GEN IV International Forum

Expertise | Collaboration | Excellence

PREPARING THE FUTURE THROUGH INNOVATIVE NUCLEAR TECHNOLOGY

Outlook for Generation IV Technologies

Preparing the Future through Innovative Nuclear Technology

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The essential role for nuclear energy

The world's population is expected to expand from 7.6 billion people today to over 9 billion people by the year 2050, all striving for a better quality of life. As the earth's population grows, so does the demand for energy and the improved standards of living that access to energy brings: better health and longer life expectancy, improved literacy and education and other socio-economic benefits. Simply expanding the use of energy along the same mix of today's production options, however, does not satisfactorily address the environmental concerns over greenhouse gas emissions, air pollution and depletion of natural resources. For the earth to support its growing population while ensuring the sustainability of humankind's development, the use of energy sources that are clean, safe, reliable and affordable needs to increase. The Generation IV International Forum (GIF) believes that nuclear energy is a key pillar of a sustainable and low-carbon energy mix.

Nuclear energy produces no carbon emissions during electricity generation and has a very small lifecycle carbon footprint from the mining, manufacturing and transportation of materials and components. It is estimated[1] that more than 66 Gt of CO_2 emissions have been avoided through the use of nuclear energy since 1971. Nuclear electricity today avoids global emissions of about 1.7 Gt CO_2 every year and is a major contributor to clean energy, accounting for 40% of low-carbon electricity generation worldwide.[2] In spite of recent challenges facing the nuclear sector, the International Energy Agency (IEA) believes that nuclear energy will play a cornerstone role in low-carbon scenarios. According to the IEA, for strategies that limit global temperature increase to 2°C by the end of the century, nuclear capacity would need to more than double over the next four decades, representing 15% of worldwide electricity production by 2060.[3]

Furthermore, nuclear energy plays a significant role towards achieving the United Nations Sustainable Development Goals.[4] The IEA Sustainable Development Scenario[5] is calling for an integrated approach combining *climate policy* with significant action on *achieving energy access* and creating *cleaner air*. Nuclear energy can play a major role in meeting these ambitious goals. Advanced nuclear energy systems (i.e. evolutionary Gen III, small modular reactors (SMRs) and Gen IV systems) and innovative applications of nuclear technologies can provide solutions that can generate economic growth and support environmental stewardship in both the electric and non-electric sectors. These dispatchable technologies can support the integration of a growing share of intermittent renewables (e.g. solar PV and wind) – and provide a reliable source of decarbonised dispatchable power generation. Moreover, existing nuclear plants, a large share of which will continue

1. Based on *World Energy Outlook 2014* (OECD/IEA) data (pp. 420-421), extrapolated to 2018.
2. 2017 IEA data: electricity generation in 2017.
3. *Energy Technology Perspectives 2017*, OECD/IEA, Paris.
4. www.iaea.org/newscenter/news/how-iaea-will-contribute-sustainable-development-goals.
5. *World Energy Outlook 2017*, www.iea.org/weo2017.

to operate in the decades to come, and advanced reactors can complement renewables in addressing evolving market needs.

Gen IV systems, projected to be commercially deployed around mid-century,[6,7] offer additional features in terms of performance and sustainability compared to today's technology. The use of high temperature coolants such as helium, liquid metals, liquid salts, or supercritical water offers additional design flexibility, allowing significant increases in thermal efficiency, while also broadening industrial heat applications that can substantially displace fossil fuel usages. When deployed with advanced closed fuel cycles, some of the Gen IV systems can enhance the uranium utilisation by a factor of up to 100, thereby ensuring sufficient fuel resources by recycling fissile materials for fission reactors to produce energy for centuries to come. In the long term, alternative fuel cycles based on thorium could also power some of the Gen IV systems. Furthermore, advanced recycling options enable the reduction of the volume and radiotoxicity of the ultimate waste to be safely stored in deep geological repositories.

While recognising that not all countries see nuclear energy as part of their national energy policies, many others believe that innovative and advanced nuclear technologies can significantly contribute to economic growth and provide effective environmental stewardship, as recently testified by the successful launch of the Nuclear Innovation Clean Energy Future (NICE Future) initiative under the Clean Energy Ministerial.[8]

Considering the aforementioned arguments, the Generation IV International Forum is renewing its call on policymakers to acknowledge the real contributions that nuclear energy is making today to the mitigation of carbon emissions from the power sector, and to support the deployment of innovative reactors and applications of nuclear technologies to accelerate decarbonisation and support the long-term sustainability of the world's energy mix in the decades to come.

