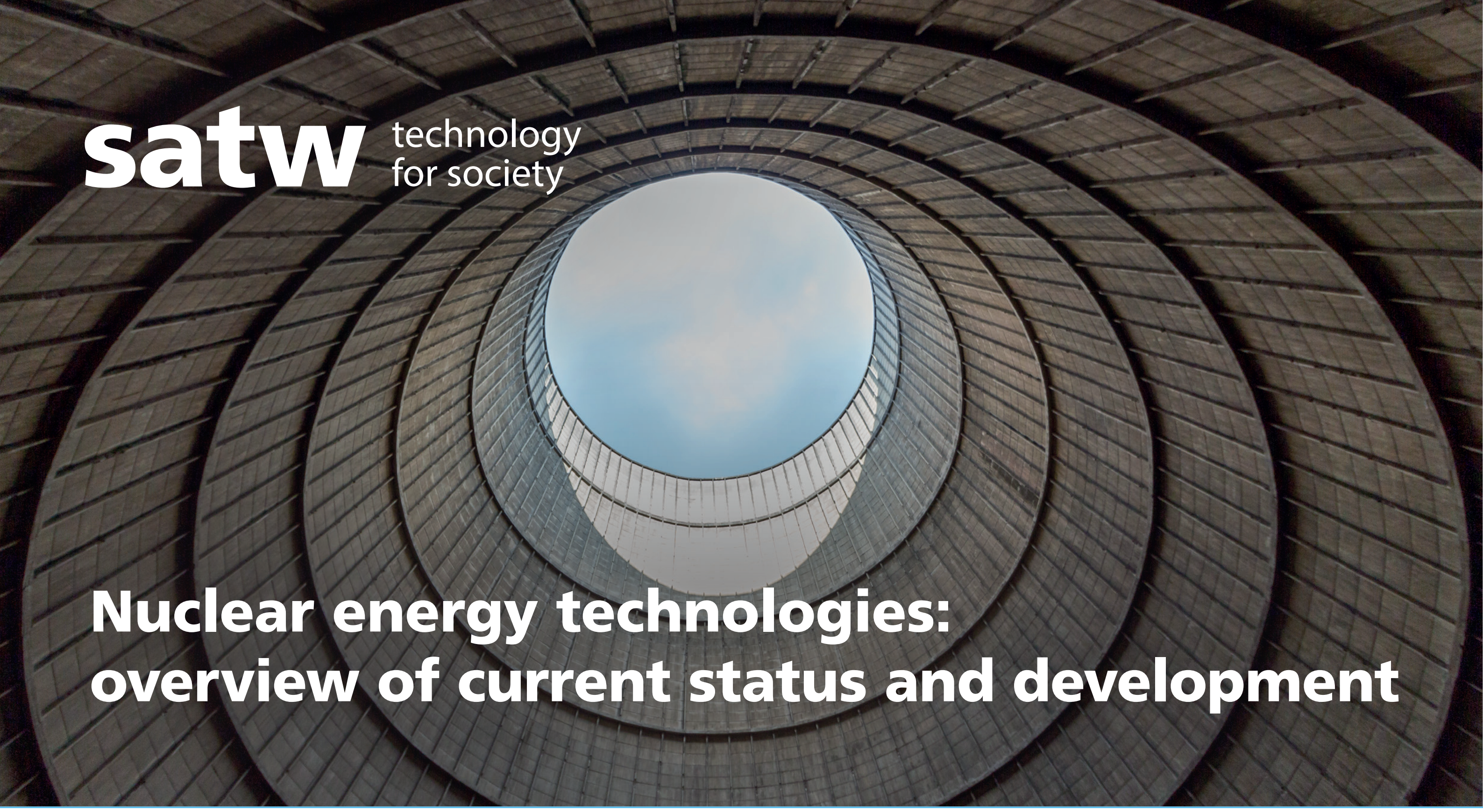


satw technology for society

Nuclear energy technologies: overview of current status and development

Background

By the end of 2021 [1], global primary energy consumption totalled 171,286 TWh, an increase of 5.5 percent compared to 2020 and 1.3 percent compared to 2019. Almost 17 percent of this total is converted into electricity. Scenario analyses predict massive growth in primary energy – mainly driven by developing countries – to cope with the expected increase in the world's population and extend energy access to billions of people. The electricity sector is expected to grow disproportionally, by an estimated 50–100 percent by 2050, primarily to penetrate non-traditional domains, i.e., e-mobility, digitalisation, buildings and fuel production.

