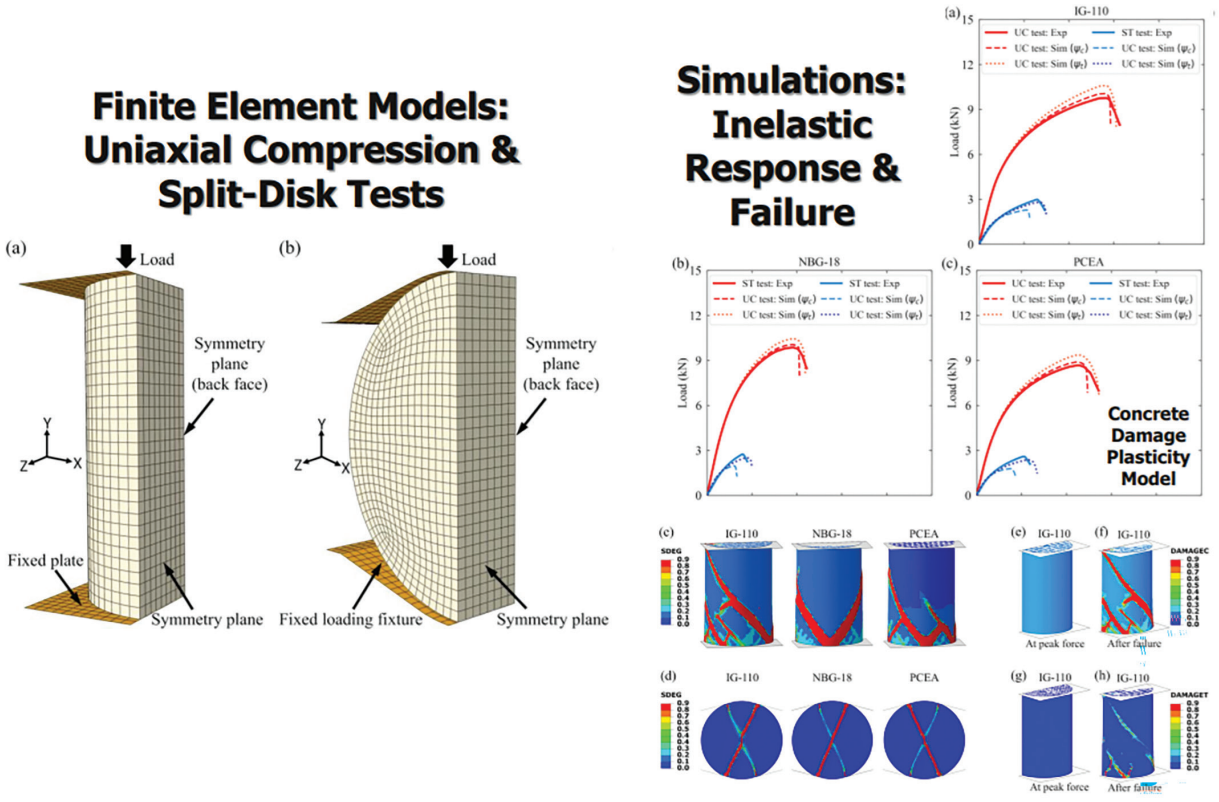
The Graphite Working Group (GWG) has made significant progress in advancing the understanding and application of graphite materials. The group has examined the properties of virgin graphite, including its oxidation, irradiation and creep behavior, with Canada, China and the United States leading the working group on graphite materials. Canada has contributed to the analysis and understanding of graphite oxidation behavior and the effect of oxidation on materials properties. The United States is continuing an experimental program on graphite irradiation-induced creep of graphite, as well as developing graphite codes and standards. It is also, together with Australia, pursuing experimental and numerical studies on graphite behavior, see Figure VHTR-5.

The GWG 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 finite element models (FEM) uniaxial compression and split-disk tests, and the results of a simulation of inelastic response and failure for three INL graphite grades (IG-110, NGB-18, PCEA). The numerical results showed that the CDP material model successfully predicted the inelastic and fracture behavior of nuclear graphite grades subjected to compression and tension loadings.

In the field of metals and design methods, the Metals Working Group (MWG), led by the United Kingdom, is focusing on conducting high-temperature creep, fatigue and creep-fatigue tests for implementation in ASME codes. The United States has continued to conduct a set of code case testing for tensile, creep rupture, fatigue and creep fatigue on alloy 709. The newly developed Class B Code Case, which uses a simplified design-by-analysis approach and includes creep-fatigue design checks, is currently being balloted by ASME Code Committees, with universal constitutive models for Class A materials (Type 316 SS, alloy 617 and Grade 91). A similar model format is under development for alloy 800H, Type 304 SS and alloy 709. Canada continues its collaboration with the United States and Australia on alloy 709, with different heat treatment, mini-tensile small punch tests on alloy 800H weldments, and alloy 709 low cycle fatigue (LCF) test and characterizations. In experimental work, Australia started collaboration with the United Kingdom on the characterization of

Figure VHTR-5: Graphite inelastic response and failure



Source: Irman et al. (2025).

various grades of SA508 steel with and without heat treatments through small-scale testing (tensile, small punch, compact tension). Australia is also pursuing collaboration with the United States on the assessment of various heat treatment procedures on microstructure and mechanical properties and in numerical modeling by developing various models using FEM and extended finite element method (XFEM) in the MOOSE software package. This includes fracture mechanics models, semi-empirical and microstructure-informed material models for predicting tensile, fatigue and high-temperature creep behavior in nuclear structural alloys (617, SA508); for predicting constituent phases, distortion and residual stresses in nuclear weldments.

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 and characterization methods. For example, Switzerland is pushing the fundamental understanding of the additive manufacturing process of composite components, such as combining steel and tungsten, by observing the local process zone operando and optimizing parameters accordingly. 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).

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 benchmarking, code-to-code comparisons and the use of diverse data sources. These data come from operating experience of existing HTGRs – for example the HTTR, HTR-10 and HTR-PM (Figure VHTR-6), historical data from past HTGRs, including 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 HTTF. Successful validation helps to reduce unnecessary design conservatism, refine cost estimates, enhance safety margins, and facilitate licensing assessments by providing robust and validated tools.

In 2025, Canada became a member of the CMVB project, supporting this work through the Canadian Federal Nuclear Science and Technology Work Plan. CNL supports the PMB through the development of best practice guidelines for CFD modeling, participation in hot gas mixing benchmarks and the preparation of validation data from the Helium-Air Natural Convection (HANC) experiment for inclusion in the CMVB validation matrix. Canada has also advanced coupled code simulations using STAR-CCM+ and ARIANT, and is pursuing advanced neutronics tools such as GRIFFIN to support multiphysics analyses

At China's INET, the development of a state-of-the-art HTGR design software package continued in 2025. The reactor physics code PANGU was improved with advanced resonance methods (Hou et al., 2026) and was used to simulate the HTR-PM operation history from December 2021 to April 2024 (Zhang et al. 2025). The alpha version of the 3D system analysis code DAYU-3D (Zhang et al. 2026) was developed, which shows great superiority in calculation efficiency over the legacy code. The HTR-PM criticality benchmark was prepared and is ready for release to CMVB members. The first maintenance outage of HTR-PM was conducted between 1 September and 12 December 2024. As of 30 November 2025, HTR-PM had reached 324 days of grid-connected operation and 595 million kilowatt-hours of total power generation. The Preliminary Safety Analysis Report the HTR-PM600S has been submitted for review. The data of INET's hot gas mixing experiment was submitted as benchmark for CMVB. The operational data of the Reactor Cavity Cooling System (RCCS) of HTR-10 is being prepared and will also be submitted as a benchmark for CMVB. CFD simulation for the air-cooled RCCS experimental facility and bypass flow experiments are ongoing.

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



Source: Tsinghua University.

In Japan, JAEA completed the HTTR safety demonstration test in 2024 to confirm that during 100% reactor power operation, and under the condition of restricted control rods insertion, the reactor power of the HTTR naturally decreases and remains stable, even after a loss of forced cooling. JAEA is advancing plans to perform various tests, including a heat application test, which will involve coupling the HTTR and a hydrogen production plant.

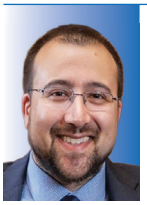
In Korea, R&D aims to improve design code development and the evaluation of key technologies for very high-temperature systems. The McCARD code has implemented functions to design a shield for the

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 EU, the Horizon Europe Framework Program project GEMINI 4.0 (GEMINI For Zero Emission) was completed in the summer of 2025. The focus areas were optimization of safety and competitiveness, decarbonization of industry, fuel and fuel cycle, licensing readiness and socio-economic impact. The GEMINI HTGR design was improved to consolidate the safety case for a polygeneration layout, while addressing 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.

In 2025, the United Kingdom became a member of the CMVB project and is working to support the project by leveraging its AMR program. The United Kingdom plans to contribute expertise in HTGR modeling, system modeling and benchmarking, and is exploring mechanisms to support technical contributions.

The United States continued to advance the CMVB project through experimental and modeling efforts. The NSTF completed a series of tests to assess natural-circulation performance. Work on the NEA benchmark using the HTTF data also progressed, with RELAP5-3D showing improved agreement for steady-state and transient conditions after refinements. The DOE has also invested in enhancing advanced software tools for HTGR analysis and is working to validate capabilities with experimental data. Collaborative efforts with Japan have focused on leveraging HTTR operational data to refine thermal-hydraulic models. Within the GIF CMVB framework, US contributions included finalizing the burnup analysis benchmark, validating lower plenum hot gas mixing models and supporting air-cooled RCCS model validation using University of Wisconsin-Madison experimental data (Okyay et al., 2025).



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

References

Cai et al. (2026), "RU-net for automatic characterization of TRISO fuel cross sections", *Materials Characterization*, Volume 232, https://doi.org/10.1016/j.matchar.2026.116019.

GIF (2025), "Education and Training Series #98: Overview and Update of the GIF VHTR Activities", Generation IV International Forum, www.gen-4.org/resources/webinars/education-and-training-series-98-overview-and-update-gif-vhtr-activities.

Hou et al. (2026), "Improvement of HTGR lattice physics calculation based on advanced subgroup method", *Annals of Nuclear Energy*, Art. 231:112193.

HySelect (2026), Homepage, www.hyselect.eu (accessed 5 April 2026).

Irman, K. et al. (2025), "Inelastic and fracture behaviour of nuclear graphite", *International Journal of Mechanical Sciences*, Vol. 296, Art. 110339, https://doi.org/10.1016/j.ijmecsci.2025.110339.

Nuclear Engineering International (2025), "CNNC launches heat-led nuclear project in Jiangsu", www.neimagazine.com/news/cnnc-launches-heat-led-nuclear-project-in-jiangsu.

Okyay, S. et al. (2025), "High-fidelity forced convection simulations of the University of Wisconsin-Madison air-cooled reactor cavity cooling system", *Nuclear Engineering and Design*, Vol. 445.

Vaglio-Gaudard et al. (2026), "Integrating nuclear Small Modular Reactors into low-carbon energy systems: an illustration using a recent European R&D initiative", *Sustainable Energy Technologies and Assessments*, Vol. 86, Art. 104787.

WNN (2025), "Contract awarded for parts of novel Chinese nuclear project" World Nuclear News, 11 September 2025, www.world-nuclear-news.org/articles/contract-awarded-for-parts-of-novel-chinese-nuclear-project.

WNN (2024), "HTR-PM heating project commissioned", World Nuclear News, 2 April 2024, www.world-nuclear-news.org/articles/htr-pm-heating-project-commissioned.

Zhang, H. J. et al. (2026), "DAYU3D: a modern code for HTGR thermal-hydraulic design and accident analysis [J]", *Nuclear Science and Techniques*, Vol. 37, No. 75, pp. 1-16.

Zhang, Z, et al. (2025), Simulation of the HTR-PM's operation history using the PANGU code, *Progress in Nuclear Energy*, 2025, 189:105883.

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 cross-cutting technologies that have the potential to impact multiple Gen IV reactor technologies.

The group undertakes activities in four topical areas:

1. A regular industry-focused survey on advanced manufacturing applications designed to gauge current sentiment towards advanced materials and manufacturing technologies. The results of this survey enable the AMME WG to focus on the most relevant manufacturing techniques and materials.
2. Development of a forum for sharing, coordinating and demonstrating work on the qualification of advanced materials and manufacturing techniques.
3. Undertaking activities and projects to promote the qualification of advanced manufactured systems, components, and structures through innovative use of modeling and simulation.
4. Undertaking activities and projects to promote the qualification of advanced manufacturing systems, components and structures, through innovative testing and monitoring techniques.

The AMME WG engages with industry stakeholders via the industry survey and the participation of industry observer members. The AMME WG also closely engages with the IAEA, both through IAEA observers, and joint meetings and workshops (see activities under Task 2).

2025 accomplishments

Task 1: Industry survey

The working group repeats the industry survey every other year. This year was an off year, with the new survey distributed in November 2025. The working group will collect and analyze the results in early 2026, reporting to the Expert Group in April.

Task 2: Information sharing

A focused survey on the global industry's current state of qualification projects and activities was conducted, with a report drafted and due to be issued in 2026. Twenty-two responses were received from industries in Canada, France, Italy, Japan, Switzerland, the United Kingdom and the United States, as well as from JRC. The survey revealed the diversity of material types and manufacturing processes for numerous reactor types currently undertaken, although very limited information was provided on accelerated qual-

Figure AMME-1: GIF AMME WG members at TMS2025's Industry Panel



ification methodologies. The qualification of additive manufacturing though laser powder bed fusion and direct energy deposition is still the main interest for qualification activities. Standard tests remain fundamental for the qualification of components and data management needs were highlighted as investment requirements. As this survey did not result in increased knowledge of the detailed qualification methodologies used in each country, AMME WG members have been tasked with undertaking directed industry outreach to gain more details in 2026.