Current market challenges

Since the publication of the GIF R&D Outlook in 2009,[9] nuclear energy is facing a number of challenges,[10] These challenges include safety concerns after the Fukushima Daiichi NPP accident, cost and regulatory uncertainties in a context where many electricity markets are distorted because of low gas prices and specific policies supporting the deployment of renewable energy sources, as well as construction cost overruns and delays for some new build projects.

6. *Technology Roadmap Update for Generation IV Nuclear Energy Systems* (2014), www.gen-4.org.
7. *GIF R&D Outlook* (2018 update, forthcoming).
8. http://cleanenergyministerial.org/initiative-clean-energy-ministerial/nuclear-innovation-clean-energy-future-nice-future.
9. www.gen-4.org/gif/jcms/c_43526/2009-rd-outlook.
10. IEA/NEA *Technology Roadmap: Nuclear Energy* (2015): www.oecd-nea.org/pub/techroadmap.

At the same time, evolving energy markets represent new opportunities and drivers for the development of innovative reactor designs. Advanced reactor systems can indeed provide the necessary, low-carbon dispatchable energy supply needed to complement variable generation from renewables, provided the challenges faced by nuclear technology today are overcome through favourable policy measures, innovation and international co-operation in the field of research and development.

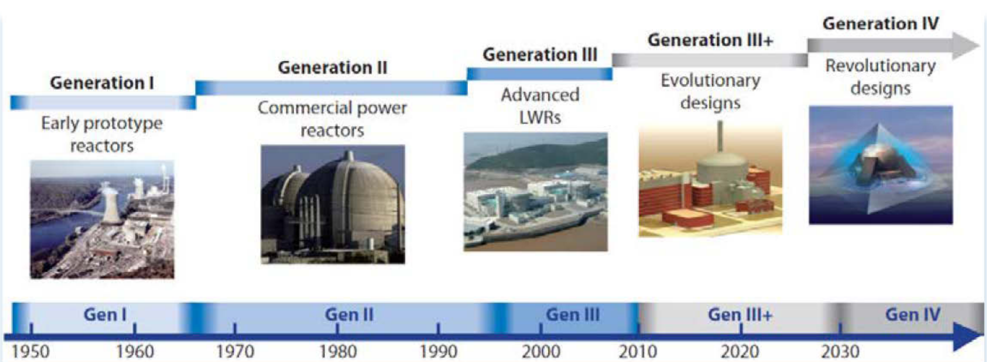
The Generation IV International Forum

GIF is an intergovernmental endeavour set up to carry out the research and development needed to establish the feasibility and performance capabilities of the next generation nuclear systems. GIF was established in January 2000 by 9 countries, and now includes 14 members,[11] all of which are signatories of the founding document, the GIF Charter,[12] and 11 of which have acceded to the Framework Agreement and are participating in collaborative R&D activities.

In its 2002 *Technology Roadmap* and the 2014 update, GIF defined four goal areas to move nuclear energy forward into its next, "fourth" generation (see Figure 1):

- safety and reliability;
- proliferation resistance and physical protection;
- economic competitiveness;
- sustainability.

Figure 1: **The four generations of reactor designs**



11. Argentina (non-active member), Australia, Brazil (non-active member), Canada, China, Euratom, France, Japan, Korea, Russia, South Africa, Switzerland, the United Kingdom (non-active member) and the United States.
12. The Charter was officially established in July 2001.

The *Technology Roadmap* also defined the R&D work required to achieve these goals and enable the initial deployment of Gen IV energy systems from 2030 onwards. Gen IV nuclear energy systems include the nuclear reactor and its energy conversion systems, as well as the associated fuel cycle technologies.

Closing the nuclear fuel cycle is an important component for achieving the sustainability goal of most GIF systems. The focus here is on recycling spent nuclear fuel, and managing each fraction using the best possible strategy. Fissile material, for example, can be recovered from the spent fuel and used to produce new fuel. Currently, almost 95% of the spent fuel from water reactors can be reused in the form of a natural uranium equivalent, reprocessed uranium and mixed oxide fuel.

With advanced fuel cycles using fast spectrum reactors and multi-recycling, it may be possible to breed fissile fuel from fertile material, producing as much or more fissile material than the reactor consumes. This would also significantly reduce the footprint of deep geological repositories for the safe disposal of waste. Advanced separation technologies for Gen IV systems are being designed to avoid the separation of sensitive materials, and include other features to enhance proliferation resistance and incorporate effective safeguards.

