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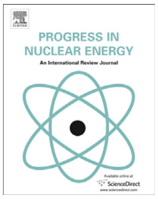

Looking ahead at reactor development

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ABSTRACT

This paper provides a historical overview of the development of advanced reactors, with a focus on Generation IV reactors and the unique international cooperative R&D framework that was put in place within the Generation IV International Forum. Drawing on the expertise developed at the Nuclear Energy Agency, the paper analyses the challenges for deploying advanced reactors in future energy markets, including evolving market requirements and economic considerations, regulatory challenges, research infrastructure needs and human resource issues. The paper concludes on the role of nuclear research and innovation to ensure the conditions for successful deployment of advanced reactors and competition with alternative technologies.

1. Advanced reactors

The use of the term “Advanced Reactors” in the community of nuclear research has a complex background. Early in the development of nuclear reactors, a range of concepts and configurations were considered and tested. Many of the concepts considered “advanced reactors” today have roots and, in some cases, were deployed in prototype form many decades ago. The U.S. Experimental Breeder Reactor I, a liquid metal-cooled reactor that used plutonium fuel, began producing electricity in 1951. Many other technologies, ranging from gas-cooled reactors, molten salt fuel systems, and supercritical water reactors have all been tested in by laboratories in many countries.

Prompted by successful demonstrations of water-cooled reactor technology, such as the Shippingport Atomic Power Station, the world generally came to commercial deployment of nuclear energy around designs of nuclear power plants using mostly light water, but also heavy water. Other approaches remained the subject of research and development.

Water–cooled reactor systems have been extraordinarily successful around the world. Today, conventional water cooled reactor systems comprise the largest source of clean electricity generation in OECD countries and the second largest such source in the world after hydroelectric power. Moreover, new water-cooled technologies available today represent significant improvements in safety and efficiency.

Nevertheless, it is also the case that the markets and operating environment for energy production are evolving. In the past, the absolute cost of nuclear construction was somewhat less important than the long-term reliability it provided; mostly because electricity demand was seen as a factor that would always increase. In many developed countries, economic growth has slowed considerably and energy-intensive heavy industries have given way to service and knowledge-based industries. Growth in electricity demand in these countries is far lower than in countries such as China and India. Further, the cost of constructing and operating new nuclear plants is under tremendous scrutiny in the shadow of recent financially-prompted plant closures and cost overruns in highly visible construction projects.

Additionally, expectations for nuclear safety have risen considerably in the aftermath of the Fukushima Daiichi accident in March 2011; market prices for electricity in many countries have become highly uncertain with the advent of various well-intentioned but disruptive governmental actions and the accelerating introduction of state-supported wind and solar capacity; fossil fuel (coal and gas)

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[3] The NEA is the association of 31 countries that represent the most advanced nuclear technology, safety, and science infrastructures in the world. NEA facilitates cooperation among its members and strategic partners such as China to address complex issues associated with the beneficial use of nuclear technology.

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prices have also dropped, especially due to the development of non-conventional gas resources in some countries, impacting the profitability of nuclear power plant operation; governments around the world have struggled to meet their commitments regarding the disposal of spent nuclear fuel; and while civilian nuclear power plants present no significant technical risk of nuclear proliferation, some suspect a few governments might use civilian nuclear activities to cloak covert weapons programs.

These headwinds have developed at the same time as important factors encourage a greater use of nuclear energy. Notably, governments of the world have indicated a desire to reduce emissions of carbon dioxide; the agreement implementing the outcomes of the 2015 Paris Climate Conference of the United Nations Framework Convention on Climate Change is the most salient indication of these policies. The need to reduce significant air pollution levels in large urban areas, for instance in China or India, is also a driver for deploying “clean air” technologies such as nuclear energy. Further, concerns about energy security and reliability have become a central interest for many countries, particularly those working toward improving the quality of life for their citizens.

The desire to find technology solutions to address the challenges while enabling nuclear energy to play a global role in the future, ever-evolving energy picture has sparked a new spirit of innovation and exploration, with several countries and numerous small companies attempting to bring new concepts to the fore.

As the next steps in the development of nuclear energy are considered, light water reactor (LWR) technology continues to play a prominent role. The development of various small modular reactors (SMRs) is continuing and, in contrast to many of the organisations pursuing the development of Generation IV systems, SMR technologies are receiving very substantial resources and investment from large industrial companies; a factor which improves the prospects for commercialisation in the foreseeable future.

Some light water SMR technologies seem likely to reach the market in the next several years and a few show considerable promise by giving ultimate expression to passive safety design approaches. Some SMRs could provide for more efficient and flexible operations and could prove more readily able to coexist with wind and solar technology in today's intensively cost-focused economic and market models.

However, even these advanced technologies do not address fully all of the safety, economic, nuclear waste, sustainability, and non-proliferation issues associated with the water-cooled reactor based nuclear industry. Some of these concerns become relevant only when very long time frames are considered or if use by developing countries are an important goal for designers. It is for these reasons that researchers and developers around the world devote their energies to the development of Generation IV nuclear energy systems.

2. Generation IV technology and the generation IV International Forum

The term “Generation IV” was coined to differentiate advanced light water reactors, including small modular reactors using light water (i.e., Generation III or III + technologies; see Fig. 1), from a set of technologies judged to have the promise to surpass light water technology in safety, economics, and other measures to be discussed later. Generation IV systems are not designated as such simply because of the coolant they apply; they ideally incorporate engineering features and strategies that allow them to address fully the concerns highlighted in the previous section.