More than seven industry and stakeholder outreach presentations were actively pursued, with highlights as follows: 1) the GIF Education and Training Series Webinar #100: "Advanced Manufacturing supporting Gen IV reactor systems" on 15 April 2025; 2) the technical workshop: "Nondestructive Evaluation of Advanced Manufacturing Components" on 29-30 April 2025 at Pacific Northwest National Laboratory (PNNL) (United States); 3) invited presentation at CONNECT-NM, 1st Annual Plenary Meeting on 9-10 September 2025 in Bratislava (Slovak Republic) (virtual); and 4) a dedicated industry panel and perspective at the TMS2025 international conference: "Current Innovation and Opportunities for Additive Manufacturing" (Figure AMME-1) (Ivan et al., 2025a and 2025b; Messner, 2025; Van Rooyen, 2025a, 2025b, 2025c and 2025d; Van Rooyen and Dutta Ray, 2025).

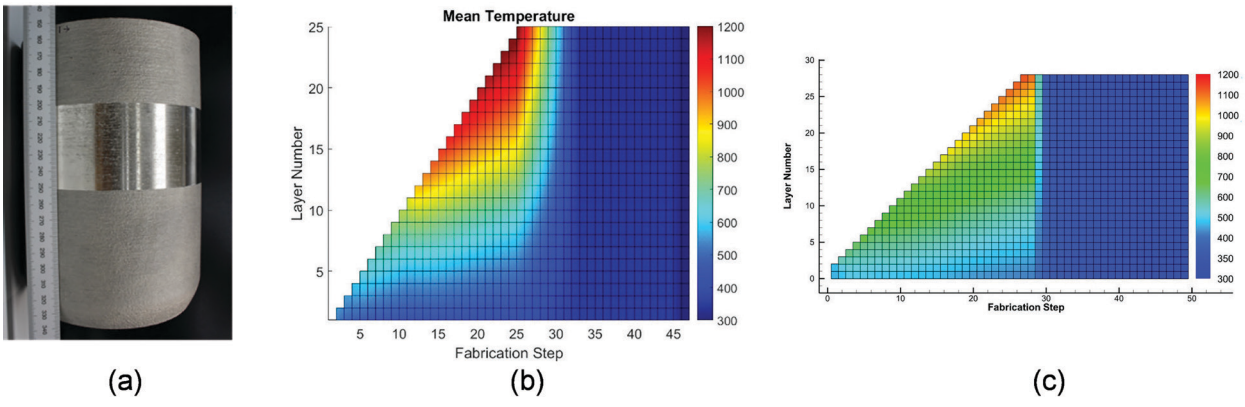
Task 3: Modeling and simulation (M&S)

Despite a variety of M&S software packages and methods proposed, the standard practice for qualifying advanced manufacturing (AM) parts does not view M&S approaches as an essential and integral part of the qualification process. This could be attributed to absent or limited validation benchmarks to demonstrate the potential of M&S tools to generate critical data, as well as a general lack of established good practices for their utilization. Therefore, key questions are yet to be addressed about what constitutes a cost-effective M&S approach that provides the appropriate level of modeling fidelity and complexity at an acceptable computational cost to ensure accurate, well-understood AM builds and repeatable components. The overarching goal of this work is to establish a comprehensive database of simulation tools that, when combined with validated benchmark studies, will enable the selection of appropriate M&S approaches for nuclear qualification and provide a set of good practice guidelines for their utilization.

To enable the wider adoption of M&S approaches for qualification, a database for industry users has been developed by the AMME WG to identify well-suited computational methods and software tools for predicting the thermomechanical history and residual mechanical properties of components made by advanced manufacturing technologies according to several features, such as manufacturing processes, prediction property and code availability. To support the qualification process, additional effort is necessary to demonstrate the benefits of the identified M&S tools based on benchmark problems and to clearly establish their modeling requirements. The work carried out in 2025 made concrete progress towards this goal by evaluating a benchmark case based on an experimentally fabricated part.

As an initial step in demonstrating the value of M&S tools for accelerating qualification, the as-built properties (i.e. temperature distribution, residual stress and warping) of a geometry-agnostic 316 stainless steel (SS) component have been predicted using two physics-based approaches for the direct-energy-deposition (DED) fabrication process (Figure AMME-2). The analysis of the results revealed consistent trends between the two approaches in the predicted transient temperature profile during the DED fabrication. However, differences of about 50 K to 100 K could also be observed, which were attributed as being likely due to differences in the deposition rates exhibited in the two approaches. These findings were published and presented at a workshop (Ivan et al., 2025a).

Figure AMME-2: Benchmark for DED fabrication



(a) the as-printed components fabricated by PNNL; (b) and (c) two of the round robin model predictions for the temperature field during fabrication.

Source: (Ivan et al., 2025a), see references.

Task 4: Testing and monitoring

Task members developed a benchmark project based on a range of components from various 316 stainless steel materials compositions, detailing a comprehensive characterization comparative matrix. In early stages, this benchmark progressed significantly during 2025 by printing a 316H DED cylinder in addition to a 316L printed cylinder (Figure AMME-2), as well as a laser powder bed fusion manufactured 316H extended elbow part. These activities will be expanded during 2026 with joint publications.

Members of the AMME WG participated in industry efforts to align codes and standards for applying advanced manufacturing to nuclear components. The working group followed an effort in France to modify RCC-M to include the L-PBF, WAAM, LMD and Hot Isostatic Pressing (HIP) manufacturing processes (submitted by EDF and Framatome), as well as US DOE efforts to qualify the L-PBF manufacturing process to Section III, Division 5 of the ASME Boiler & Pressure Vessel Code. A collaborative industry effort in Canada is in progress to print and qualify nuclear valve and advanced heat exchanger components. The working group also participated in a joint benchmarking effort related to the procurement and characterization of 316 powders for DED manufacturing.



Mark Messner
Co-Chair of the AMME-WG



Isabella van Rooyen
Co-Chair of the AMME-WG, with contributions from AMME members

References

Ivan, L. et al. (2025a), "A case study assessment of qualification acceleration informed by physics-based modelling", OECD/NEA Workshop on Regulatory Frameworks and Technical Approaches for Qualification and Through-Life Performance of Materials in Advanced Reactors, 3-5 June 2025; Rockville, Maryland, www.gen-4.org/gif/upload/docs/application/vnd.ms-powerpoint/2025-12/wrffqualif_june2025.pptx.

Ivan, L. et al. (2025b), *A case study assessment of qualification acceleration informed by physics-based modelling*, Generation IV International Forum, Paris, www.gen-4.org/gif/upload/docs/application/msword/2025-12/wrffqualif_2025_ivanetal_paper.docx.

Messner, M. (2025), "GIF AMME Working Group Report", 53 GIF EG/PG meetings, 7-11 April 2025, Baden, Switzerland, www.gen-4.org/gif/upload/docs/application/pdf/2025-12/gif_amme_report_--_april_2025_mark_messner.pdf.

Van Rooyen, I. (2025a), "GIF AMME Working Group: Advanced Manufacturing Benchmarks through International Collaboration", Proceedings of the OECD/NEA 7th International Workshop on Structural Materials for Innovative Nuclear Systems (SMINS-7), 31 March to 3 April 2025, Madrid, Spain, www.gen-4.org/gif/upload/docs/application/pdf/2025-12/gif_amme_wg__smins__spain_march_31_2025__i.van_rooyen.pdf.

Van Rooyen, I. (2025b), "Advanced Manufacturing Supporting Gen IV Reactor Systems", GIF Webinar, 15 April 2025, www.gen-4.org/resources/webinars/education-and-training-series-100-advanced-manufacturing-supporting-gen-iv.

Van Rooyen, I. (2025c), "Advanced Manufacturing & Materials Engineering (AMME) Working Group Collaboration", CONNECT-NM, 1st Annual Plenary Meeting, 9-10 September 2025; Bratislava, Slovak Republic (virtual), www.gen-4.org/gif/upload/docs/application/pdf/2025-12/connect-nm_amme_overview_final.pdf.

Van Rooyen, I. (2025d) "GIF AMME Working Group Report", 54th GIF EG/PG meetings; 13-17 October 2025, Busan, Korea, www.gen-4.org/gif/upload/docs/application/pdf/2025-12/gif_amme_october_2025_feedback_final_oct_14_2025.pdf.

Van Rooyen, I. and A. Dutta Ray (2025), "GIF-IAEA Advanced Manufacturing Collaboration", 19th GIF-IAEA Interface Consultancy Meeting, 26-27 June 2025; IAEA, Vienna, Austria (virtual), www.gen-4.org/gif/upload/docs/application/pdf/2025-12/19th_gif-iaea_interface_consultancy_meeting_final.pdf.

Economic Modeling Working Group

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

- the lifecycle 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 Gen 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 publicly available through the GIF Technical Secretariat. Subsequent publications have demonstrated EMWG methodology for 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 non-financial 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 financing challenges and how the impact of the way in which projects are established can considerably influence their financing.

Also 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 has been completing a thorough review to identify and implement the updates required.





Figure EMWG-1: 2024 Special Gen IV Financing Workshop

In conjunction with the fall 2024 Experts Group and Policy Group meetings in London, the EMWG has held a special Gen IV financing workshop (Figure EMWG-1).

EMWG activities in 2025

During the biannual meetings of the EMWG, plans were discussed and outlined to prepare the next installment of the ANTSER Strategy Framework. Several EMWG member countries are actively investigating plans for transitioning coal sites to nuclear power plants. ANTSER Strategy no. 4 will provide a case study summary on membership learnings regarding Gen IV concepts for coal-to-nuclear transitions. The expectation is for ANTSER no. 4 to be published in 2026, although plans have not yet been finalized.

The EMWG financing taskforce continues to consider the changes to the financing market and the best structures for developing and financing Gen IV reactor projects. The taskforce is working with the IAEA and NEA on these issues, with the intention to jointly publish a report updating the 2021 ESG paper and a report on the changes in financing, particularly around the World Bank products that are available to nuclear projects. The task force is also looking to publish a paper on the financing of a FOAK Gen IV reactor project, with guidance on the risks and risk mitigations for the finance industry (GIF, 2025).

In November, the EMWG presented at the NEA Workshop on "Initial Estimation of Backend Costs for Advanced Reactors and Small Modular Reactors". The EMWG shared the GIF cost estimation framework and the G4ECONS tool, specifically highlighting how fuel cycle costs are calculated. Following the meeting, the Technical Secretariat received numerous requests to access EMWG tools, including G4ECONS and G4ECONS-FCF.

The EMWG continues progressing with the update to the cost estimating guidelines. A review of current state-of-the-art approaches documented in literature has been completed, and the first draft of the report will begin review by EMWG members in January 2026. The revised document includes expanded discussions on scale and modularity to better address SMRs, and to further explore how to best provide cost estimates for direct steam use, and cogeneration of both heat and electricity. In 2026 the EMWG will proceed with a review of the cost estimating guidelines and, in parallel, begin work on G4ECONS version 4.



Megan Moore
Co-Chair of the EMWG



Fiona Reilly
Co-Chair of the EMWG



Jason Hansen
Co-Chair of the EMWG

References

GIF (2025), "Proceedings, Synopsis and Findings of Financing Taskforce Workshop", Generation IV International Forum, London, www.gen-4.org/resources/events/workshop-gif-emwg-financing-taskforce-workshop-london.

GIF (2022), *Advanced Nuclear Technology Cost Reduction Strategies and Systematic Economic Review, Cost Reduction Strategy #2: Design – Modularity at Scale*, Generation IV International Forum, Paris, www.gen-4.org/resources/reports/advanced-nuclear-technology-cost-reduction-strategies-and-systematic-economic.

GIF (2021), *Nuclear Energy: An ESG Investable Asset Class*, Generation IV International Forum, Paris, www.gen-4.org/gif/upload/docs/application/pdf/2021-09/gif_final_esg_010921_2021-09-01_12-08-5_979.pdf.

GIF (2007), *Cost Estimating Guidelines for Generation IV Nuclear Energy Systems*, Generation IV International Forum, Paris, www.gen-4.org/gif/upload/docs/application/pdf/2013-09/emwg_guidelines.pdf.

Education and Training Working Group

The Education and Training Working Group (ETWG) was initially established as a GIF taskforce in November 2015 and elevated to a GIF working group in 2019. The GIF webinar series was launched in September 2016 and has continuously expanded to meet the growing demand for developing a skilled and trained nuclear workforce. By the end of 2025, some 107 webinars had been proposed, recorded and archived on the GIF portal. These webinars are also accessible on the GIF ETWG YouTube channel and the Bilibili Channel.[1] 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 about these advanced reactors.