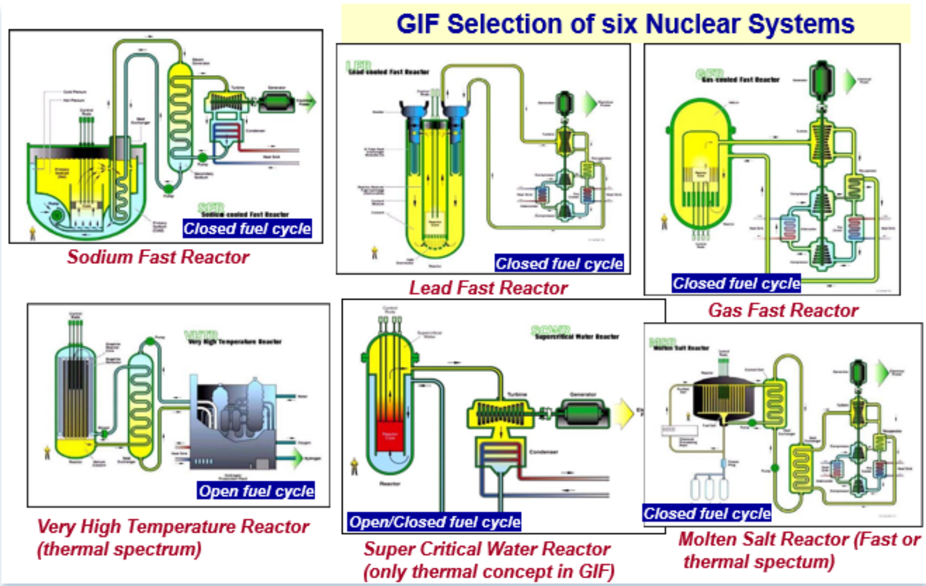
The *Technology Roadmap* clearly outlined the potential of combining different reactors in "symbiotic" fuel cycles, for example, combining thermal reactors and fast reactors, to accommodate transition periods. This was one of the primary motivations for having a portfolio of Gen IV systems rather than a single system, since combinations of several systems in the portfolio can provide a global symbiotic system.

The six GIF systems

In 2002, GIF ran a multi-criteria analysis to identify the most promising concepts against the four goal areas previously defined. Six systems (see Figure 2) were selected, from nearly 100 concepts, as Gen IV technologies:

- gas-cooled fast reactor (GFR), with a closed fuel cycle;
- lead-cooled fast reactor (LFR), with a closed fuel cycle;
- molten salt reactor (MSR), with thermal and fast neutron concepts and a closed fuel cycle;
- sodium-cooled fast reactor (SFR), with a closed fuel cycle;
- supercritical water-cooled reactor (SCWR), with fast and thermal neutron concepts (although designs with fast neutron spectrum are no longer developed by GIF), and an open or closed fuel cycle;
- very-high-temperature reactor (VHTR), with thermal neutrons and an open fuel cycle.

Figure 2: **The six GIF systems, four of which use a closed fuel cycle and a fast spectrum**



International collaboration

The involvement of GIF members in Gen IV systems R&D as of 2018 is presented in Table 1.

Table 1: **GIF members' involvement in Gen IV systems R&D**

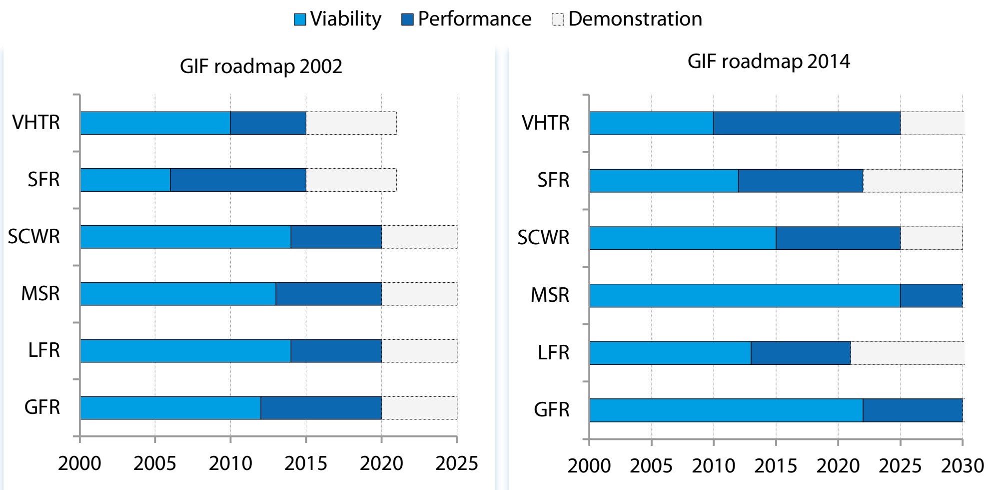
(date indicates signature of GIF Charter)