At the end of 2016, 55 out of the 61 reactors under construction were of LWR technology (mostly Generation III/III + designs), and

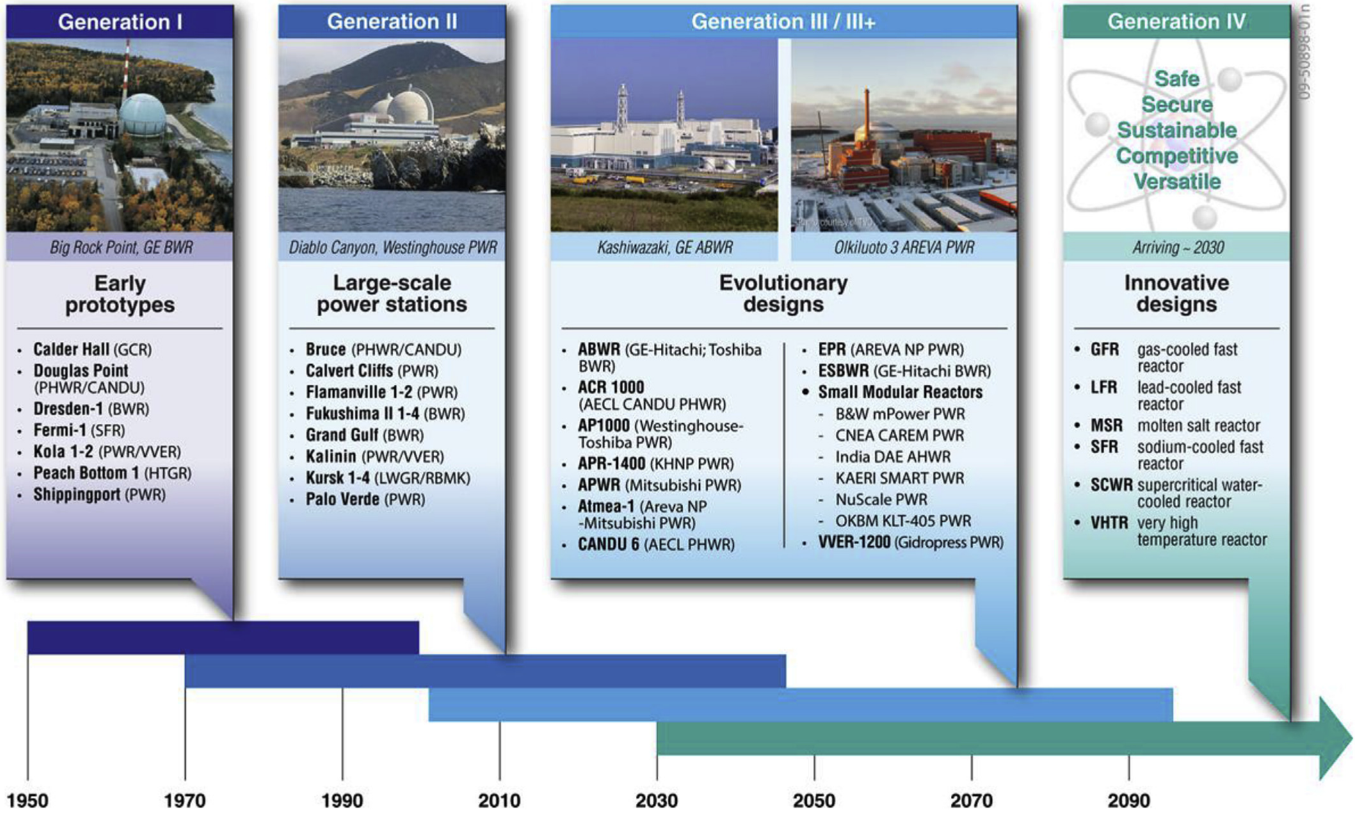

Fig. 1. Evolution of fission reactor technology (www.gen-4.org).

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four of heavy water reactor technology. The remaining two, while not meeting Generation IV goals, are based on sodium-cooled fast reactor and gas-cooled high temperature reactor technologies. Both technology areas are being explored within the Generation IV International Forum (GIF). The construction of the 200 MW pebble-bed gas cooled reactor HTR-PM in China, scheduled for completion at the end of 2017, marks an important step towards the goal of Generation IV Very High Temperature Reactors (VHTR). India's 500 MW Prototype Fast Breeder Reactor PFBR in Kalpakkam, now scheduled to reach criticality in 2017, is based on sodium-cooled fast reactor (SFR) technology, a proven technology for several decades, with prototypes having operated in the United States, the United Kingdom and France, and experimental reactors in operation in Japan and in China.

Russia has by far the most extensive recent experience in sodium reactor technology, and 2016 saw the start of commercial operation of Russia's largest SFR so far, BN-800 (800 MW), in Beloyarsk. There are also a large number of Generation IV-related development projects at various stages of design: France's ASTRID project for a 600 MW SFR prototype, Russia's BN-1200 SFR project or BREST-OD-300 for a lead-cooled fast reactor (LFR), and more recently, the U.S. company TerraPower's Travelling Wave Reactor, which is based on SFR technology. There are also many small modular reactor designs based on gas-cooled high temperature reactor technology or molten salt reactor (MSR) technology. In all cases, research and development – and innovation - will be necessary to carry out the design, and perform the validation and qualification of materials, fuels, systems and components and ensure that these advanced reactors meet the safety, reliability, flexibility and economic performance necessary for successful market deployment.

Formed in 2001, the GIF brings together 13 countries including Argentina, Australia, Brazil, Canada, China, France, Japan, the Republic of Korea, the Republic of South Africa, the Russian Federation, Switzerland, the United Kingdom and the United States, as well as Euratom, itself representing the 28 EU member countries. The main objective of the forum is precisely to coordinate research and development (R&D) into advanced nuclear energy systems that offer improved sustainability, economics, safety and reliability, proliferation resistance and physical protection. By pooling and leveraging research efforts, and drawing on skills and facilities of participating countries, the GIF aims at accelerating the development of Generation IV systems up to their commercial deployment.