2025 highlights

2025 Pitch your Gen IV Research Competition

To encourage and energize 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 invites the participation of Ph.D. students, postdoctoral fellows and early career professionals who received their Ph.D. after 1 January 2023, and whose research is related to Gen IV advanced nuclear energy systems. This is the third edition of the competition, which continues to attract and showcase the work of talented young students and researchers from around the world. The 2025 competition concluded with the following outcomes: First place was awarded to Dr. Hannah Patenaude (Los Alamos National Laboratory, United States) for the presentation of her work on "Novel Diamond

Table ETWG-1: GIF webinars organized, presented and archived in 2025

Presenter	Title of webinar	Date
Jiři Křepel, PSI, Switzerland	Overview and update of MSR activities within GIF	22 January 2025
Gerhard Strydom, INL, United States	Overview and update of VHTR activities within GIF	19 February 2025
Shin Whan Kim, IAEA	Nuclear power: Electricity and beyond the grid. Data-driven insights from IAEA's Power Reactor Information System	27 March 2025
Isabella Van Rooyen, PNNL, United States	Advanced manufacturing supporting Gen IV reactor systems	15 April 2025
Speakers: Tatiana Tagirova, OKBM, Russia; Kirk Sorensen, Flibe Energy, United States; Esben Klinkby, Saltfoss Energy (formerly Seaborg), Denmark; Hussam Khartabil, IAEA **Moderators:** Patricia Paviet, GIF ETWG and Vladimir Kriventsev, IAEA **Coordinator and technical support**: Nicole Virgili, IAEA	GIF/IAEA joint webinar: Advanced nuclear technologies for maritime applications	14 May 2025
Kaylee Cunningham University of Florida, United States, winner of the 2024 ANS Ph.D. competition	Modeling UO_2 fission gas release (FGR) thresholds in BISON	12 June 2025
Xiaojing Liu Shanghai Jiao Tong University, China	Thermal hydraulics of supercritical pressure water-cooled reactor (SCWR)	30 July 2025
Chukwudi Azih, CNL, Canada; Brent Wilhelm, OECD-NEA	Analysis and engagement on non-electric and cogeneration applications of nuclear energy	28 August 2025
Bryan Van der Ende, CNL, Canada	3S interfaces of a pebble-bed small modular advanced reactor	24 September 2025
Francesca Quinto and Frank Heberling, Karlsruhe Institute of Technology, Germany	Science for the safe disposal of nuclear waste – a German perspective	8 October 2025
Frédéric Bertrand, CEA, France Nathalie Seiler, CEA, France Shigenobu Kubo, JAEA, Japan	Severe accidents in sodium fast reactors: Safety study approach, prevention and mitigation by design	5 November 2025
Mauricio Tano Retamales, INL, USA	Overview of Nuclear Energy Advanced Modeling and Simulation (NEAMS) tools to accelerate the development of advanced reactor systems	10 December 2025

1. www.gen-4.org/resources/webinars; www.youtube.com/@gifetwg/videos; https://space.bilibili.com/435834911/lists.

Sensor to Investigate High-Valence Actinides in Molten Salts". Second place was awarded to Mr. Paul Baret (CEA, France), who presented his work on "Austenitic steels, a new golden age for ODS steels?" Finally, the Popular Vote Winner, determined by the highest number of likes on YouTube and Bilibili, was Mr. Dorian Da Cunha (CEA, France), for his research pitch on "Decay heat calculation validation based on revisited local thermal measurements".

2025 GIF webinar series

In 2025, 11 webinars were streamed live and are archived on the GIF portal (Table ETWG-1). Additionally, as in previous years, a joint GIF/IAEA webinar was organized and moderated by Vladimir Kriventsev from IAEA and Patricia Paviet from PNNL, with a focus on "Advanced nuclear technologies for Maritime Applications". The objectives of this joint webinar were: 1) to present insights into the latest developments and innovations in advanced nuclear reactor technologies tailored for maritime use; 2) to explore potential applications by discussing a range of possible uses, including floating power plants, nuclear-propelled cargo ships and icebreakers, seawater desalination and hydrogen production aboard ships or platforms; and 3) to examine the benefits and challenges of advanced nuclear reactor technologies in the context of potential maritime applications.

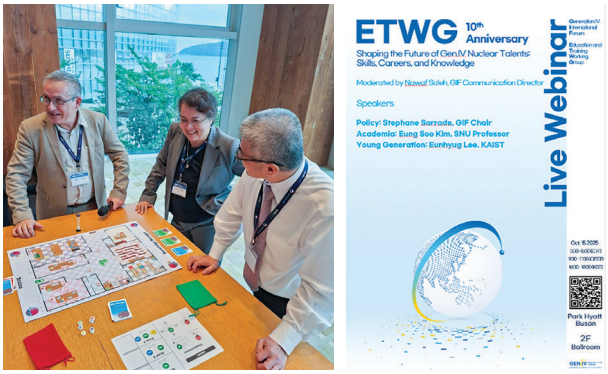
INPRO School-GIF ETWG session

From 7-18 July 2025, the Regional INPRO School on Strategic Planning for Sustainable Nuclear Energy was held in Daejon, Korea. To promote cooperation between the two organizations, a joint GIF ETWG and INPRO session was held. Dr. Jinyeong Jo (GIF Vice Chair for Education and Training, Korea), Dr. Hayafune Hiroki (GIF Vice Chair for Research and Infrastructure, Japan) and Dr. Hyunjin Kim (ETWG member) presented on GIF activities during this session.

Knowledge management and knowledge preservation (KMKP)

After a series of national good practice examples in knowledge management (KM) and knowledge preservation (KP) presented over the last two years, the ETWG must now define a simplified KM method that fits well with the needs of GIF. The process is broad and must start with thorough knowledge mapping of the GIF database and deliverables produced over 20 years, which is a necessary but time-consuming process. ETWG members are recommending that in parallel with this mapping, some key easy-to-perform KM actions are carried out to provide symbolic results in the short term. For example, AI could be used to analyze a wide set of GIF webinars, potentially enabling a cross synthesis from several webinars dealing with the same subject. Another immediate action was to test the serious game "KM CHANGER" during the Busan EG/PG meeting (Figure ETWG-1) to help familiarize participants with KM. This serious game was a first and fun approach of KMKP challenges for GIF volunteers.

Figure ETWG-1: ETWG meeting at the Fall 2025 Experts Group and Policy Group meeting



10th anniversary webinar

The year 2025 marked a significant milestone, as the ETWG celebrated its 10th anniversary. To commemorate this decade of achievement, a special hybrid webinar was held in Busan (Figure ETWG-2), bringing together approximately 100 students and GIF experts. This event featured three key sessions that were broadcast live to both onsite and online attendees: a presentation by students who participated in the 2025 Pitch Competition, a progress report from the academic sector regarding Korea's human resource development program for Gen IV high-temperature gas-cooled reactors (HTGR) and a policy-focused address by the GIF Policy Group Chair emphasizing the strategic importance of the ETWG.

Figure ETWG-2: Announcement of ETWG 10-year webinar





Eunju Jun
Chair of the ETWG,
with contributions from ETWG members

Non-Electric and Cogeneration Applications Working Group

Group goals: Highlight on demonstration and industry engagement opportunities

Non-electric and cogeneration applications of nuclear heat include the ensemble of solutions and processes that make optimal use of the energy produced by a nuclear fission reactor. These solutions can provide alternatives to the use of fossil fuels as a source of thermal energy, as well as energy services that are complementary to the electric grid. This approach is designed to optimize energy utilization efficiency, system economics and decarbonization.

In response to evolving energy needs, the GIF Policy Group approved the establishment of the Non-Electric and Cogeneration (NECA) Working Group as a permanent collaborative effort in October 2024, following the successful mandate of the Non-Electric Applications of Nuclear Heat (NEANH) Task Force. The overall objective of the NECA WG is to advance knowledge and access to energy system design, analysis and optimization tools that may allow decision makers to find optimal energy system solutions for different socio-economic, industrial and geographical contexts.

The NECA WG explores common areas of interest with respect to GIF reactor technology exploitation for non-electric and cogeneration applications, striving to advance several key priorities:

- **System analysis**: The NECA WG leverages GIF knowledge and capabilities to conduct system analysis with respect to key performance indicators. This includes objective techno-economic analysis of specific systems, and discussions of the perceived readiness and gaps of a given non-electric or hybrid energy system.
- **Engaging potential end users**: The NECA WG engages industry beyond the nuclear sector through virtual events and targeted workshops to help understand end-user requirements, supporting ongoing analysis within the WG.
- **Non-Electric Applications Public Database**: In 2023, the NEANH Task Force finalized an initial version of the GIF NEANH Database, which became publicly available in 2024. The NECA WG maintains the public database and releases updated versions periodically.
- **Support for regulatory readiness**: Building on informal engagement among NECA WG members with regulators, the NECA WG aims to support analysis by regulators on non-electric applications, working to ensure that they have access to the range of relevant analyses and modeling capabilities.
- **International collaboration**: The NECA WG strengthens collaborations with other GIF groups, including cross-cutting working groups and the Senior Industry Advisory Panel (SIAP). The NECA WG continues to stay engaged with complementary international efforts exploring non-electric applications of nuclear heat, including the IAEA, NEA, IEA, World Nuclear Association (WNA) and SNETP.

2025 highlights of working group achievements

In 2025, NECA focused on three core areas: 1) technical analysis; 2) stakeholder engagement; and 3) regulatory readiness.

NECA partnered with the NEA Working Group on Hydrogen Value Chains (H2 VAL WG) to publish its first comprehensive techno-economic analysis focused on hydrogen production, using high-temperature steam electrolysis (HTSE) coupled with high-temperature gas reactors (HTGRs) (GIF/NEA, 2025). This report evaluates the commercial readiness of such systems through a techno-economic analysis based on shared baseline assumptions and modeling by international research teams, summarized in Table NECA-1. The results indicate that a levelized cost of hydrogen ($LCOH_2$) is close to 4 USD/kgH_2, which is approximately three to four times higher than equivalent predictions for steam-methane reforming. The report also highlights other key challenges to deployment and provides recommendations to improve commercialization pathways for nuclear-assisted hydrogen production systems.

Alongside the technical work, NECA strengthened its engagement with industrial end users and regulators through targeted workshops that facilitated interactive dialogue and knowledge sharing between key stakeholder groups. In June 2025, the "NECA Virtual Workshop with End Users" brought together energy-intensive industries including chemicals, agri-food and steel production to discuss the practical requirements and operational/logistical challenges for coupling nuclear energy with industrial processes (GIF, 2025a). Key insights from this workshop included:

- **Historical precedent**. Heat applications using nuclear energy is technically mature, with over 750 reactor years of experience globally; however, paths to further deployment depend on local infrastructure and regulation.
- **Near-term opportunities**. Past and current projects demonstrate feasibility, but factors such as siting, grid interaction, market changes and permitting complexity influence their replicability today. Process industries familiar with complex and large-scale infrastructure projects may be best positioned to lead early deployments.
- **Operational/logistical challenges**. Policy and permitting must evolve to support industrial-scale nuclear applications, streamlined licensing, market recognition for nuclear heat and mechanisms to reward early adopters. Regarding end use, interface considerations (e.g. balance of plant, cross-contamination, physical security, regulatory and ownership jurisdictions), redundancy planning, contractual flexibility for long-term steam supply, and public and regulatory scrutiny readiness must be addressed.

Table NECA-1: Predicted cost and amount of hydrogen produced from select scenarios

Model	$LCOH_2$ (USD/kgH_2)	LCOH2 with offset from O_2 sales (USD/kgH_2)	H_2 produced (tonnes per year)
CNL HESO	4.52	3.72	55 600
CEA PERSEE model	3.76	3.04	70 700
UKNNL literature value	3.53	-	-
UKNNL model	-	-	70 400
IAEA HEEP	3.89	3.17	66 800

Source: GIF/NEA (2025).

In November 2025, the "NECA Virtual Workshop with Regulators" was held as a follow-on to the end user workshop. This workshop engaged organizations related to regulation, codes and standards, and safety analysis of NECA systems in GIF member countries (GIF, 2025b). Key insights from the workshop included:

- **Existing framework**. Regulators have the mechanisms to handle new technologies and innovations, and non-electric or cogeneration applications are not expected to be unique within these frameworks.
- **Confidence through demonstration**. Demonstration projects and pilot plants are critical for building operational experience, validating safety cases and increasing stakeholder confidence. To maximize learning from early demonstrations, collaboration among vendors, licensees, regulators and industrial partners is crucial.
- **Collaborative approach**. There is a mismatch between the high safety standards required for nuclear facilities and those required at most industrial sites. Cooperation with regulators in non-nuclear industries is encouraged. Changing the typical nuclear boundary in cogeneration projects was identified as a potential option to enable holistic regulatory review. Early demonstrations could benefit from a wider boundary, with subsequent projects having a smaller boundary once impacts are understood.

Overall, tangible outcomes from both the end-user and regulator workshops included discussions of specific technical, logistical and licensing challenges for case studies from past, and current and hypothetical cogeneration deployment scenarios globally, for example, highlighting the benefits and drawbacks of single vs. multiple off takers.

The NECA WG also supported education and training initiatives within and external to GIF, such as providing historical context, and ongoing deployment and analyses of NECA systems, in the GIF Education and Training Webinar Series in August 2025 (GIF, 2025c), and the IAEA Nuclear Energy Management School in June 2025.

Looking ahead, the NECA WG plans to update the 2025 report *System Analysis: Hydrogen Production from Nuclear Energy* with updated modeling results and new details related to the readiness of regulating hydrogen production systems (GIF/NEA, 2025). The NECA WG will continue to maintain its database on non-electric systems, engage regulators and end users in GIF member countries, and advance techno-economic systems analysis to support the commercialization of non-electric and cogeneration systems globally.

References

GIF (2025a), "Non-Electric & Cogeneration Virtual Workshop with End Users: Workshop Synopsis and Findings", Generation IV International Forum, Paris, www.gen-4.org/sites/default/files/2025-07/NECA_Virtual_Workshop_Proceedings-2025-07-15.pdf.

GIF (2025b), "Non-Electric & Cogeneration Virtual Workshop with Regulators: Workshop Synopsis and Findings", Generation IV International Forum, Paris, www.gen-4.org/resources/events/non-electric-cogeneration-virtual-workshop-regulators.