	AUS (2016)	Canada (2001)	China (2006)	France (2001)	Japan (2001)	Korea (2001)	Russia (2006)	RSA (2001)	Swiss (2002)	USA (2001)	EU (2003)
SFR			● (blue)	● (blue)	● (blue)	● (blue)	● (blue)			● (blue)	● (blue)
VHTR	● (blue)	● (green)	● (blue)	● (blue)	● (blue)	● (blue)			● (blue)	● (blue)	● (blue)
LFR					● (black)	● (black)	● (black)			● (black)	● (black)
SCWR		● (blue)	● (blue)		● (blue)		● (blue)				● (blue)
GFR				● (blue)	● (blue)						● (blue)
MSR	● (black)			● (black)			● (black)		● (black)	● (black)	● (black)

● (blue) : signatory of System Arrangement
● (green) : signatory of Project Arrangement
● (black) : signatory of MoU

The 2014 update of the *Technology Roadmap* confirmed the selection of these six systems and reassessed the technology readiness level (TRL) of these systems (see Figure 3). GIF recognises the benefits of fast neutron systems with a closed fuel cycle. The SFR and LFR concepts are clearly the most advanced among the four fast spectrum GIF systems.

Figure 3: **TRL level for the six GIF systems (2014 update of the Technology Roadmap)**



Status of development

Timelines and research needs were developed for each system and categorised into three successive phases:

- the *viability phase*, when basic concepts are tested under relevant conditions and all potential technical show-stoppers are identified and resolved;
- the *performance phase*, when engineering-scale processes, phenomena and materials capabilities are verified and optimised under prototypical conditions;
- the *demonstration phase*, when the detailed design is finalised and licensing, construction and operation of the system are carried out, with the aim of bringing it to the commercial deployment stage.

The status of development of the six systems in 2018 remains consistent with the 2014 TRL projections.

Innovation for advanced reactors

Gen IV systems are aimed at improved sustainability, economics, safety and reliability, proliferation resistance and physical protection through innovation. Three types of innovation are identified: institutional, organisational and technological.

Technical innovation

GIF is pursuing technical innovations and advanced reactor designs aiming at reducing costs, increasing revenues by identifying new market opportunities (e.g. heat market, hybrid energy systems, dispatchable energy) and improving thermal efficiency. Promising technologies dealing for instance with modular construction, "advanced concrete" solutions, innovative fuels and materials (accident tolerant fuels, oxide dispersion-strengthened cladding, etc.), or 3D printing of advanced fuels and/or components are being investigated by designers of advanced reactor systems. To better understand the impact of cross-cutting technologies on R&D activities, GIF decided to launch a feasibility study on advanced manufacturing and materials engineering.

In addition, high performance computing and improved modelling capabilities are opening the way for various applications in reactor physics and nuclear engineering, such as multi-criteria design optimisation, multi-scale and multi-physics calculation code systems, design of smart experiments for the qualification of innovative designs and components. To validate such tools and reduce uncertainties, new experimental data is required, to be provided by modern R&D infrastructures. Access to such facilities can be opened within the international community to share expertise and costs. GIF is therefore reviewing R&D infrastructures to identify existing key facilities, potential gaps and to facilitate access to such facilities.

Additional innovations in the area of power conversion (for instance advanced Brayton cycles), passive safety systems, fuel and core design, in-service inspection and repair (ISIR) technologies, fuel handling devices, are also being investigated.

Institutional innovation

Institutional innovations are also needed to share operational feedback and best practices, leading to international safety standards with the long-term objective of a unified and stable licensing process. The work of a dedicated GIF Task Force to develop safety design criteria (SDC) and guidelines (SDG) for the design of next generation SFR represents an important first step towards helping regulators become familiar with the technical characteristics of Gen IV systems and the associated safety research conducted within GIF. The approach is being extended to other Gen IV systems. Exchanges with the IAEA and experts from the OECD NEA Working Group on the Safety of Advanced Reactors (WGSAR) are contributing to the development of international safety standards and requirements for advanced reactors.