One of the first tasks carried out by the GIF was to select advanced reactor concepts for which there was consensus to move R&D forward. More than a hundred concepts, received from developers from around the world, were screened down to a final set of six systems. This required consensus among experts on a number of criteria which Generation IV systems should meet. In the end, six conceptual nuclear energy systems (see Fig. 2) were selected in July 2002 for collaborative R&D, comprising the sodium-cooled fast reactor (SFR), the very high temperature reactor (VHTR), the supercritical water-cooled reactor (SCWR), the gas-cooled fast reactor (GFR), the lead-cooled fast reactor (LFR), and the molten salt reactor (MSR).

A year later, a technology roadmap for the GIF was published. The 2002 Technology Roadmap of the GIF (GIF, 2002) was updated with the publication in January 2014 of the GIF's “Technology Roadmap Update” (GIF, 2014), which provides a clear picture of how the GIF members will focus their R&D efforts in the coming decade, with several systems having already entered (VHTR, SFR or LFR) or are entering (SCWR) their so-called ‘performance phase’ (testing of processes and materials at engineering scale under prototypic conditions) in the period to 2023 (Kelly, 2014). It should however also be recognised that reduced R&D budgets in the participating countries have slowed down the rate of progress in advancing these technologies towards their demonstration phase.

2.1. GIF goals

Eight goals were developed for Generation IV nuclear energy systems. In the area of economics, Generation IV nuclear energy systems aim to have:

1. A clear life-cycle cost advantage over other energy sources and
2. A level of financial risk comparable to other energy products.

Given the increasingly deregulated and uncertain energy markets, this is an absolute necessity. The risks associated with construction are not the only ones to be considered, as external factors such as public acceptance and licensing may be even more important. Life-cycle costs are typically costs at the plant level (busbar), and include capital costs, operation and maintenance costs, fuel cycle costs and decommissioning and dismantling costs. System costs, for example grid costs as well externalities should also be considered. Contrary to other energy sources, nuclear energy already includes decommissioning and dismantling costs in overall production costs. Currently, capital costs and length of construction, including considerable interest payments before any income is earned, seem to be the main obstacles new nuclear energy systems face.

Regarding safety and reliability, Generation IV nuclear energy systems aim to:

3. excel in both of these areas,
4. reduce the likelihood and severity of reactor core damage and enable the rapid return to plant operation and
5. eliminate the need for off-site emergency response.

Existing nuclear power plants already meet a high level of safety and reliability. The Fukushima Daiichi accident has rightly led to a further strengthening of safety requirements which all nuclear power plants must meet, whether existing plants or those to be built, irrespective of their technology (while noting that in some cases, the resilience of Generation III + reactors already satisfy the new requirements). Reducing the number of events that can initiate accidents, reducing the probability of severe core damages and mitigating their consequences, notably potential off-site radioactive releases, should be achieved by using future technological advances. It is anticipated that these technologies will also benefit the performance and the economics of Generation IV nuclear energy systems as well as protect the owner's investment and increase local public confidence.

In terms of sustainability, Generation IV nuclear energy systems and fuel cycles aim to:

6. provide sustainable energy generation through long-term availability of systems and effective fuel utilisation for worldwide energy production,
7. minimise and manage their nuclear waste, enabling them to surpass current levels of protection for public health and the environment, and notably reduce the long-term stewardship burden in the future and
8. increase the assurance that they are very unattractive and the least-desirable route for the diversion or theft of weapons-usable materials.

Elaborated in the late 1980s, the concept of sustainable development was defined as “development that meets the needs of the present without compromising the ability of future generations to

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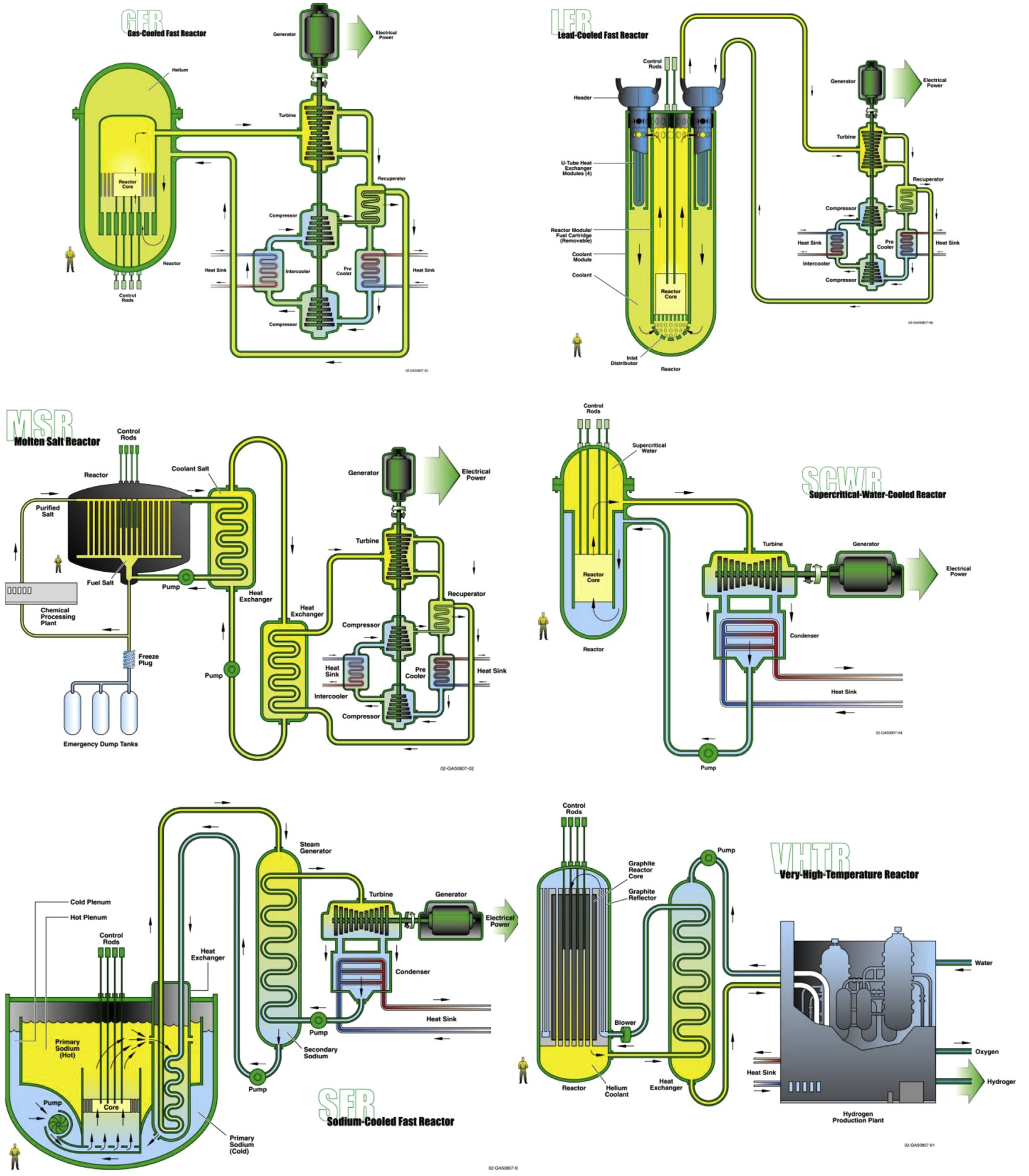