GIF (2025c), "Education and Training Series #103: Analysis and Engagement on Non-electric and Cogeneration Applications of Nuclear Energy", Generation IV International Forum, 28 August 2025, [Online], www.gen-4.org/resources/webinars/education-and-training-series-103-analysis-and-engagement-non-electric-and.

GIF/NEA (2025), "System Analysis: Hydrogen Production from Nuclear Energy", Generation IV International Forum, Paris, www.gen-4.org/resources/reports/system-analysis-hydrogen-production-nuclear-energy-2025.



Chukwudi Azih
Co-Chair of the NECA WG



Aiden Peakman
Co-Chair of the NECA WG
with contributions
from NECA WG members

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 against the GIF proliferation resistance (PR) and physical protection (PP) goals. The methodology provides designers and policy makers with a technology-neutral framework and a formal, comprehensive approach to evaluate the PR and PP characteristics of advanced nuclear systems according to a challenges–system response–outcomes paradigm. The PRPPWG aims to offer opportunities to improve the PR and PP robustness of system concepts throughout their development and deployment cycle.

Advancing group goals, methodology and industry engagement

A major objective for the PRPPWG in 2025 centered on making progress with the PP methodology revision and enhancing engagement with industry stakeholders. Building on the review conducted in 2023/2024, the PP aspect of the methodology was determined to benefit from an expansion of its metrics to include a wider range of intrinsic attributes. The updates involve proposing new measures and metrics, such as adding "inherent protection" as a high-level metric for sabotage scenarios. New metrics are intended to better represent intrinsic PP aspects, including dispersibility, energetic mechanisms and inherent coolability. The timeline for the revision remains contingent on feedback from key stakeholders, including the Experts Group, Policy Group and industry representatives.

To ensure the robustness of the revised methodology, the group discussed testing the updated PP section using a demonstration case study, similar to the European Sodium Fast Reactor (ESFR) study previously conducted. The PRPPWG considered including PP experts from member organizations that specialize in areas such as force-on-force assessments, regulatory frameworks and power plant security. The ultimate decision on whether to conduct a formal case study will depend on interest from industry designers. Consequently, the PRPPWG plans to present the updated methodology at the next GIF Industry Forum to gauge interest.

A core mission of the PRPPWG is to enhance the practical applicability and visibility of its work. The group recognizes the need to make PRPP work more digestible for AMR and SMR vendors as they move towards licensing and deployment. Discussions were initiated on how to best engage with vendors and, potentially, regulators. These are open questions the GIF Expert Group and Policy Group continue to reflect upon. While direct, custom-made work for individual vendors is not currently feasible due to resource constraints, the PRPPWG aims to share final drafts of reports, such as the 3S report and the siting study (see below), with vendors to receive feedback. This focus aligns with the broader GIF initiative of looking beyond "reactors" and recognizing the interfaces between reactors and fuel cycle facilities, and is in line with the PRPPWG's technology-neutral methodological approach. Furthermore, the group is committed to supporting the future generation pipeline by collaborating with the Education and Training Working Group (ETWG) and actively engaging with universities and industry. Planning has also begun for the PRPPWG's contribution to the future GIF Industry Forum, which is the key arena for industry interaction.

2025 highlights and key deliverables

The 35th PRPPWG meeting, held from 18-20 February 2025 in Ispra, Italy, focused on advancing the working group's goals through technical discussions and strategic planning. The meeting featured in-person attendees from Euratom, Canada, France, Japan, the United Kingdom and the United States, alongside IAEA observers (Figure PRPPWG-1).

A major focus of the PRPPWG's technical work in 2025 was the completion and dissemination of two high-priority reports: the *Siting Study for Advanced Modular Reactors (AMRs) and Microreactors* (Ahn et al., 2025) and the *VHTR 3S Interface Case Study Report* (Ammirabile et al. 2025).

1. The siting study was developed as a follow-up to suggestions raised at the 2022 GIF Industry Forum. This report analyzes the PRPP implications associated with various deployment scenarios for SMRs and microreactors, including coastal, remote, city and industrial complex locations; it also explores several cross-cutting topics. The report was reviewed by other GIF members and IAEA staff. In 2025, the report was finalized and published.
2. The *VHTR 3S Interface Case Study Report* (van der Ende, et al. GIF [2025a]) documents the collaboration between the PRPPWG, the Risk and Safety Working Group (RSWG) and the VHTR SSC to identify commonalities, synergies and conflicts among safety, security and safeguards (3S). The case study uses a generic small modular VHTR pebble-bed reactor design and employs a bottom-up approach, analyzing both 2S and 3S interfaces. The latest revised version was reviewed by the PRPPWG, RSWG and VHTR SSC, IAEA members, as well as external representatives of selected vendors under non-disclosure agreements. The findings of this report were actively disseminated at international events, including the INMM Annual Meeting in August 2025 (Nguyen, F. et al. [2025]). The PRPPWG also liaised with the ETWG to host a webinar that presented the findings of the 3S case study.[1] The document is now in the publication workflow and is expected to be released in the first part of 2026.

1. Webinar: www.gen-4.org/resources/webinars/education-and-training-series-104-safety-security-safeguards-3s-interface-case; recording link: www.youtube.com/watch?v=C1pxJSw55Rw.

Figure PRPPWG-1: In-person participants of the 35th PRPPWG Meeting



Ongoing technical work and collaboration is focused on advancing the metrics for PP methodology revisions. The United Kingdom performed a tabletop exercise to confirm the benefit of the proposed metrics such that the system's response to sabotage could be optimized by appropriate design.

The PRPPWG is investigating the possibility of issuing a new report focusing on the consequence analysis of sabotage for SMRs/AMRs/microreactors, aiming to produce a result that industry can directly use. To facilitate this, the group planned outreach to the RSWG and IAEA Nuclear Security experts to explore cooperation on aligning consequence analysis work with areas such as emergency planning zone sizing.

The PRPPWG maintained strong ties with the IAEA in 2025, including participating in the GIF-IAEA Interface meeting in June, and presenting two papers at the IAEA Technical Meeting on Proliferation Resistant Features of Fast Reactors and Advanced Fuel Cycles in August 2025 (van der Ende et al., 2025b). The PRPPWG also actively contributed to the organization of the technical meeting, with members participating as experts in two consultancy meetings, as members of the program committee and as session chairmen. The group also explored potential new collaboration with the IAEA on Safeguards by Design (SbD) for AMRs that will further strengthen existing collaboration.

References

Ahn, S.K. et al. (2025), *Generation IV Proliferation Resistance and Physical Protection Siting Study for AMRs and Microreactors*, GIF/PRPPWG/2025/001/, GIF PRPPWG, www.gen-4.org/resources/reports/proliferation-resistance-and-physical-protection-siting-study-advanced-modular.

Ammirabile, L. et al. (2025), "A Case Study of 3S Interfaces in a Generation IV Advanced Modular Reactor", INMM25, Washington D.C., 24-28 August 2025.

Nguyen, F. et al. (2025), "Proliferation Resistance and Physical Protection Crosscutting Topics", IAEA Technical Meeting on Proliferation Resistance Features of Fast Reactors and Associated Fuel Cycles, Vienna, 18-22 August 2025.

van der Ende, B.M. et al. GIF (2025a), *Generation IV International Forum Case Study of Safety, Security and Safeguards (3S) Interfaces for a Very High Temperature Reactor System*, GIF/PRPPWG/2025/002/, 3S Interfaces Sub-Group, www.gen-4.org/resources/reports/case-study-safety-security-and-safeguards-3s-interfaces-very-high-temperature.

van der Ende, B.M. et al. (2025b), "Proliferation Resistance and Physical Protection (PR&PP) Evaluation Methodology in Support of PR&PP by Design for Fast Reactors and Associated Fuel Cycles", IAEA Technical Meeting on Proliferation Resistance Features of Fast Reactors and Associated Fuel Cycles, Vienna, 18-22 August 2025.



Frédéric Nguyen
Co-Chair of the PRPPWG



Guido Renda
Co-Chair of the PRPPWG



Ben Cipiti
Co-Chair of the PRPPWG,
with contributions from the PRPPWG members

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 2025, RSWG membership included representatives from the European Commission, Canada, China, France, Japan, Korea, South Africa, the United Kingdom and the United States. The IAEA Department of Nuclear Safety and Security also participated as an observer.

The RSWG has developed the Integrated Safety Assessment Methodology (ISAM) as a technology-neutral toolkit that supports design, safety and risk evaluation, subsequently coordinating with the SSCs to apply ISAM to 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 the different 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.

The RSWG actively seeks feedback on its publications from the international regulatory community, as represented by organizations such as the NEA Working Group on New Technologies (WGNT) and the IAEA. In 2025, the RSWG drafted a revised version of the VHTR SDC (GIF 2023a) in response to comments received from the WGNT and IAEA. A revised version of the *Risk-informed Framework for Safety Design of Gen IV Systems* (GIF, 2023b) was also drafted in response to comments received from the IAEA. Both revised documents are expected to be published in 2026.

The RSWG maintains a direct technical interface with the IAEA, with this relationship reaffirmed during the GIF-IAEA Interface meeting that took place 26-27 July 2025. The highlights of GIF-IAEA safety-related cooperation in 2025 included GIF's participation in the IAEA's Nuclear Harmonization and Standardization Initiative (NHSI), and the execution of the Joint IAEA-GIF Workshop on the Safety of Non-Water Cooled Reactors.

The NHSI Industry Track Topic 3 initiative focuses on experiments and safety analysis computer code validation. The initiative has created the NEXSHARE platform (IAEA, 2024), which contains a catalogue of experimental facilities that can provide validation data and a platform for the exchange of information between the operators of these facilities, code-users requiring data and other stakeholders. The RSWG represents GIF on the steering committee for the NEXSHARE platform, where GIF is recognized as a partner alongside the IAEA, NEA and European Commission.

The Joint IAEA-GIF Workshop on the Safety of Non-Water Cooled Reactors was hosted by the IAEA in Vienna between 30 June and 4 July 2025. The workshop was co-organized by the GIF RSWG and the IAEA Safety Assessment Section of the Department of Nuclear Safety and Security. The workshop had 96 participants from 32 IAEA Member States and one international organization (NEA). There were 53 presentations delivered over six technical sessions on cross-cutting and technology-specific topics. There was strong participation from both technology developers and regulators at the workshop, showing how the RSWG can advance the safety demonstration of Gen IV technologies through its interface with both.

Within GIF, the RSWG worked on three specific topics in 2025:

1) The 3S (safety, security, safeguards) interface case study on the VHTR system was completed in coordination with the PRPPWG and the VHTR SSC.
2) Investigations on the topics of mechanistic source term (MST) assessment and practically eliminated situations (PES) for Gen IV systems were carried out.
3) White papers on both MST and PES were drafted, with review by the GIF Experts Group anticipated in 2026.

References

GIF (2025), "Risk and Safety Working Group", Generation IV International Forum, Paris, www.gen-4.org/gif-activities/working-groups/risk-and-safety-working-group.

GIF (2023a), Safety Design Criteria for Generation IV Very High Temperature System, GIF/VHTR-SDC/2023/001, Generation IV International Forum, Paris, www.gen-4.org/resources/reports/safety-design-criteria-generation-iv-very-high-temperature-reactor-system-2023.

GIF (2023b), A Risk-Informed Framework for Safety Design of Generation IV Systems, GIF/RSWG/2023/001, Generation IV International Forum, Paris, www.gen-4.org/resources/reports/risk-informed-framework-safety-design-generation-iv-systems-2023.

IAEA (2025), IAEA NEXSHARE homepage, International Atomic Energy Agency, https://nucleus.iaea.org/sites/connect/NEXPublic/SitePages/Home.aspx (accessed 6 April 2026).



David Hummel
Co-Chair of the RSWG



Christoph Döderlein
Co-Chair of the RSWG,
with contributions from RSWG members

5

GIF Senior Industrial Advisory Panel (SIAP) report

SIAP's role is to provide industry-informed advice to GIF on long-term strategic issues (regulatory, commercial and technical), and on R&D priorities and strategies across the six GIF systems. The scope includes: progress and plans (including technical viability and licensing readiness), deployment perspectives and fuel cycle considerations, and the evolution of international nuclear safety standards and regulatory frameworks. SIAP membership is approved by the GIF Policy Group (by consensus), with up to four members per country and a broad multi-country industry representation.

This chapter summarizes the main outcomes, discussion themes and follow-up actions arising from SIAP's meeting held in 2024 and consolidates SIAP's response to the two-part SIAP Charge covering 1) qualification of new materials and manufacturing techniques; and 2) engagement with international codes and standards.

It also offers advice regarding industry perspective on GIF engagement and proposes actions to be taken by the Policy Group.

Summary of meeting themes and key outcomes

In 2025, SIAP meeting discussions converged on a set of recurring constraints and enabling actions for Gen IV reactor deployment. The principal outcomes are summarized below:

- **Regulatory engagement and institutional collaboration**. A dominant theme was the need for structured engagement with regulator communities to build regulatory confidence in advanced materials and manufacturing techniques. This is reflected in the prioritization of direct interaction with the OECD NEA regulatory community (CNRA) to explore a cooperation pathway and better align expectations for qualification evidence, acceptance criteria and licensing frameworks.
- **Codes and standards (C&S) landscape, and convergence**. Meeting takeaways emphasized that existing C&S are only partially aligned to Gen IV needs. While harmonized approaches may exist for certain non-nuclear components, nuclear-grade advanced materials and advanced manufacturing methods remain under-codified, with fragmented acceptance pathways and insufficient qualification data packages. A proposed response is a structured "landscape" exercise – engaging nuclear standards development organizations (SDOs) (e.g. via a code convergence board) – to map current coverage and identify gaps by system, SSC category and fabrication route.
- **Technology prioritization for industry-relevant demonstrations**. Another consistent outcome was the need to focus near-term demonstrations on a limited set of high-leverage materials and manufacturing techniques that 1) materially reduce cost and schedule risk; and 2) are feasible to qualify with available or near-term test infrastructure. The meeting takeaways also stress the value of aligning technology focus with the Advanced Manufacturing and Materials Evaluation (AMME) workstream and building on industry survey-type inputs to identify the most deployable priorities.
- **Knowledge management, access and industry value proposition**. Meetings also highlighted barriers to sustained industry engagement: limited participation from nominated members, low response rates to consultations/surveys and practical burdens associated with in-person attendance. In response, SIAP supports the GIF initiatives to clarify the "industry value proposition" of GIF (and SIAP), to expand access to GIF deliverables (including a searchable digital repository of historic reports), and to strengthen knowledge management/preservation mechanisms so that outputs are discoverable and reusable by industry stakeholders.