Organisational innovation

As recently observed in some countries, interest from the private sector in advanced reactors is a positive signal for the nuclear industry and an obvious opportunity to attract young, skilled and highly motivated scientists and engineers. The latter can bring a new innovation culture with ideas coming from other fields (applied mathematics, multi-criteria optimisation, augmented reality/digital economy, etc.) in support of the development of advanced reactors and fuel cycles. In addition to new approaches to engineering and design, this new generation is promoting new entrepreneurial ways of thinking and working, and enthusiastically developing new business model approaches for the development of nuclear energy applications. GIF recently launched a Task Force providing a platform to enhance open education and training (E&T) through webinars so as to facilitate networking of individuals and organisations involved in the development of Gen IV systems and contribute to maintaining a highly skilled workforce in the nuclear sector.

Meeting Gen IV goals

Risk and safety

Gen IV systems have taken into account the lessons learnt from the Fukushima Daiichi accident, by reinforcing the defence-in-depth approach against external events and promoting the robustness of the safety demonstration. Current R&D work focuses on enhancing the safety characteristics of the Gen IV systems, aiming at excluding any large radioactive release to the environment in case of accidents, to eliminate the need for emergency measures and minimise the impact on the population.

Safety design criteria and guidelines first developed for SFR systems are being extended to other systems. White papers on the safety of GIF systems are regularly updated along with the GIF safety basis report. The GIF integrated safety assessment methodology was developed as a technology neutral toolkit to evaluate the safety characteristics of all Gen IV systems.

GIF will continue to engage with regulatory authorities and technical support organisations (through the WGSAR, for instance) with the goal of harmonising requirements in the long term and better understanding licensing applications and costs.

Proliferation resistance and physical protection

GIF has developed a proliferation resistance and physical protection (PR&PP) methodology[13] and has defined the metrics against which PR&PP can be measured.

13. GIF PRPPWG, "Evaluation Methodology for Proliferation Resistance and Physical Protection of Generation IV Nuclear Energy Systems", Rev. 6, GIF/PRPPWG/2011/003 (2011), available at: www.gen-4.org/gif/jcms/c_9365/prpp.

White papers on the PR&PP aspects of all Gen IV systems have been prepared and documented in a report openly available and updated periodically. The PR&PP evaluation methodology is available for use by designers for more detailed assessments of Gen IV systems.

GIF is promoting the integration of safety, security and safeguard requirements in the development of new fuel cycles and reactors (PR&PP by design).

Economics

GIF is carrying out economic modelling analysis and has developed a methodology to assess Gen IV systems against the economic goals of GIF. This methodology consists of a comprehensive guideline document for cost estimation, and an EXCEL-based software package called G4ECONS that is widely used by practitioners. GIF has also developed a new work stream on the economic aspects and challenges of deployment of Gen IV systems in an integrated grid with significant renewable energy resources, requiring flexible operation and load following capabilities. This work is continuing with the designers of the six GIF systems in order to identify the merits and R&D challenges of each system in order to meet flexibility needs and address new market opportunities, such as non-electric applications.

Sustainability

According to the well-known definition[14], "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs". In the GIF roadmap, sustainability goals are defined with a focus on waste management and resource utilisation. Other factors that are commonly associated with sustainability, such as economics and environment, are also considered in a wider definition.

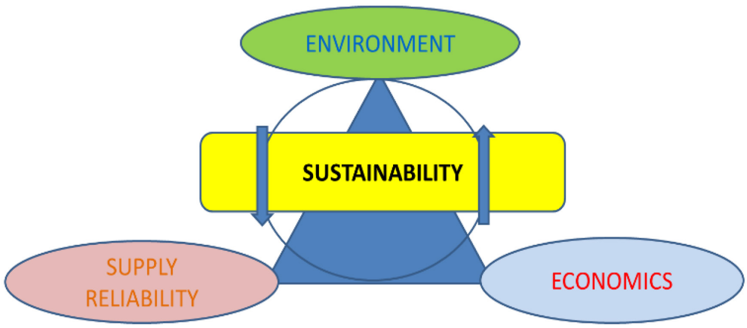
As mentioned above, the environmental benefits of nuclear energy extend beyond the low-carbon production of electricity. For example, nuclear energy can be used to generate hydrogen, which can then be used in a range of applications including transport, and to desalinate water in areas where fresh water is in short supply. The GIF Senior Industry Advisory Panel, consisting of industry representatives from GIF member countries, has highlighted three attributes for Gen IV systems to compete in the energy market: competitiveness, public acceptance and flexibility to meet future market needs (operational, deployment and product flexibility).