Fig. 2. GIF systems, conceptual diagrams (courtesy of GIF).

meet their own needs". Producing energy in accordance with sustainable development requires the conservation of natural resources, protection of the environment and avoiding, to the greatest extent possible, transmitting burdens on to future generations. Increasingly, sustainable development is examined from three points of view: economic, environmental and social. In the Generation IV context, the "sustainability" category includes aspects related to the above definitions and not previously covered under the economics and safety and reliability goals.

With the international convention implementing the outcomes

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of the COP21 conference entering into force in November 2016, countries around the world have stated their intent to reduce greenhouse gas emissions to levels that will ensure global warming is limited to well under 2 °C at the end of the century. Analysis performed by the Nuclear Energy Agency (NEA) and the International Energy Agency (IEA) indicate that reaching these goals will be very difficult without an ambitious deployment of new nuclear electricity-generating capacity. The IEA 2 °C scenario, which attempts to project the most most-effective path to meet global carbon emission reduction targets, projects that over 900 GW installed nuclear capacity would be needed globally by the middle of the century (IEA-NEA, 2015a) (NEA, 2016). While Generation III/III + LWRs are likely to be the workhorse of any such nuclear expansion, Generation IV systems and other advanced reactors are also likely to be gradually deployed in parallel, at a smaller rate until 2050, addressing specific needs such as closing the fuel cycle and improving on the fuel efficiency, or offering low carbon process heat applications. The rate at which Generation IV technologies can be deployed (whether evolutionary "large" reactors or small modular reactors) in the long term will, to a large extent, depend on the competitiveness of these systems against LWRs but also alternative low carbon technologies such as variable renewables and storage, or carbon capture and storage (CCS). The GIF emphasised the long-term role of Generation IV systems in tomorrow's decarbonised energy future in a joint statement published on the GIF website in November 2015 (GIF, 2015).

2.2. Six GIF systems

As mentioned above, the six systems that were selected by the Generation IV International Forum for further advancement were the result of a down-select process involving more than a hundred concepts. The six systems represent a mixture of fast neutron reactors (the SFR, the LFR and the GFR – as well as some of the SCWR concepts), thermal reactors (the VHTR and most of the SCWR concepts), and epithermal reactors (the MSR). Coolants include water (SCWR), helium (GFR and VHTR), sodium (SFR), lead or lead-bismuth for the LFR, and fluoride salts (MSR), and their sizes vary from a few tens or a few hundreds of MWs for the SMR versions to large reactors comparable to today's largest LWR designs. Table 1 summarises the technical features of the six Gen IV systems.

2.3. Towards the deployment of generation IV reactors

According to the updated roadmap (GIF, 2014), the first Generation IV systems that are likely to be demonstrated as prototypes are the SFR, the LFR, the SCWR and the VHTR. The demonstration of GFR and MSR are more long term given some technical challenges that need to be addressed. The benefits of fast reactors include a better use of fuel – for the same amount of uranium, fast reactors can produce 60 or more times the energy than Gen III LWRs by multi-recycling of the fuel – and improved waste management by reducing long-term radiotoxicity of the ultimate waste. The main advantage of the SCWR is its improved economics compared to LWRs, due to higher efficiency and plant simplification. The benefits of VHTRs include the passive safety features of high temperature reactors and the ability to provide very high temperature process heat that can be used in a number of cogeneration applications, including the massive production of hydrogen through thermo-chemical cycles or high temperature steam electrolysis. Many industrial process heat applications up to temperatures of around 550 °C are also accessible to other Generation IV systems.

As seen in Fig. 1, the start of the demonstration and commercial deployment of Gen IV reactors is not foreseen before 2030 at the earliest. For many decades after that, Gen IV reactors will likely be deployed alongside advanced Gen III reactors. Yet, because of the potential benefits that these reactors can bring, innovation through R&D and demonstration projects, especially in the area of fuels and materials that can withstand higher temperatures, higher neutron fluxes or more corrosive environments, is needed to bring concepts towards commercialisation. Prototype development and testing is seen as particularly important. Construction, licensing and operation of Gen IV prototypes in the period up to 2030 are necessary if Gen IV technology is to be deployed commercially from 2030 onwards.