Response to SIAP Charge 2025

Charge 1: Qualification of new materials and manufacturing techniques

R&D efforts required for qualification

Based on the survey carried out by SIAP, the required R&D program should be structured around qualification evidence that is credible to regulators and fabricators, including:

1. **Reactor-relevant test and validation protocols:**
   - Establish and/or harmonize test standards for new materials under representative operating environments (temperature, chemistry and irradiation conditions, as applicable).
   - Ensure consistent comparison of performance, with emphasis on structural integrity and corrosion resistance metrics.
2. **Codification pathway for advanced manufacturing (AM) and joining processes:**
   - Treat the codification of AM techniques as an explicit deliverable – not as a downstream activity – as codification is necessary to build regulatory confidence and consistent vendor qualification pathways.

- Embed reproducibility and quality control at scale, as core qualification criteria.

3. **Address infrastructure and data gaps**:
   - Close gaps in irradiation/testing infrastructure and develop data packages sufficient for acceptance criteria.
   - Recognize that fragmented regulatory requirements and limited harmonization increase cost and time; therefore, qualification planning should incorporate multi-country acceptance needs early.

Priority techniques and materials (industry critical path)

SIAP has identified the following as especially critical for Gen IV deployment:

- **Manufacturing/joining techniques**: Hot Isostatic Pressing (HIP), PM-HIP, electron beam welding, additive manufacturing (including hybrid approaches with welding) and selected coating techniques – each require robust quality assurance and reproducibility.
- **Materials**: Robust cladding materials and low-carbon concrete as key enablers for structural integrity and sustainability objectives.

Near-term demonstration priorities

Demonstrations should be selected to reduce the largest licensing and supply-chain risks first, including:

1. **Laboratory coordination under industrial quality standards**. Organize and qualify existing laboratories under recognized industrial quality assurance frameworks to validate new testing protocols and improve the comparability of results.
2. **Heat transfer fluid and chemistry validation**. Use existing or developing facilities to validate coolant chemistry stability and compatibility with structural materials (explicitly including lead-based system considerations where relevant).
3. **Pilot-scale manufacturing readiness and economics**. Demonstrate manufacturability and economic viability, including reduced manufacturing time, and commission pilot-scale facilities to prove repeatable production and inspection regimes.

Key barriers to manage explicitly

SIAP wishes to highlight major barriers that must be treated as program risks: high development costs, fragmented regulatory requirements, gaps in irradiation/testing infrastructure, insufficient cross-country harmonization, and the need for updated licensing frameworks capable of accommodating novel methods.

Charge 2: Engagement with international codes and standards

Current gaps and limitations

From the fabricator/operator perspective, present C&S coverage is incomplete for Gen IV deployment for the following reasons:

- Acceptance criteria are fragmented across jurisdictions and/or SDO frameworks.
- Provisions for advanced materials and advanced manufacturing routes remain limited.
- Qualification is constrained by insufficient technical databases and agreed evidence thresholds for nuclear-grade deployment.

Recommended GIF/SIAP engagement model

A credible engagement approach requires moving from general advocacy to structured, technology-specific collaboration. This involves:

1. **Developing system-specific guidelines**. Lead development of guidance tailored to each Gen IV technology to translate design and operating needs into codifiable requirements.
2. **Formalizing regulator and SDO interfaces**:
   - Strengthen cooperation with the NEA CNRA and national regulators to align on qualification evidence expectations and reduce re-work.
   - Engage nuclear SDO coordination forums to build a shared landscape of applicable codes, identify gaps and prioritize convergence initiatives. There is a proposal to share SIAP's survey results with the SDO Code Convergence Board.
3. **Coordinating with international harmonization bodies and industry platforms**. Increase coordination with IAEA and WNA/CORDEL initiatives to leverage existing harmonization work and avoid duplicative frameworks.
4. **Enabling knowledge sharing while managing intellectual property (IP) constraints**. Implement IP management and structured knowledge-sharing mechanisms to support dissemination of codified practices without undermining commercial incentives.

Practical outputs expected from this charge

The meeting-derived actions imply the following tangible deliverables: 1) a Gen IV C&S landscape and gap analysis; 2) a prioritized roadmap of codification needs by system/SSC/material/process; and 3) a regulator-facing engagement plan with defined cooperation touchpoints and expected artefacts.

Consolidated recommendations and forward actions

In addition to the charge-specific responses, SIAP's meeting cycle crystallized three strategic recommendations to GIF to improve industry engagement and deployment readiness:

1. **Clarify the industry value proposition via technology-readiness level (TRL) assessment** across GIF systems to focus collaboration where systems are closest to market.
2. **Preserve and leverage GIF knowledge assets** through a structured knowledge management and preservation initiative, including a digital archive of all GIF reports, searchable by AI-powered cognitive search engines.
3. **Establish an industrial-friendly, harmonized C&S-based framework** aligning design, safety, licensing approaches and standards development, explicitly incorporating fuel and fuel cycle considerations.

Industry perspective on GIF engagement and proposed changes

Industry perspective on GIF engagement

From an industry standpoint, GIF remains a uniquely valuable international mechanism for coordinating long-horizon R&D and aligning approaches across Gen IV systems, particularly where deployment depends on regulatory confidence, supply-chain readiness and internationally credible qualification evidence. However, industry partners have indicated that the current mode of engagement through SIAP is not consistently translating that potential into sustained, high-participation industrial impact.

The prevailing industry view is that engagement is constrained by limited participation from nominated industry members and low response rates to SIAP surveys, which reduces the representativeness and actionable value of SIAP outputs. This engagement challenge is reinforced by structural issues: SIAP meets on average twice per year and is primarily driven by an annual Policy Group "charge", which limits SIAP's ability to address complex issues that require multi-year continuity and iterative technical/regulatory coordination.

Industry also perceives that the most deployment-limiting barriers are not yet being addressed in a sufficiently integrated and harmonized manner. There are fragmented regulatory requirements, gaps in testing infrastructure and the need for updated licensing frameworks, as well as incomplete alignment of codes and standards for advanced materials and advanced manufacturing techniques. In practical terms, this fragmentation raises qualification cost and schedule risk for vendors, weakens investor confidence, and creates uncertainty for operators and fabricators attempting to plan industrialization pathways.

Finally, SIAP's current emphasis on formal industry representation does not adequately support innovation and cross-fertilization with broader expert communities (academia, research institutions and non-GIF initiatives), despite these communities being central to accelerated materials qualification, manufacturing validation, digitalization (including AI) and emerging best practices.

Proposed changes to strengthen GIF-industry engagement

To address these issues, this report supports a shift from periodic, charge-driven engagement towards a more proactive, program-based operating model that industry can recognize as reducing deployment risk and accelerating codification. Specifically:

1. **Move from annual charges to multi-year mandates with defined timelines**. Replace (or complement) the annual SIAP charge with multi-year mandates focused on a small number of strategic deployment blockers (e.g. qualification pathways, codification gaps and regulator engagement). This enables continuity, deeper technical work and measurable deliverables over time.
2. **Broaden participation beyond nominated members through structured expert outreach**. Formalize SIAP's ability to engage subject matter experts from academia, research institutions and relevant international initiatives (e.g. NEA, EC/JRC and IAEA-related alliances). This increases technical depth, improves legitimacy of recommended practices and strengthens buy-in for later codification.
3. **Deliver "industry practices" and roadmaps that can be converted into codes and standards**. Industry practice gives rise to new codes and standards. Position SIAP to help produce practical, consensus-oriented industry practices for qualifying advanced materials, advanced manufacturing (e.g. electron beam welding, powder metallurgy and HIP), new SSCs and AI-enabled methods (AI4GIF), explicitly designed as input to SDOs.
4. **Strengthen codes and standards leadership via formal engagement with SDOs**. Establish a structured SIAP interface with major nuclear SDOs (e.g. ASME, JSME, AFCEN and KEPIC) to drive the harmonization of acceptance criteria and close codification gaps that impede operator/fabricator readiness. Note that SDOs also use industry experts to develop codes, so SIAP can play an advisory role to SDOs.
5. **Institutionalize regulatory engagement through recognized channels**. Create an explicit mechanism for SIAP to present developments in codes, standards and qualification practices to regulators via established international pathways (notably the IAEA and the NEA CNRA), reducing regulatory uncertainty and supporting licensing framework evolution.
6. **Improve knowledge management to increase tangible value for industry**. Launch a knowledge preservation and dissemination initiative so that GIF outputs, prior SIAP findings and relevant technical artefacts are easier to find, reuse and reference, supporting supply-chain development and reducing duplication of effort. GIF should consider having a digital repository of all reports.
7. **Clarify the "value proposition" using TRL-informed prioritization**. Systematically assess and communicate technology-readiness levels to focus industry collaboration where it is most impactful and where near-term deployment benefits are plausible, improving engagement incentives and resource alignment. SIAP can assist the NEA with a new assessment and possible prioritization of GIF systems, complementing the NEA SMR Dashboard criteria.

Collectively, these changes reposition SIAP from a periodic advisory function into an enabling platform that produces deployment-relevant artefacts (roadmaps, best practices, codification inputs) and strengthens two-way alignment among industry, regulators and standards bodies, addressing the principal engagement deficits and industrialization barriers.

A Appendix 1. Country reports 2025

Australia

Australia remains committed to participating in GIF as an Observer and will continue to assess its ability to provide country updates for future annual reports.

Canada

Government updates

Government of Canada – Domestic updates

The Government of Canada (GoC) continues to support nuclear energy development and deployment in recognition of its pivotal role in Canada's clean energy mix, now and in the future. In March 2025, the GoC signed a preliminary agreement with AtkinsRéalis to lend up to CAD 304 million for developing the MONARK CANDU nuclear reactor. Also in March, the GoC announced CAD 55 million in funding to support Ontario Power Generation's (OPG) Darlington New Nuclear Project, CAD 56 million to Saskatchewan's Crown Investments Corporation in support of SaskPower's SMR project and CAD 13 million to Capital Power in Alberta. In May, a new federal government was elected and reaffirmed nuclear energy's role in Canada's vision as a clean energy superpower, with the GoC planning to advance major projects and streamline approvals through its new Major Projects Office.

On 19 August 2025, the Minister of Energy and Natural Resources announced a CAD 13 million federal investment for a second isotope production system at Bruce Power's CANDU unit 6. In October, the GoC committed CAD 2 billion to the Darlington New Nuclear Project, alongside CAD 1 billion from Ontario. The 2025 federal budget, released in November, allocates CAD 4.2 million over three years, starting in 2027-28, plus CAD 1.4 million ongoing, to Natural Resources Canada to support nuclear energy exports and strategic engagement in key markets.

Government of Canada – International updates

In January 2025, Canada and Poland signed a nuclear cooperation agreement for peaceful technologies. On 25 August, both prime ministers issued a joint statement to strengthen the partnership and foster industry collaboration. A Polish nuclear trade mission to Canada followed in November.

On 15 June 2025, Canadian and UK leaders committed to deepening cooperation on nuclear fission and developing fusion energy collaboration.

Canadian Nuclear Safety Commission (CNSC)

In January 2025, the CNSC held the second hearing for OPG's license to build a BWRX-300 reactor at Darlington (DNNP). In April, the license to construct was granted for DNNP. In May, the CNSC approved expanding medical isotope production at Darlington to include Y-90 and Lu-177. On 25 September 2025, the CNSC renewed OPG's operating license for Darlington for 20 years.

Canadian provincial government updates

Alberta: In April 2025, Energy Alberta submitted an Initial Project Description (IPD) to the Impact Assessment Agency of Canada detailing the potential inclusion of up to four 1 000 MWe CANDU MONARK reactors for the proposed Peace River Nuclear Power Project. On 25 August 2025, the Government of Alberta announced the launch of a public engagement exercise, including an expert panel, on the potential of nuclear energy in Alberta to help inform a nuclear energy roadmap. In November 2025, the Government of Alberta committed to collaborating with Canada's federal government to develop a nuclear generation strategy as part of a memorandum of understanding signed by Canadian Prime Minister, Mark Carney and Alberta Premier, Danielle Smith.

Ontario: On 15 May 2025, the Government of Ontario released its Budget 2025, which outlined a significant investment in Ontario's nuclear sector, including an additional CAD 15.5 million over three years to increase the McMaster Nuclear Reactor's production of medical isotopes to a 24/7 schedule. Following this, on 12 June 2025, the Government of Ontario released Energy for Generations, which is an integrated energy plan that leverages every energy resource to provide Ontario with affordable, secure, reliable and clean energy.

On 30 July 2025, the Government of Ontario launched the Nuclear Isotope Innovation Council of Ontario (NIICO). This new expert advisory panel will help leverage Ontario's world-class nuclear fleet to double the number of medical isotopes produced in the province by 2030.