The commercial fleet deployment of Gen IV systems is expected around the middle of the century. Industry needs to have a proven technology available in this time frame, and timely R&D and demonstration in the next decade should make this possible.

14. *Our Common Future* (also known as the Brundtland Report, 1987), www.un-documents.net/our-common-future.pdf.

The attributes indicated above relate to the wider definition of sustainability, depicted in the energy policy triangle (Figure 4) with three drivers: environment, supply reliability (or security), and economics (affordability). Sustainability results from satisfying all three drivers.

Figure 4: **Energy policy triangle**



Conclusion

Recognising that not all countries see nuclear energy as part of their national approaches, there remains a need for investigating the role that clean, innovative and advanced nuclear technologies can play in simultaneously furthering economic growth and effective environmental stewardship.

The Generation IV International Forum calls on policymakers to acknowledge the real contributions that nuclear energy is making today to the mitigation of carbon emissions from the power sector, and to further support R&D and consider accelerating the deployment of advanced reactors and innovative applications of nuclear technologies, including heat applications, to further contribute to the decarbonisation of the world's energy mix in the decades to come.

Key objectives and R&D activities for the six Gen IV systems in the next decade

Sodium fast reactor (SFR)

Prototypes in operation in 2020-2030

- Advanced non minor actinides bearing, minor actinide bearing, and high burn-up fuels evaluation, optimisation and demonstration (a cross cutting challenge for all fast neutron spectrum systems)
- Development of innovative ISIR technologies
- Advanced energy conversion systems
- Development of leak before break (LBB) assessment procedures and instrumentation
- Development of steam generators including investigations of sodium water reactions and development of advanced inspection technologies
- Validation of passive decay heat removal
- Improved economics

Lead-cooled fast reactor (LFR)

Prototypes in operation in 2020-2030

- Phenomenology of the lead water and lead steam interactions
- Prevention and mitigation of sloshing
- New corrosion resistant materials (including surface modifications)
- Operation and maintenance
- Fuel and fuel reprocessing (nitride, minor actinide bearing, and high burn-up fuels)
- Advanced modelling and simulation.
- Severe accident management
- Design code and standards

Molten salt reactor (MSR)

Baseline design of molten salt reactor (liquid fuel)

- Salt and material combinations
- Integrated (physics and fuel chemistry) reactor performance modelling and safety assessment capabilities
- Demonstration of the MSR safety characteristics at laboratory level and beyond
- Establishment of a salt reactor infrastructure and economy that includes affordable and practical systems for the production, processing, transportation, and storage of radioactive salt constituents
- MSR safety approach, licensing and safeguard framework
- Alternative track with solid fuel: explore commonalities with other systems using molten salts or HTR fuels

Gas-cooled fast reactor (GFR)

2 400 MW_{th} reference design

- Finalising design and initiating licensing process of a GFR experimental reactor (ALLEGRO)
- Qualification of the mixed oxide fuel adapted to the specific operating conditions of the ALLEGRO start-up core
- Development of dense fuel elements capable of withstanding very high temperature transients
- Validation studies (experiments addressing innovative ceramic materials, unique GFR specific abnormal operating conditions such as depressurisation and steam ingress, …)
- Air and helium tests on subassembly (mock-ups under representative temperature and pressure conditions)
- Large-scale air and helium tests to demonstrate passive decay heat removal functions
- GFR-specific components development and qualification

Key objectives and R&D activities for the six Gen IV systems in the next decade (cont'd)

Supercritical water reactor (SCWR) **Pressure vessel and pressure tube designs**	**Very-high-temperature reactor (VHTR)** **1st step: reactor with outlet temp. 750-900°C**
• Safety analysis • Testing of materials and selection and qualification of candidate alloys • Out-of-pile fuel assembly testing • Qualification of computational tools • Integral component tests • In-pile tests of small-scale fuel assembly • Start design studies of prototype • NB: Some of these challenges can be mitigated through lowering the operating temperature of the coolant in SCWRs in order to reduce the peak cladding and fuel temperatures	• Qualification of graphite, hardening of graphite against air/water ingress, management of graphite waste • Coupling technology and related components • Establishment of design codes and standards for new materials and components • Advanced manufacturing methods • Costs reduction, licensing and siting issues • System integration with other energy carriers in hybrid energy systems • Feedback from demonstration and industrial prototype tests • 2nd step: Materials and fuels for temperatures up to 1 000°C and fuel burnup of 150-200 GWd/tHM

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