A number of countries are already pushing ahead with the design and/or construction of reactor prototypes that prepare the ground for future Generation IV designs. For fast reactor technology, the Russian Federation has a long history of operating sodium-cooled reactors. The 600 MW BN-600 reactor, connected to the grid in 1980, is still in operation today, and the 800 MW BN-800 reactor entered commercial operation at the end of 2016. An ever larger reactor is currently being designed, BN-1200, which could be deployed by 2030 and would meet Generation IV goals. France is also moving ahead with the detailed design study of the advanced sodium technological reactor for industrial demonstration (ASTRID) reactor, which could be completed by 2019, though the decision to build has not been taken yet. China is operating the China experimental fast reactor (CEFR), a 20 MW research reactor connected to the grid in 2011, and is designing a 1000 MW prototype reactor. Finally, India, which is not a member of GIF, has been working on sodium-cooled fast breeder reactors for decades, for their potential to operate on the thorium cycle, and is planning to start the commissioning of the 500 MW prototype fast breeder reactor (PFBR) before the end of 2017. Modular SFRs, such as the PRISM reactor based on the integral fast reactor technology developed in the United States in the 1980s, are also being considered by some countries as part of a plutonium (from reprocessed spent fuel) recycling strategy. The TerraPower company is also developing a sodium-cooled fast reactor based on the

Table 1
Technical characteristics of the six Gen IV systems (www.gen-4.org).

System	Neutron Spectrum	Coolant	Outlet Temperature°C	Fuel cycle	Size (MW)
VHTR(Very-high-temperature reactor)	Thermal	Helium	900–1000	Open	250–300
SFR(Sodium-cooled fast reactor)	Fast	Sodium	500–550	Closed	50–150 300–1500 600–1500
SCWR(Supercritical-water-cooled reactor)	Thermal/fast	Water	510–625	Open/closed	300–700 1000–1500
GFR(Gas-cooled fast reactor)	Fast	Helium	850	Closed	1200
LFR(Lead-cooled fast reactor)	Fast	Lead	480–570	Closed	20–180 300–1200 600–1000
MSR(Molten salt reactor)	Thermal/fast	Fluoride salts	700–800	Closed	1000

Travelling Wave Reactor concept. While MSR was considered until recently one of the longer-term Generation IV concepts, a recent surge in interest in this technology, sometimes in combination with an interest in the thorium cycle, is evident, with many start-up companies promoting various designs: TerraPower and Terrestrial Energy are two such examples of companies that have managed to establish public-private partnerships to advance their designs. While the GIF does not exclude the possibility of private companies joining its R&D projects, this has not yet happened.

As far as high-temperature reactors are concerned, China is building a first prototype (HTR-PM), a twin-unit 210 MW prototype to be used for electricity generation, and which is scheduled to enter into operation in 2018. China has been operating a 10 MW research reactor (HTR-10) for more than a decade. The Japanese 30 MW high temperature engineering test reactor (HTTR) started operating in 1999. The reactor's maximum outlet coolant temperature is 850 °C in rated operation mode and 950 °C in high-temperature test operation mode. HTTR was operated for 30 days in rated operation mode and 50 days in high-temperature operation from January to March 2010. The deployment of high-temperature reactors will depend essentially on the development of non-electric applications such as hydrogen production or industrial process heat.

As mentioned before, there are many process heat applications at temperatures below 1000 °C which are also accessible to other types of Generation IV systems. Beyond the decarbonisation of the electricity sector which can be achieved by proven low carbon technologies such as renewables and nuclear power, the penetration of nuclear technology into the heat market has a significant potential to decarbonise this sector (NEA, 2017).

It is important to note that these systems are not necessarily competitors with one another or even direct competitors with advanced LWR technologies. Some technologies may be deployed in combinations with others—for example, researchers explore various scenarios that feature advanced LWRs operating in tandem with fast reactors as part of an integrated fissile materials management system that minimizes the need to dispose of high-level radioactive wastes. Further, systems based on VHTR technology may ultimately be best applied to energy needs other than electricity production—such as the need for hydrogen, process heat, and clean water.

3. Role of international collaboration

The development of early Generation I and II nuclear technologies was the result of either national research programmes, supported by national industries, or technology transfers from pioneer companies in the United States, such as Westinghouse, General Electric or Combustion Engineering. Generation III technology developed in the 1980s and 1990s benefitted from a higher degree of international collaboration among industrial partners. One can cite for example the Advanced Boiling Water Reactor (ABWR) developed by General Electric, Hitachi and Toshiba, or the European Pressurised Water Reactor (EPR), developed by Framatome (which then became AREVA NP) and Siemens. Projects undertaken by research organisations working together on topics such as severe accident management also contributed to these advancements. In the case of Generation IV technologies, a higher degree of cooperation was established among governments through the GIF to advance the next generation of nuclear systems, at least through the pre-competitive stage (Kelly et al., 2013).

One of the immediate benefits of this international cooperation is the sharing of the results of R&D carried out by the different participating research organisations, as well as through general exchange of information. Over 1000 technical deliverables were produced since the creation of GIF, including valuable material property data to aid in design and licensing, and exchanged among the signatories of the 11 projects that were set up under four so-called system arrangements, related to the SFR, the VHTR, the GFR and the SCWR systems. The GIF has also engaged in cooperative work to develop common safety design criteria and guidelines which have been discussed with regulators and safety research organisations. The conceptual designs under development also benefit from the discussions taking place among scientists and engineers from different backgrounds and experience. The GIF community represents over 300 R&D managers from 8 active countries (Canada, China, France, Japan, Korea, Russia, Switzerland and the United States) and Euratom working on the development of the six systems. But beyond the managers, more than 3000 engineers and scientists work on GIF-related R&D projects in various research institutes and universities, or in industry, making the GIF well equipped to face the technical challenges that developing the next generation of reactors entail. The GIF has in particular the capacity to focus on priority cross-cutting topics, such as materials or advanced power conversion technologies.