In August 2025, Bruce Power completed the first phase (planning) of the federal impact assessment process and started the integrated impact assessment for the Bruce C Nuclear Project. In September 2025, Phase 1 (i.e. unit 1) of the Darlington New Nuclear Project got referred to the Major Projects Office.

Industry updates

Atomic Energy of Canada Limited (AECL)

In January 2025, AECL and Canadian Nuclear Laboratories (CNL) issued a Request for Expression of Interest (RFEOI) to understand market interest in licensing AECL's SLOWPOKE and nuclear battery reactor technologies for commercialization opportunities.

In June 2025, AECL announced that Nuclear Laboratory Partners of Canada (NLPC) Inc. has been selected as the preferred bidder for the contract to manage CNL. AECL announced in December that this contracting process was completed as part of the government-owned, contractor-operated model, and NLPC will officially take on responsibility for the ownership and management of CNL.

Nuclear Waste Management Organization (NWMO)

Following the 2024 site selection for Canada's deep geological repository (DGR) for used nuclear fuel, NWMO is now entering the regulatory review process. In addition to advancing Canada's plan for used nuclear fuel under the Nuclear Fuel Waste Act, NWMO is leading the development of a second DGR to safely manage intermediate-level and non-fuel high-level radioactive waste under the Integrated Strategy for Radioactive Waste. On 5 June 2025, NWMO launched its engagement process with Indigenous Peoples and the public to gather their input to inform the design of its proposed site selection process. Engagement will be taking place until 2027.

Utilities and vendors

Bruce Power's refurbishments of Units 3-8 are underway and expected to finish by 2033, extending the station's life into the 2060s. In April 2025, Bruce Power confirmed plans for Unit 5's Major Component Replacement starting in 2026 and completed its largest cobalt-60 harvest during the unit's outage. Work continues on the Bruce C Nuclear Project, which could add up to 4 800 MWe. On 19 August 2025, the Impact Assessment Agency and CNSC began an integrated impact assessment. In December 2025, Bruce Power issued an additional CAD 950 million in green bonds; to date, Bruce Power has cumulatively issued CAD 3.3 billion in green bonds through five offerings.

At Darlington, OPG's refurbishment remains on time and budget, with Units 1-3 complete and Unit 4 finishing in 2026. OPG is advancing its grid-scale SMR project: in May 2025, it awarded AtkinsRéalis a CAD 450 million contract for the first of four SMRs, and in June it broke ground on the first BWRX-300 unit.

OPG is planning to refurbish Pickering Units 5-8 and will be in the Project Definition Phase during 2026. Pending approvals, completion is expected by the mid-2030s. OPG is also exploring large-scale nuclear generation at its Wesleyville site, which could host up to 10 000 MW. In March 2025, OPG issued CAD 1 billion in green bonds for low-carbon projects under its Sustainable Finance Framework. In August 2025, OPG and Capital Power released an SMR feasibility study for Alberta, confirming viability, early community support and potential economic benefits. In June 2025, OPG submitted a renewal application for license to operate in preparation for Pickering's refurbishment.

In March 2025, Moltex announced successful validation of its revolutionary Waste to Stable Salt (WATSS) process on used fuel bundles from CANDU reactors through state-of-the-art hot cell experiments, executed by CNL, marking a pivotal moment in closing the nuclear fuel cycle and advancing next-generation nuclear sustainability.

In May 2025, Westinghouse and the Pabineau and Eel River Bar First Nations, signed a memorandum of understanding (MoU) to explore AP300 SMR opportunities at the Port of Belledune in New Brunswick. In October 2025, Energy Alberta and Westinghouse signed an MoU to collaborate on exploring the deployment of an AP1000 reactor.

In June 2025, AtkinsRéalis signed an agreement with France's EDF to expand their existing global partnership to collaborate and respond to new nuclear reactor opportunities around the world. Also in June 2025, the Canadian Nuclear Association (CNA) and the Japan Atomic Industrial Forum (JAIF) deepened their cooperation following the Canada-Japan Nuclear Forum held in Tokyo on 19 June 2025. The forum explored opportunities for collaboration and reaffirmed the role of Canada and Japan as strategic partners.

On 25 September 2025, X-energy Canada announced a completed study that confirmed the feasibility and benefits of repurposing a TransAlta thermal generation site in Alberta with Xe-100 SMR.

Research and education

In April 2025, McMaster University and UK firm Astral Systems announced their partnership to produce actinium-225 and lead-212, two highly sought-after radioisotopes critical to new cancer treatments.

In June 2025, CNL, AECL and the University Network of Excellence in Nuclear Engineering (UNENE) signed an MoU to pursue the development of the Canadian Nuclear Learning Centre. The vision of the center is to coordinate education, training, knowledge management and workforce development across Canada's growing nuclear sector.

In July 2025, the University of New Brunswick's Centre for Nuclear Research (CNER) formally opened its new Advanced Nuclear Reactors Laboratory (ANRL), which will experiment with advanced reactor coolants such as molten salt and liquid metals and support the design and operation of SMRs.

China

1. Nuclear energy development

- By the end of September 2025, 58 nuclear power units were in operation, and 54 more had approval and were under construction on the Chinese mainland, with a total installed capacity of 125 GW.
- On 27 April 2025, China's State Council approved five new nuclear power projects, which will total ten reactor units. The projects include Phase III of Sanmen in Zhejiang; Units 1 and 2 of the PWR project in Xiapu, Fujian; Phase III of Haiyang in Shandong; Phase II of Taishan in Guangdong; and Phase III of Fangchenggang in Guangxi. Of the ten newly approved units, eight will adopt the domestically developed "HPR1000" technology.
- On 12 September 2025, the Atomic Energy Law was adopted by the Standing Committee of the National People's Congress, China's top legislature, as it closed its latest session. The 62-article law took effect on 15 January 2026. The new law will improve the legal systems and measures in the atomic energy field, align them with existing laws, and translate China's international obligations in areas such as nuclear safety and non-proliferation into domestic legal requirements.
- On 15 September 2025, IAEA and CNNC signed an agreement to establish the world's first IAEA Collaboration Center for Advanced Technology in Research Reactor Decommissioning at the CIAE.

2. GIF activities in China

- VHTR: Designs have been completed for the larger HTR power plant HTR-PM600 for electricity generation and HTR-PM600S for cogeneration of high temperature steam. Designs were based on multiple standardized NSSS modules verified on HTR-PM. The HTGR experience in China will contribute to IAEA activities to revise current safety requirements and a safety guide to cover non-water-cooled reactors.
- SFR CEFR completed the comprehensive digital transformation of the neutron detection system, rod control system and protection system, as well as the commissioning work, as scheduled. The annual maintenance work was also completed during this period. CEFR will be restarted after inspection by the nuclear safety regulatory authorities. R&D for the CiFR 1000 is underway, which is composed of six fast reactors and one fuel regeneration facility on the same site.
- SCWR: A pseudo-two-phase method has been developed to improve the stability of an in-house code for simulating the trans-critical depressurization process of the Chinese Supercritical SMR - CSR150, transitioning from supercritical to subcritical pressures following an accident.

Euratom

Ensuring autonomy and independence of energy-related supplies remains essential given the present geopolitical context. Several EU member states are expressing or reaffirming interest in deploying new or additional nuclear energy technologies, particularly SMRs, including advanced Gen IV systems. However, decisions on the national energy mix remain under the responsibility of each individual member state.

Policy developments in 2025

Clean Industrial Deal[1]: On 26 February 2025, the European Commission published the Clean Industrial Deal (CID), a comprehensive business plan aimed at decarbonizing, reindustrializing and innovating, with a significant focus on ensuring a "technology-neutral" approach, permitting for new nuclear technologies such as SMRs.

Nuclear Illustrative Programme[2] **(PINC)**: The PINC was updated in June 2025, outlining nuclear development and investment needs. Nuclear installed capacity is projected to grow from 98 GWe in 2025 to 109 GWe by 2050, requiring investments of around EUR 241 billion. Scenarios for SMR capacity range from 17 GWe to 53 GWe by 2050, with significant portions dedicated to heat and hydrogen production.

SMR Industrial Alliance[3]: In 2025, the SMR Industrial Alliance approved its Strategic Action Plan, which aims to drive the commercialization and deployment of SMRs across Europe by strengthening supply chains, reducing regulatory barriers, enhancing financing frameworks, and coordinating demonstration and first-of-a-kind projects. The Alliance selected an initial set of nine flagship SMR projects, representing a range of technologies and industrial partners. Three of the projects are Gen IV technologies: 1) EU-SMR-LFR (Ansaldo Nucleare, SCK CEN, ENEA and RATEN); 2) European LFR-AS Project (Newcleo); and 3) Thorizon One MSR (Thorizon).

State aid rules: In 2025, the European Commission approved, under EU state aid rules, a revised Belgian support measure for the lifetime extension of two nuclear reactors, Doel 4 and Tihange 3, Belgium's's most modern reactors, for ten additional years. It also approved a EUR 42 billion aid package to support the construction and operation of the first nuclear power plant in Poland. The nuclear plant, with an electricity generation capacity of up to 3 750 MW, is

1. https://commission.europa.eu/topics/competitiveness/clean-industrial-deal_en.
2. https://ec.europa.eu/commission/presscorner/detail/en/ip_25_1488.
3. https://single-market-economy.ec.europa.eu/industry/industrial-alliances/european-industrial-alliance-small-modular-reactors_en.

scheduled to start operating in the second half of the 2030s. The project will play a central role in Poland's strategy to decarbonize electricity production and address security of supply concerns.[4]

Safeguards: A new Euratom safeguards regulation[5] was adopted on 25 May 2025. The main changes are linked to considering different developments in recent years in the nuclear sector and in information technology. The aim is to ensure the continued effectiveness and efficiency of Euratom safeguards in guaranteeing the peaceful use of civil nuclear materials in the EU.

Euratom Programme Extension: The 2026-2027 Euratom Programme was adopted in June 2025, extending the previous program, with a budget of EUR 598.4 million. The program will focus on nuclear fission, safety and radiation protection; direct actions by the JRC; and fusion research and innovation.[6]

Multiannual Financial Framework (MFF): In September 2025, the European Commission proposed the MFF 2028-2034, with a funding allocation of EUR 9.8 billion for the Euratom Research and Training Programme. This doubled research and innovation budgets as compared to the previous MFF.[7]

Status of the Euratom adhesion to the new GIF Framework Agreement: The JRC is advancing Euratom's adhesion to the new GIF FA. A major milestone was achieved with a positive Council Decision on accession in September 2025, with FA signature anticipated in the first half of 2026.

Euratom contributions to GIF

JRC and Euratom member state representatives continue to proactively contribute to the six systems in steering committees, projects, working groups and task forces.

Indirect actions: Typically, several multi-partner projects are financed per year for a duration of 3-4 years. They are co-funded by the European Commission's Directorate-General for Research and Innovation (DG RTD). Recent projects include EASI-SMR, GEMINI 4.0, ESFR-SIMPLE and ECC-SMART, which focus on safety demonstrations, SMR versions of ESFR and collaborations on SCWR. Additional financing goes into cross-cutting programs such as the CONNECT-NM European partnership on Nuclear Materials, a European User Facility Network of infrastructures (OFFERR) and building a European Nuclear Competence Area (ENEN2plus).

Direct actions: The JRC contributes to GIF with research in safety, security and safeguards by design of SMR and AMR; it produces experimental data from tests on structural and nuclear materials, characterizes various nuclear fuels, and evaluates non-electric applications and workforce assessments, all in support to EU policies.

EU member states contributions: Examples include Polish contributions to HTGR POLA test reactor, Italian and Romanian contributions to ALFRED (LFR), and investments in facilities such as ATHENA and CHEMLAB in Romania.

Initiatives and events

SET Plan Conference: This event emphasized the safety of SMRs and nuclear integration in the future energy mix.

European Nuclear Energy Forum[8]: This event focused on nuclear investment strategies and digital applications.

FISA – EURADWASTE 2025 conferences: Supported by Euratom, these conferences were held in Warsaw under the Polish Presidency of the EU Council. There were over 700 participants, including stakeholders involved in the Euratom Research and Training Programme, and over 250 participants from the international nuclear Young Generation Network.[9]

The updated Nuclear Illustrative Programme (PINC) confirms that nuclear energy, including conventional reactors and SMRs, is expected to continue playing a role in the EU energy mix over the coming decades, in line with member states' plans and investment needs. Euratom remains committed to supporting nuclear research and innovation across fission and fusion, with the proposed increase in the MFF providing a stable framework for continued research and innovation activities, including on advanced reactor systems, safety, waste management and fusion development

France

Since 2023, President Emmanuel Macron has held four Nuclear Policy Councils to define the main orientation of the national nuclear policy. The Fourth Council was held in March 2025, which involved reviewing the progress made in implementing the EPR2 program, a program to build six new large-scale reactors by 2038, and refining strategies for uranium supply security, mining development and fuel recy-

4. https://ec.europa.eu/commission/presscorner/detail/en/ip_25_2963.

5. https://eur-lex.europa.eu/eli/reg/2025/974/oj/eng.

6. https://eur-lex.europa.eu/eli/reg/2025/1304/oj/eng.

7. https://commission.europa.eu/strategy-and-policy/eu-budget/long-term-eu-budget/eu-budget-2028-2034_en#factsheets.

8. https://energy.ec.europa.eu/events/18th-european-nuclear-energy-forum-2025-10-06_en.

9. https://fisa-euradwaste2025.ncbj.gov.pl.

cling. A key priority remains the renewal of nuclear fuel cycle facilities to reduce France's dependence on imported uranium. The Council confirmed the strategic objective of achieving closure of the nuclear fuel cycle from 2050 onwards. It requested that industrial players (EDF, Framatome and Orano), together with the CEA and all relevant stakeholders, submit to the government a work program for fast neutron reactor development, along with a proposal for industrial organization, by the end of 2025.