While it is true that most GIF members have on-going bilateral or tri-lateral cooperative agreements with other GIF members, the GIF remains a powerful framework for multi-lateral technical cooperation on advanced reactors. The Framework Agreement, which is the legally binding treaty between the active GIF member countries, took three years to negotiate before it was signed in 2005. It took nearly two years for the countries to sign its Extension for another ten years in 2015–2016, but all confirmed their interest in continuing their cooperation within the GIF. Under the Framework Agreement, four system arrangements were signed for the SFR then the VHTR, GFR and SCWR. These ten-year agreements, under which individual R&D projects are negotiated between signatories, were also extended for another ten years in 2016. Only the MSR and the LFR remain under a less formal cooperative arrangement, but as partners realise the benefits of identifying joint projects and protective intellectual property associated with the research output, it is likely that they will formalise their cooperation model. Table 2 lists the 14 GIF members, the ten active members that signed the Framework Agreement, and the systems on which these members are working, as of January 2017.

It is worth noting that an important motivation in the formation of the GIF was the belief that new technologies should avoid one aspect of the nuclear industry that has reduced its economic success; the limited progress in deploying the same designs in multiple countries. It was foreseen that multilateral development might help set the stage for future multilateral deployment. However, the GIF has also found resolving intellectual property issues across countries can be difficult. These issues are less apparent in the case of systems that are early in their development cycle, but for systems closer to demonstration, intellectual property concerns can prove to be substantial barriers to multilateral and even bilateral cooperation. It is clear that going forward, some approach to addressing these matters must be found for multilateral development to proceed.

4. Five challenges ahead

While the GIF provides a robust R&D cooperation framework, there are a number of additional challenges that developers of advanced reactor technology need to address if the technology is to be commercially viable in tomorrow's energy markets.

4.1. Right designs for future energy market needs

Even when a substantive effort is made to develop a technology,

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Table 2
GIF members and participation in the development of the six Generation IV systems.

Member (signatory of the GIF Charter)	Implementing agents (active members having signed the GIF Framework Agreement)	System Arrangements (SA)				Memoranda of Understanding (MOU)	
		GFR	SCWR	SFR	VHTR	LFR	MSR
Argentina (AR)							
Australia (AU)							
Brazil (BR)							
Canada (CA)	Department of Natural Resources (NRCan)		●				
Euratom (EU)	European Commission's Joint Research Centre (JRC)	●	●	●	●	●	●
France (FR)	Commissariat à l'énergie atomique et aux énergies alternatives (CEA)	●		●	●		●
Japan (JP)	Agency for Natural Resources and Energy (ANRE) Japan Atomic Energy Agency (JAEA)	●	●	●	●	●	
Korea (KR)	Ministry of Science, ICT and Future Planning (MSIP) and Korea Nuclear International Cooperation Foundation (KONICOF)			●	●	●	
People's Republic of China (CN)	China Atomic Energy Authority (CAEA) and Ministry of Science and Technology (MOST)		●	●	●		
Russian Federation (RU)	State Atomic Energy Corporation "ROSATOM" (ROSATOM)		●	●		●	●
South Africa (ZA)	Department of Energy (DoE)						
Switzerland (CH)	Paul Scherrer Institute (PSI)				●		●
United Kingdom (GB)							
United States (US)	Department of Energy (DOE)			●	●		●

it can take many years to reach deployment. The Westinghouse AP1000, which is today under construction in China and the United States, began its development in projects that date back to the 1980s. Even in its current form, detailed design and regulatory approval required another decade before the first concrete was poured. The U.S. reactors will each take an additional six years to construct. The first AP1000 will be China's Sanmen 1 unit which is expected to come online in 2017.

Similarly, Areva's EPR project started in 1992, and the first of a kind reactor to be connected to the grid is expected to be China's Taishan 1 reactor towards the end of 2017, twenty five years after the start of the development programme.

As these examples demonstrate, the development cycle for modern LWR-based plants is at least two decades. The need to develop appropriate licensing frameworks in some countries, to conduct additional R&D, the lack of established supply chains, and the uncertainties inherent to a first-of-a-kind project make it likely that if a decision were made today to build a plant based on a Generation IV technology, commercialisation would be likely to take at least as long as the cases highlighted above, at least initially.

The lengthy time frames required to develop and construct Generation III/III + plants were less of a concern in the past, when power requirements and prices were considered relatively predictable—plants that could operate reliably and with great cost predictability for 60–80 years was a very desirable asset. Today, however, the global energy picture is in a state of flux. The pace at which economies and energy systems are changing is often much faster than the rate at which nuclear technology evolves.

As a result, developers of advanced reactors today need to consider how their designs meet the future energy market needs of the 2030s, 2040s or even far beyond. Given the uncertainties that exist today, looking into the future at the different pathways which world economies can follow to determine how future energy markets will evolve is a difficult exercise.

Energy scenarios developed by the International Energy Agency provide some insight into the possible market penetration of technologies, on the basis of technological merits, economics, market drivers, policies and regulations. While the Energy Technology Perspectives 2 °C scenario (2DS) (IEA, 2016) projects over 900 GW of nuclear capacity by 2050 and a share of nuclear electricity of 16% (compared to 11% today), the scenario does not say how those 900 GW of capacity are split among various nuclear technologies. What the scenario does say however, is that the electricity system by that time, if countries follow decarbonisation policies, will include a very large share of renewables (over 66%) with 30% consisting of intermittent sources (wind, solar). Clearly, if nuclear energy is to be present at this scale by the middle of the century, it should be competitive against other sources of electricity, and able to be technically integrated into electricity systems with distributed and intermittent generation. The question of scale or size of nuclear generation units is certainly one of the issues to be looked at closely. The design trend in the 1980s and 1990s, driven by the principle of economies of scale, was to design large power reactors (up to 1700 MW), but the question whether advanced reactors should be as large needs to be investigated.

Assuming countries that have committed to climate change mitigation goals confirm their engagement, electricity systems will become decarbonised in a few decades and evolve towards greatly interconnected electricity grids, with large shares of variable renewables providing distributed generation. Studies (NEA, 2012a) have shown that this comes at the expense of baseload generation and, unless electricity market designs fully recognise the costs associated with the development of intermittent sources, penalises nuclear generation. Some experts advocate the need

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for nuclear generation to be more flexible, with faster ramping rates than those of LWRs that operate in load-following manner (for instance in France) (NEA, 2011a). Others believe greater grid interconnectivity and more efficient demand-side management will maintain the need for low-carbon baseload generation, though at lower levels than today. Another important factor in determining tomorrow's demand for electricity generation is the rate at which cost-effective electricity storage can be deployed. Hybrid energy systems (Ruth, 2014) may integrate all these aspects.

Finally, while the discussion above has focused only on electricity generation, it is also clear that global carbon objectives are also targeting the heat sector. Nuclear energy is both a low-carbon source of power and a low-carbon source of heat, yet non-electric applications of nuclear energy have been fairly limited so far, mainly restricted to district heating. With countries committed under the Paris Agreement to reduce greenhouse gas emissions to levels such that global warming will be limited to “well under 2 °C” by the end of the century, it is clear that while the power system can be almost fully decarbonised by the middle of the century, more effort needs to be made to decarbonise the heat sector. Advanced reactor systems that can provide cogeneration applications (process heat, hydrogen production for example) could help displace many fossil-fuelled applications (NEA, 2017).

4.2. *Developers and regulators in sync to advance technology*

Another challenge for developers of advanced reactors is to ensure that the new technology meets regulatory approval and can be licensed. With enhanced safety requirements put in place after the Fukushima Daiichi accident, even regulators familiar with light water reactor technologies may need time to accept innovative designs. The explosive-actuated squib valves or the digital instrumentation and control systems (I&C) of some advanced light water reactors required regulators to carefully assess the reliability of these new systems. For more revolutionary advanced reactors, the licensability of the design needs to be addressed before it is completed. Limited resources at the regulator, or limited knowledge of new reactor designs, can complicate the discussion between regulators and developers but it is essential that the conversation takes place well before designs are finalised. Workshops such as those organised by the U.S. Department of Energy and the U.S. Nuclear Regulatory Commission (NRC-DOE, 2016) bring together key stakeholders to share perspectives, reach a common understanding, identify potential challenges, and explore opportunities.

More globally, the NEA, as an intergovernmental organisation focused on providing its members with the “scientific, technological and legal bases required for a safe, environmentally sound and economical use of nuclear energy for peaceful purposes” can help set up a constructive dialogue between regulators and developers of advanced reactor technology. The ad hoc group on the safety of advanced reactors (GSAR), set up under the auspices of the Committee for Nuclear Regulatory Activities (CNRA) and the Committee for the Safety of Nuclear Installations (CSNI), has engaged a dialogue with the GIF, to discuss safety research needs and frameworks for regulation of advanced reactors. The GSAR has selected the SFR as the first technology to be investigated, and will consider high-temperature gas-cooled reactor technology as a next step. One of the motivations for this engagement is the realisation that with reduced budgets, developers and regulators should try to agree on common safety research needs and experiments that can support both the developers and the licensing authority.

4.3. *Network of infrastructures to support development needs and safety research*

As mentioned previously, the GIF's progress has been slowed by reduced national R&D budgets, leading to delays or even cancellations in some experimental programmes. The constrained budgetary situation of fission R&D programmes in many countries is actually an added motivation for international collaborative endeavours such as the GIF, or NEA's joint projects (NEA, 2012b). Pooling resources to take advantage of unique – sometimes underused – research facilities can help optimise research efforts to advance reactor development. Databases exist in many institutions, for instance the NEA's research and test facilities database (RTFDB) – as well as reports that identify specific experimental facilities (NEA, 2009, 2011b). But beyond the actual lists, what is really required is for researchers and developers to agree on the key experimental facilities that are essential to advance and qualify the technologies of advanced reactors, for example the facility that can test, qualify and validate the design of advanced fuels under operational and accidental conditions.

4.4. *Attract young people*

With the long time-scale of nuclear development comes the question of ageing of technical staff, researchers and engineers, and that of keeping them motivated through that period. Already today, some technical areas experience shortage of expertise, and action is needed across whole range of skills and competencies. Attracting young people to nuclear science and technology is a major challenge for the long-term existence of nuclear energy. The GIF has recognised this need and has set up an “education and training” task force spanning the various GIF technologies and member countries. This task force has recently set up a series of technical webinars which can be accessible to the general public on the GIF website. Activities involving the “young generation” are also planned, for example in relation to the 4th GIF Symposium planned in 2018.

At the NEA, a recent initiative for Nuclear Education, Skills and Technology (NEST) aims at setting a framework for attracting young talent. The objective is to energise young engineers and scientists to pursue careers in nuclear science and technologies by establishing a multinational framework among interested countries to maintain and build skills capabilities, establishing international links between universities, academia, research institutes and industry, attracting technologists from other disciplines to address nuclear technology issues. Further, NEST aims to provide opportunities for students and young professionals to participate in multinational projects jointly with experienced engineers and researchers, university professors and academia, to work with their counterparts around the world as part of international teams to pursue research projects, to create practical knowledge on nuclear science, advanced and innovative nuclear technologies and materials, experimental facilities and computer codes and to bring creativity and expand the boundaries of current knowledge and foster innovations. The near-term focus will be on building a core of qualified experts and future leaders, on engagement with university programmes as the source of the brightest and best young scientists and to help them foster sustainable long-term international relationships, and on establishing projects offering opportunity for NEST Fellows from participating countries to work in an international environment on real-world problems applying cutting-edge science and technology.