The Council also acknowledged the success of the first phase of the France 2030 program related to small modular and innovative reactors and confirmed the state's commitment alongside stakeholders to develop these technologies. From the France 2030 program, a total of 11 start-ups have been selected in the initial phase, representing a diverse range of reactor technologies, including SFR, HTR, MSR, LFR, LWR and fusion designs. These start-ups may be supported in different ways under the guidance of the CEA, which plays a role both in research and development, as well as giving advice to French authorities on the selection process.

In June 2025, the French government and the nuclear industry – EDF, Orano, Framatome and CEA – forged a long-term strategic partnership for innovation and workforce development for the 2025 to 2028 period. The partnership's key priorities include:

- boosting industrial performance;
- developing skills, with a target of 100,000 new jobs over the next decade;
- accelerating research and innovation;
- advancing sustainability, particularly through recycling and the circular economy.

On July 2025, a new General Administrator of CEA, Anne-Isabelle Etienvre, was appointed. During her public interview, she reaffirmed her willingness to commit CEA to revitalizing civil nuclear energy in France, with a particular focus on supporting Gen IV reactor projects. She emphasized CEA's leading role in the development of Gen IV fast neutron reactors, which aim to enhance nuclear waste management and optimize the fuel cycle. She highlighted the importance of integrating nuclear energy within a low-carbon energy mix, in synergy with renewable energy sources.

Under the France 2030 program, the government reaffirmed its support for SMR technologies, targeting the operation of a demonstrator reactor by the early 2030s. The CEA will continue to play a central role in guiding R&D developments.

On 14 December 2025, the European Pressurised Reactor (EPR) of Flamanville 3 officially reached 100% of its nominal power, achieving a gross installed electrical capacity of 1 669 MWe. This milestone for the French nuclear fleet followed authorization granted by the Nuclear Safety and Radiation Protection Authority (ASNR) on 12 December 2025, allowing operation above 80% power.

ASNR is the result of the merger of the Nuclear Safety Authority (ASN) and the Institute for Radiological Protection and Nuclear Safety (IRSN). This institutional reform, effective in January 2025, aims at streamlining regulatory oversight and improving decision making efficiency.

Japan

The *7th Strategic Energy Plan*, approved by the Cabinet on 18 February 2025, outlines Japan's long-term nuclear energy strategy. It calls for lifetime extensions of existing LWRs beyond 60 years, and development of advanced reactors – including innovative LWRs and fast reactors – as secure, decarbonized power sources after 2040. The plan emphasizes strengthening the fundamentals of nuclear fields through improved business conditions, safety and compensation frameworks, human resource development and supply-chain resilience. It promotes completion of the Rokkasho facilities, advancement of MOX reprocessing R&D, responsible plutonium management and stable operation of fuel cycle facilities. Other key priorities include safe decommissioning, final waste disposal, public engagement and international cooperation on safety, non-proliferation and peaceful use of nuclear energy.

On 10 February 2023, the Cabinet approved a basic policy aimed at implementing the Green Transformation (GX). The Japanese government's GX Implementation council (chaired by then Prime Minister KISHIDA Fumio) 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 focal points towards securing stable supplies of energy:

- promoting thorough energy efficiency improvement;
- making renewable energies the main power source;
- materializing plans for building next-generation advanced reactors within the sites of existing nuclear power plants that are to be decommissioned, ensuring that local communities are kept informed and understand the plans.

Fast reactor development is ongoing, based on the revised strategic roadmap for fast reactors that was decided by the Inter-Ministerial Council for Nuclear Power on 23 December 2022. In July 2023, the government selected a medium power pool-type SFR concept (planned to start operation in the 2040s) proposed by Mitsubishi FBR Systems as the design to be developed, and Mitsubishi Heavy Industries as the main manufacturer and constructor. The conceptual design and related R&D are taking place between 2024 and 2028, and from 2028 the decision to move on to the next step (i.e. basic design stage and licensing application for the demonstration reactor) will be made.

On 26 July 2023, the experimental fast reactor Joyo was granted a reactor modification license under the new regulatory standards, with modification and reinforcement of facilities and buildings ongoing. Joyo will be used for irradiation tests of fuels and materials being applied in the demonstration reactor, and for demonstration of medical radioisotope (RI) production demonstration.

The HTGR demonstration project has been undergoing based on the plan by Mitsubishi Heavy Industries, which is the core company of the project.

A demonstration project for hydrogen production using the existing HTTR is underway, with plans to demonstrate hydrogen production using high-temperature heat from the HTTR by JFY 2028. The NRA licensing process started in March 2025.

As of December 2025, and under the new nuclear regulation, 14 LWR units (12 pressurized water reactor [PWR] and 2 BWR) have been restarted, four (1 PWR and 3 BWR) have been certified, one unit is uncertified, and eight units (2 PWR & 6 BWR) are under review.

Korea

As of September 2025, there are 26 nuclear power plants (23 PWRs and 3 CANDUs) in operation in Korea with a combined nuclear capacity equivalent to 26.05 GWe, accounting for 16.9% of total generation capacity. In 2024, these nuclear power plants generated 188 754 GWh of electricity, representing 31.6% of total domestic production.

Nuclear energy policy and R&D in Korea

In March 2025, the government finalized the 11th *Basic Plan for Long-term Electricity Supply and Demand*, setting a target to increase the share of nuclear power generation from 30.7% in 2030 to 35.2% by 2038. The plan includes the construction of two new large-scale nuclear power plants, the long-term operation of existing reactors and the demonstration of a 0.7 GW SMR.

To strengthen demand-driven R&D and prepare for a Gen IV ecosystem, the government and private sector launched the Advanced Nuclear Reactor Research Association of Korea (ANRAK) in 2025. ANRAK serves as a dedicated public-private cooperation platform for advanced reactors, representing industry perspectives in policy making and coordinating joint development projects. It will play an important role in building an ecosystem where private companies actively participate in Gen IV reactor technology development and commercialization.

In September 2025, at the IAEA General Conference in Vienna, the Korean delegation introduced the "Artificial Intelligence for Nuclear Power" initiative. Korea emphasized applying AI, robotics and digital twin technologies across the entire lifecycle of design, operation and safety management to lead innovation in next-generation reactors. The delegation also highlighted Korea's ongoing R&D on SFR, HTGR and MSR, while stressing the importance of establishing a science-based and rational regulatory framework, to ensure the safe and responsible deployment of SMRs.

Sodium-cooled fast reactor (SFR)

Korea's SFR program has made steady progress in developing a power generation reactor known as SALUS, which is based on SFR technology, and incorporates transuranic (TRU) transmutation capabilities. SALUS is designed to produce 100 MWe of electricity and is being developed as a long-fuel-cycle core reactor targeted at the near-term SMR market. Current R&D projects in the SFR domain encompass three core areas: 1) enhancing sodium experimental infrastructure, including projects such as the STELLA program; 2) advancing modeling and simulation technologies, with emphasis on high-performance computing; and 3) innovating metal-fuel technologies, covering fuel fabrication, irradiation testing and the broader supply-chain development. In 2025, Korea is launching a new public-private partnership project for SFR development, with particular emphasis on enabling export-oriented SMR technology based on SALUS.

Very high-temperature gas-cooled reactor (VHTR)

In Korea, interest in carbon-free heat supply is growing, especially in industries that require high temperatures for their processes. To meet this demand, the government and private companies launched a joint development project in 2024 to design an HTGR that can supply heat at 750°C. This project brings together the Korea Atomic Energy Research Institute (KAERI), construction and plant engineering companies, and chemical process industries. It is designed to support close collaboration between technology developers and end-user companies to ensure the reactor meets real industrial needs. Based on this progress, KAERI is planning a demonstration project, with increasing emphasis on industrial demand for process heat supply.

Molten salt reactor (MSR)

Korea has initiated a new Gen IV project focused on developing key technologies for MSRs. Recognizing the significance of collaboration with private companies to expedite MSR demonstration, the government established a Molten Salt Reactor Development Agency in 2023. It also agreed to invest almost USD 21 million over four years in MSRs. Private companies have shown a keen interest in MSR technology development, and KAERI is actively collaborating with several leading Korean companies to realize MSR technology in the near future. Currently, Korea is extending the earlier conceptual design project into a new basic design project, aiming to move MSR development from early research towards more practical engineering.

South Africa

South Africa is still in the process of ratifying the revised GIF Framework Agreement.

Switzerland

Molten salt reactors (MSR): The long-term goal of MSR research in Switzerland is to improve the safety and sustainability of the nuclear fuel cycle, without focusing on a specific MSR concept. This research builds on national and international collaborations and includes extensive student training.

Switzerland (ETH Zurich and PSI) participates in the EU project ENDURANCE, which started on 1 October 2024. The first task at PSI within the project was to review and update previous MSR system code modifications. This work was completed in September 2025, and all past simulations of the MSRE and MSFR reactors were successfully reproduced. Further research will continue through a new Ph.D. position financed by Swiss Nuclear (the Association of Swiss Nuclear Power Plant Operators), scheduled to start in January 2026.

In parallel, within a Ph.D. position funded by the ENDURANCE project, PSI is coupling its two in-house tools, EQLD (a dedicated MSR burnup tool) and GEMS (the open-source Gibbs Energy Minimization code containing the PSI salt property database). This coupling will enable salt speciation calculations during burnup simulations.

In June 2024, PSI signed a large-scale experimental collaboration agreement with the Danish molten salt reactor developer Copenhagen Atomics. The related BALDER project is ongoing, focusing primarily on licensing aspects. Discussions with the Swiss nuclear regulator have been initiated.

S**odium fast reactor (SFR)**: Research on SFRs advanced during the reporting period under the Euratom ESFR-SIMPLE project, coordinated by CEA. As part of this effort, a new secondary system was designed for the large-power European Sodium Fast Reactor, replacing conventional shell-and-tube steam generators with compact printed-circuit steam generators. This design significantly reduces the size of the secondary system and the required building volume, with potential economic benefits currently under evaluation.

Additionally, a series of unprotected transients was analysed for the SMR version of the ESFR. The results demonstrate robust and inherently safe reactor behaviour, even under extreme accident conditions.

Heavy liquid metal cooled reactors (HLMR): Research on radionuclide volatilization from liquid metals continued within the Euratom PATRICIA and PASCAL projects. For PATRICIA, the final deliverables have been submitted and final reporting is in progress. In PASCAL, a manuscript on iodine speciation in evaporated LBE was published, and two additional manuscripts on tellurium evaporation are in preparation. Complementary experiments on tellurium volatilization are ongoing.

Two new projects, TRANSPARANT and LESTO, have gained momentum. These projects address safety -related topics of lead-alloy-cooled reactors. In TRANSPARANT (focused on partitioning and transmutation), a new Ph.D. student designed a gas loop for studying polonium evaporation under varying oxygen and moisture concentrations. Component acquisition and system construction are ongoing.

In LESTO (focused on safety studies for lead-cooled fast reactors), PSI is developing models to simulate the transport of volatile species released from the coolant by combining CFD and thermodynamic modeling. A master's thesis on CFD modeling of evaporation experiments was successfully completed in the late summer of 2025. The developed model will serve as a baseline for coupling with GEMS.

In the ANSELMUS project, and related to the design of the LFR ALFRED, a PSI postdoctoral researcher is investigating the interaction of noble gas fission products with liquid lead to support the development of fuel-pin failure detection systems. An experimental setup for studying xenon and krypton retention in liquid lead has been designed and is currently being commissioned.

Very high-temperature reactor (VHTR): The reports announced in the previous period, specifically on the SiC composite analysis and the in situ creep, are currently being worked on. Switzerland continues to play an active role in the VHTR program, holding a seat in the SSC, chairing the Materials PMB and leading its Working Group on Ceramics.

A major research effort is devoted to additive manufacturing of advanced materials, including ODS steels and metal composites, using directed energy deposition (DED) 3D printing. The related Ph.D. thesis is expected to be finalized in February 2026. A DED 3D printing machine has been installed, enabling operando studies of the printing process. Initial experiments using neutron diffraction provided insights into melt pool dynamics and more recent operando synchrotron X-ray diffraction measurements have expanded understanding of material behavior during printing.

The goal is to achieve a comprehensive understanding of printing mechanisms, including material interfaces and microstructure evolution, to optimize process parameters and improve component performance. PSI also plans to construct a new irradiation station for flexible irradiation studies, which could support future VHTR Materials PMB research. In March 2025, PSI hosted the VHTR SSC, CMBV PMB and Materials PMB meetings.

Politics and regulation: In August 2025, Switzerland's Federal Council proposed draft legislation to lift the existing ban on new nuclear power plants. The proposal seeks to amend the Nuclear Energy Act so that general licences can again be granted for new nuclear power plants and for modifications to existing ones.

ENSI participated in the 69th IAEA General Conference in September and engaged in bilateral talks to strengthen nuclear safety and regulatory cooperation.

Operation of the Swiss nuclear power plants and waste management: The Gösgen nuclear power plant (KKG) has been offline since its scheduled outage on 24 May 2025. The restart was delayed to February 2026 due to additional verification and reinforcement work on the feedwater system required by ENSI under updated safety assessment methods.

Framatome signed a contract in May 2025 to supply advanced Atrium 11 fuel assemblies to the Leibstadt nuclear power plant (operating from 2028 to 2035).

In June 2025, Nagra published its general licence applications for both the deep geological repository and the spent fuel encapsulation plant, making all related documents publicly available. The publication aims to facilitate broad public and technical discussion at an early stage of the licensing process.