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4.5. Economics

The future of nuclear energy will be limited if it cannot compete effectively with other low-carbon technologies. This is all the more challenging because alternative technologies, in particular renewable technologies such as solar or wind, have benefited from generous policies (i.e. feed-in tariffs) that helped their deployment. Large scale deployment and technology-learning curves have also brought significant cost reductions for wind and solar (IRENA, 2016), while in the same period, with difficulties encountered with first of a kind Generation III reactor projects in a number of countries, the cost of nuclear power has increased (IEA-NEA, 2015b). While the merits of nuclear energy still hold today, i.e. nuclear energy provides large scale and "competitive" electricity production (with stable production costs vs. volatility of fossil fuel prices), contributes to the security of energy supply and is a major contributor to low carbon electricity generation, cost-reduction programmes are needed and are being implemented by vendors. Whether these programmes can effectively bring down the cost of nuclear generation and therefore become very attractive to utilities remains to be seen.

In addition to the issue of the competitiveness of nuclear on a levelised cost of electricity (LCOE) generation basis, the issue of financing nuclear projects remains one of the main challenges for nuclear development. Nuclear power plant construction projects are capital-intensive projects, and therefore also projects that are very sensitive to the cost of financing. The NEA has been working on this topic for a number of years (NEA, 2015), and more recently, within the framework of the International Framework for Nuclear Energy Cooperation (IFNEC), with the organisation of a joint NEA-IFNEC international conference (IFNEC-NEA, 2016) which discussed a number of financing models.

As described above, many of the advanced reactors are small modular reactors. While generation costs of SMRs on a LCOE basis are likely to be higher than those of much larger reactors (economies of scale), financing of SMR construction projects is certainly going to be easier. To compete with other technologies, SMRs will need to have comparable generation costs and/or be able to provide other services than electricity generation. Cogeneration applications, such as desalination or hydrogen production, could help increase revenue streams to operators of these nuclear systems and help the general economics of the projects.

5. Innovation and the future of nuclear energy

GIF has been operating for more than 15 years, successfully fostering exchanges on R&D programmes, developing and applying assessment methodologies related to safety, economics and proliferation resistance, and producing over 1000 deliverables shared between partners of its eleven R&D projects. But R&D budgets have been reduced in many countries, and there is a significant risk that continuing at the current pace will not allow Generation IV systems to be ready for commercial deployment in the 2030–2040 timeframe. The nuclear community, at large, needs to act together to tackle this challenge, realising that budgets are constrained, and will likely remain that way, even if governments are supportive of developing nuclear power. There is a need to better focus research efforts and improve their efficiency.

This is where innovation comes into play: how to bring the results of R&D to the stage of market deployment faster and more cost-effectively. If the research community is generally keen to play its part, industry needs to be more active in expressing its needs. Without a clear signal of interest from industry, defining its requirements, sharing its knowledge and vision of the evolution of the energy markets, the enterprise of taking nuclear energy to the next generation will fail. Similarly, licensing aspects need to be addressed at an early stage, and regulators must be on-board too. Innovative technologies developed through research need to get tested, validated and qualified using approaches and methods aiming at reducing the time to market, by anticipating and integrating the licensability (safety performance demonstration requirements) at an early stage. This requires a cooperative approach among all stakeholders (research, industry, regulators), and, if done at international level at a pre-competitive stage, it might lead to increased harmonisation and further economic effectiveness.

In that respect, the NEA has recently launched the Nuclear Innovation 2050 initiative (NI2050, see Fig. 3) having as one of its goals the ambition to develop a global consensus on high priority R&D needed to propel nuclear energy into the future and identify barriers and pathways to progress. It is hoped that initiatives such as this might serve to highlight to governments the opportunities that are likely to be lost if R&D—such as that anticipated by the GIF—is not pursued.

6. Conclusions

Looking ahead at reactor development is a complex endeavour. Complex since the future is unknown, with many possible trajectories for world economies that depend on national policies, geopolitics, multi-lateral initiatives, global trade and economics. Complex since the future of nuclear energy depends not only on the merits and public acceptance of the current technology and that of advanced reactors under development, but also on the competition with other technologies and potential game changers (for example massive and competitive energy storage). It also depends on the ability for nuclear developers to address challenges related to the evolution of energy markets, licensing risks associated with advanced reactor technologies, economics, availability of research infrastructures and skilled personnel. The Generation IV International Forum is a unique intergovernmental initiative within the framework of the NEA that sets the stage for cooperating and advancing fission technologies, including with industrial partners at the pre-competitive stage. If the GIF can succeed in its ambitious goals of delivering the advanced nuclear technologies needed from 2030 onwards, it will have served a very valuable service to the future.

As noted previously, the reduced priority many countries have placed on long-term technology R&D has severely impacted the GIF's agenda and limited progress. We today benefit from the important work conducted by scientists and engineers in many countries in the 60 years since Shippingport went on-line. Many of

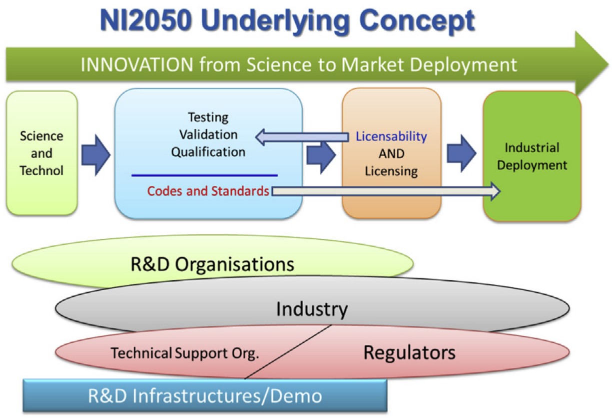

Fig. 3. Nuclear innovation 2050.

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the technologies in nuclear and other fields sprang from the investments and programmes of the Shippingport era. Governments in those early days of nuclear had ambitious plans and hope for the future and were not hesitant to bring them before the public. Without a similar vision for the future today, we can only wonder from where the technologies needed 60 years from today, will emerge.

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