Education: On 5 September 2025, the new semester of the joint EPFL–ETH Zurich Master's program in Nuclear Engineering began. With 30 enrolled students, the program has reached full capacity.

United Kingdom

The UK government remains committed to developing both large- and small-scale reactors. Hinkley Point C (HPC), a two-unit 3 200 MWe EPR plant, is under construction, with first operations expected in 2030, while the final investment decision for Sizewell C was confirmed in July 2025, using the same design and lessons from HPC. Great British Energy – Nuclear (GBE-N) has been established as the government's delivery body for new nuclear technologies, with Rolls-Royce SMR selected as the preferred partner to develop SMRs, subject to approvals. Additionally, the government's *Advanced Nuclear Framework* supports privately led advanced technology deployment.

Siting

A new *National Policy Statement for Nuclear Energy Generation* establishes a planning framework for nuclear projects beyond 2025. It reflects significant changes in the nuclear sector and supports a wider range of technologies, while providing clear guidance for developers to identify and assess potential sites using robust criteria.

Small modular reactors

Following a competitive process, Rolls-Royce SMR was chosen in July 2025 as the preferred partner for GBE-N, to deliver the UK's first small modular reactors. Wylfa in North Wales has been selected as the site for the first SMR nuclear power station.

Advanced modular reactors

The AMR Research Development and Demonstration project has advanced HTGR technology in collaboration with Japan, including significant redesigns of key systems and components. The UKJ-HTR's primary application is high-temperature heat production, with potential for supplementary electricity generation. In September 2025, Centrica and X-Energy signed a Joint Development Agreement to deploy up to 12 Xe-100 advanced modular reactors at Hartlepool, adjacent to the existing station scheduled to close in 2028. The proposed plant would generate up to 960 MWe and supply high-temperature heat to support Teesside's heavy industries.

Holtec International, EDF (UK) and Tritax announced plans in September 2025 to deploy Holtec's SMR-300 at a former coal-fired power station, aiming to supply clean power to new data centers. Also in September 2025, an MoU was signed between Last Energy and DP World to develop the world's first port-centric micro nuclear plant at London Gateway. The proposed PWR-20 microreactor is targeted to begin operations in 2030, powering the logistics hub and exporting surplus electricity to the grid.

Nuclear fuel

In September 2025, the UK government announced plans to legislate an end to Russian uranium use by 2028, signaling the need for alternative supply chains and supporting this through a GBP 300 million investment in UK high-assay, low-enriched uranium (HALEU) capability. Additionally, the Coated Particle Fuel program has commissioned a pilot-scale facility enabling end-to-end production of coated particle fuel including kernel production, coating, overcoating and compaction, restoring this capability in the United Kingdom after an absence of many decades.

Nuclear regulation

Their three-step Generic Design Assessment (GDA) process ensures safety, security and environmental standards. Rolls-Royce SMR entered Step 3 of the GDA process in July 2024, Holtec International's SMR-300 started Step 2 in August 2024 and GE-Hitachi's BWRX-300 reactor started Step 2 in December 2024.

Skills and capability

The *National Nuclear Strategic Plan for Skills* highlights the need to quadruple the UK's output of nuclear fission Ph.D.s to build a pipeline of experts for civil and defense sectors. To achieve this, the government has announced GBP 45 million for doctoral awards aimed at producing around 500 Ph.D. graduates over four cohorts who will be equipped with advanced technical skills, experience and industry connections to enter the nuclear workforce.

United States

Nuclear energy continues to be a vital part of the energy strategy for the United States to enable affordable, reliable and secure energy. The following is a list of key advanced reactor related accomplishments for 2025.

Executive orders relevant to nuclear energy

On 23 May 2025, President Trump announced four executive orders aimed at reinvigorating America's nuclear energy industry. The orders lay out a plan to modernize nuclear regulation, streamline nuclear reactor testing, deploy nuclear reactors for national security and reinvigorate the nuclear industrial base.

Reactor Pilot Program

To support these executive orders, in June 2025, the DOE established the reactor pilot program to leverage their authority to expedite the research and development of advanced nuclear reactor technologies with the larger goal of reaching criticality for at least three advanced nuclear reactor concepts located outside of the national laboratories by 4 July 2026. Eleven projects have been accepted into the pilot program: Aalo Atomics Inc., Antares Nuclear Inc., Atomic Alchemy Inc., Deep Fission Inc., Last Energy Inc., Oklo Inc for the Aurora reactor and the Pluto reactor, Natura Resources LLC, Radiant Industries Inc., Terrestrial Energy Inc. and Valar Atomics Inc. The reactor types span all concepts, including high temperature gas-cooled reactors, pressurized water reactors, heat pipe reactors, liquid metal cooled reactors and molten salt reactors.

Fuel Line Pilot Program

The DOE also established the Fuel Line Pilot Program, which supports the Reactor Pilot Program and establishes a domestic nuclear fuel supply chain for testing new reactors. The program leverages the DOE authorization process to build and operate nuclear fuel production lines for research, development and demonstration purposes and to provide a fast-tracked approach to commercial licensing. There are four active projects in the Fuel Line Pilot Program: Oklo Inc., Terrestrial Energy Inc., Standard Nuclear and Valar Atomics Inc.

AI Data Center and Energy Infrastructure Development on Federal Lands

In 2025, the DOE issued four Requests for Application (RFAs) to seek proposals from US companies to build and power AI data centers with nuclear or other energy generation at Idaho National Laboratory (INL), Oak Ridge Reservation, Paducah Gaseous Diffusion Plant and Savannah River Site (SRS).

Gen III+ SMRs

In December 2025, the DOE announced the selection of the Tennessee Valley Authority (TVA) and Holtec Government Services to support early deployments of advanced light-water SMRs in the United States. The project teams will each receive USD 400 million in federal cost-shared funding to advance initial projects in Tennessee and Michigan and help expand the country's capacity, while facilitating additional follow-on projects and associated supply chains.

Advanced Reactor Demonstration Program

In 2025, the U.S. Nuclear Regulatory Commission (NRC) completed the final safety evaluation for the TerraPower Natrium construction permit application, concluding that there are no safety aspects that would preclude issuing the construction permit. Additionally, NRC accepted Dow's construction permit application to build X-energy's first advanced SMR plant to power its manufacturing facility in Seadrift, Texas[10]. In May 2025, Kairos Power completed the first installation of nuclear safety-related concrete for their Hermes Low-Power Reactor, marking the start of "nuclear construction" on the project in Oak Ridge, Tennessee. Additionally, researchers at INL successfully created the first batch of fuel salt for the molten chloride reactor experiment.

National Reactor Innovation Center (NRIC)

The DOE's National Reactor Innovation Center is establishing two test beds at INL for testing fueled advanced reactor designs. In July 2025, DOE made conditional selections for the first tests in the DOME facility.

Advanced Reactor Concepts-20 (ARC-20)

The Office of Nuclear Energy (NE) supported three projects that enable the development of designs that could have significant impact on the energy market in the mid-2030s or later. Two of these projects, the Fast Modular Reactor (FMR) Conceptual Design project by General Atomics and the Horizontal Compact High Temperature Gas Reactor by the Massachusetts Institute of Technology, were successfully completed in 2025.

Microreactor Applications, Research, Validation and Evaluation (MARVEL)

The DOE is working to establish the MARVEL nuclear test bed at INL. In 2025, the team completed testing of a non-nuclear mockup of MARVEL to validate models for predicting thermal hydraulic behavior. Fabrication of key MARVEL components such as the guard vessel and reactivity control system were also initiated.

High-assay low-enriched uranium (HALEU) Distribution

In 2025, the DOE made conditional commitments to provide HALEU to eight US companies to meet near-term fuel needs.

10. NRC (2025), NRC Accepts for Review Construction Permit Application for Long Mott Generating Station, www.nrc.gov/cdn/doc-collection-news/2025/25-031.pdf.

A

Appendix 2. List of abbreviations and acronyms

3S	Safety, security and safeguards
AI	Artificial intelligence
ALFRED	Advanced Lead Fast Reactor European Demonstration Project
AM	Advanced manufacturing
AMME	Advanced manufacturing & materials engineering
AMME WG	Advanced Manufacturing and Materials Engineering Working Group
AMR	Advanced modular reactor (SMR models other than Light Water cooled)
ANL	Argonne National Laboratory (United States)
ANTSER	Advanced Nuclear Technology Cost Reduction Strategies and Systematic Economic Review
BWR	Boiling water reactor
C&S	Codes and standards
CEA	Alternative Energies and Atomic Energy Commission (France)
CFD	Computational fluid dynamics
CHF	Critical heat flux
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
CNRS	National Center for Scientific Research (France)
CNSC	Canadian Nuclear Safety Commission
DED	Direct energy deposition
DHRS	Decay heat removal systems
DOE	Department of Energy (United States)
ECC-SMART	European Canadian Chinese – Small Modular Reactor Technology project
EG/PG	Experts Group and Policy Group
EMWG	Economic Modeling Working Group
ENEA	National Agency for New Technologies (Italy)
EPR	European Pressurised Reactor
ESFR	European sodium fast reactor

ESFR-SIMPLE	European sodium fast reactor – Safe, simple, and flexible
ESG	Environmental, social and governance
ETWG	Education and Training Working Group
EU	European Union
FA	Framework Agreement
FCCI	Fuel cladding chemical interaction
FEM	Finite element models
FP	Fission Product
Gen IV	Generation IV
GFR	Gas-cooled fast reactor
GIF	Generation IV International Forum
GW	Giga Watt
GWe	Giga Watt electric
GWt	Giga Watt thermal
HALEU	High-assay low-enriched uranium
HIP	Hot isostatic pressing
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)
IP	Intellectual property
JAEA	Japan Atomic Energy Agency
JRC	Joint Research Centre (Euratom)
JRCMSD	Joint Research Centre Molten Salt Database
KAERI	Korea Atomic Energy Research Institute
KCl	Potassium chloride
KIT	Karlsruhe Institute of Technology (Germany)
LBE	Lead-Bismuth Eutectic
LFR	Lead-cooled fast reactor
LWR	Light water reactor
MFF	Multiannual financial framework

MIT	Massachusetts Institute of Technology
MMR	Micro Modular Reactor (Canada)
MoU	Memorandum of understanding
MOX	Mixed oxide (fuel)
MPA	Materials project arrangement
MPa	Mega Pascal
MSFR	Molten salt fast reactor (Euratom)
MSR	Molten salt reactor
MW	Megawatt
MWe	Megawatt electric
MWt	Megawatt thermal
Na	Sodium
NaCl	Sodium chloride
NEA	Nuclear Energy Agency
NEAMS	Nuclear Energy Advanced Modeling and Simulation
NEANH	Non-electric applications of nuclear heat
NECA	Non-electric and cogeneration applications
NRIC	National Reactor Innovation Center
NSTF	Natural Convection Shutdown Heat Removal Test Facility
NRCan	Natural Resources Canada (Canada)
ODS	Oxide dispersion strengthened
OPG	Ontario Power Generation
ORNL	Oak Ridge National Laboratory
PA	Project arrangement
PG	Policy Group
PGSFR	Prototype Gen IV Sodium-cooled Fast Reactor
PMB	Project management board
PNNL	Pacific Northwest National Laboratory
PP	Physical protection
PR	Proliferation resistance
PR&PP	Proliferation resistance and physical protection
PRPPWG	Proliferation Resistance and Physical Protection Working Group
PSI	Paul Scherrer Institute (Switzerland)
pSSC	Provisional System Steering Committee
PuCl3	Plutonium(III) chloride
PWR	Pressurized water reactor

R&D	Research and development
RFEOI	Request for Expression of Interest
RSWG	Risk and Safety Working Group
SA	System arrangement
SCK CEN	Belgian Nuclear Research Centre
SCWR	Supercritical water-cooled reactor
SCW-SMR	Supercritical water-cooled small modular reactor
SDC	Safety design criteria
SDO	Standards development organisations
SFR	Sodium-cooled fast reactor
SIAP	Senior Industry Advisory Panel
SiC	Silicon carbide
SME	Small and medium-sized enterprise
SMR	Small modular reactor
SNETP	Sustainable Nuclear Energy Technology Platform
SOEC	Solid-oxide electrolyzer cell
SSC	System Steering Committee
TRISO	Tri-structural isotropic (nuclear fuel)
TRL	Technology-readiness level
UCl3	Uranium(III) chloride
UCO	Uranium oxycarbide (fuel)
UKNNL	UK's National Nuclear Laboratory
ULOF	Unprotected loss of flow
UN	Uranium nitride (fuel)
UNIPI	University of Pisa
UO2	Uranium oxide
USNC	Ultra Safe Nuclear Corporation
UTOP	Unprotected transient over power
VHTR	Very high-temperature reactor
WNA	World Nuclear Association
XJTU	Xi'an Jiaotong University
ZrC	Zirconium carbide

THE GENERATION IV INTERNATIONAL FORUM

Established in 2001, the Generation IV International Forum (GIF) was created as a co-operative international endeavor seeking to develop the research necessary to test the feasibility and performance of fourth generation nuclear systems, and to make them available for industrial deployment by the 2030s. Under the new 2025 GIF Framework Agreement, GIF brings together countries, as well as Euratom, representing 27 EU member states, to co-ordinate research and develop these systems. GIF has selected six reactor technologies for further research and development: the gas-cooled fast reactor (GFR), the lead-cooled fast reactor (LFR), the molten salt reactor (MSR), the sodium-cooled fast reactor (SFR), the supercritical-water-cooled reactor (SCWR) and the very-high-temperature reactor (VHTR).

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.



A report produced by

GEN IV International Forum

Expertise | Collaboration | Excellence

Printed by the

NEA

NUCLEAR ENERGY AGENCY

www.gen-4.org