This challenging trajectory stands in opposition to the urgent need for comprehensive decarbonisation of the energy system. In 2021, this was about 82 percent reliant on fossil fuels, while almost 2/3 of electricity was generated using fossil fuels, which contributed nearly 30 percent to global energy-related CO_2 emissions of roughly 34 Gt. Thus, to meet climate targets, the electricity sector needs to dramatically increase its share of low-carbon generation assets by 2050, while at the same time taking account of other factors such as costs, land use and other resources. Many countries' energy strategies focus on expanded use of renewable energy sources. In addition to hydropower, which accounts for a roughly constant 12 percent, wind and solar – the main contributors – plus other renewables represent roughly 13 percent of global power production. The exact figures are 23.5 percent in Europe and 8.3 percent in Switzerland, with a global growth rate of 17 percent. Nuclear power accounted for nearly 10 percent of global power production – roughly 23 percent in Europe, 69 percent in France and 29 percent in Switzerland[1]. Nuclear power's share going forward is unclear, varying up to growth of 28 percent by 2040 [2].

[1] Other key figures for Switzerland are: 0.19 percent of global primary energy, 0.25 percent of electricity consumption, 0.1 percent of global CO_2 emissions while the primary energy consumption per capita of 131.5 GJ exceeds the world average by almost 75 percent.

Use and characteristics of nuclear energy

Nuclear energy contributes substantially to baseload power production worldwide. Mean plant capacity factor was 82 percent globally, with peaks of up to 90 percent in Switzerland and more in other countries (e.g. USA). At the end of 2021 [6], there were 437 reactor units with 393 GWe installed capacity in 33 countries. The majority (80 percent) of all operating units use demineralised light water as their moderator and coolant. Most of these light-water reactors (LWRs) are fuelled by uranium, using U-235 as their fissionable isotope, enriched from 0.7 percent natural uranium to 3-5 percent. About one third are boiling water reactors (BWRs), where the primary coolant undergoes phase change to steam inside the reactor. The remainder are pressurised water reactors (PWRs), where the primary cooling circuit operates at a higher pressure (15.5 instead of 8 MPa) and is separated from the conventional water-main steam cycle by a steam generator.

Accumulated experience exceeds 18,000 reactor-years. 55 units with a capacity of 57.5 GWe are under construction in 18 countries, the majority in China (16 units) and India (8 units). New builds are rare in the Western world and, like the European Pressurised Water Reactors (EPRs) in Finland and France, are plagued by massive cost and construction time overruns – in contrast to Asian projects, which tend to stay within initial budget and schedule. Six units with a capacity of 5.2 MWe were connected to the grid for the first time in 2021, while nine reactors have decommissioned (three prematurely in Germany). Several countries have recently, revisited their views on nuclear power by suspending phasing-out decisions, planning new power plants and/or even aiming to increase the contribution made by nuclear, while Germany has stopped the use of nuclear power. Further, extending minimum lifetime to 60 years has become a cost-effective practice in some major countries. This option seems to be of particular interest to countries such as Switzerland, that operate a safety policy of continuous retrofitting to the current state of the art.

Uranium has a uniquely high energy density: Under optimal conditions, one kilogram is the equivalent of burning 3,500 tons of black coal. Based on current annual consumption, the world's known low- and higher-cost-range reserves will yield enough uranium for the next 125 years. It is estimated that these reserves are set to double when reasonably assured resources are taken into account and to become practically unlimited once the shift is made to advanced nuclear technology (incl. breeding options) and new mining and extraction technologies. Furthermore, many of the next-generation nuclear systems are capable of using fertile thorium, which is three to five times more abundant in the earth's crust than uranium.

At slightly less than 10 grams per kWh, greenhouse gas emissions from current nuclear technology are very low – 50 times lower than natural gas, comparable to hydro and wind and four times less than roof-mounted photovoltaics across its entire life cycle and based on today's technology [5].

Nuclear power is not without its drawbacks: the physical process leads to a surplus of neutrons and the fission energy manifests as the kinetic energy of the two radioactive nuclei splitting. As such short-lived "fission products" decay, they produce heat that has to be continuously removed after the reactor has been shutdown, while long-lived fission products and the actinides[2] produced by neutron absorption require ultra-long confinement times. This creates major technological design challenges and necessitates implementation of safety functions for reactivity control, fission product confinement and decay heat removal under all conceivable circumstances, as well as for management and long-term storage of nuclear waste[3].

Under the IAEA's lead, a design philosophy was developed, and fundamental safety principles were agreed. The primary strategy for preventing accidents, or at least mitigating their consequences, is that of defence in depth, a combination of several independent levels of protection that would all have to fail for people or the environment to experience harmful effects.

However, certain aspects of the majority of current generation large LWRs[4] are still problematic, notably their vulnerability to coolant loss and their reliance on properly functioning "active" safety systems based on electrically operated pumps and valves, reliable actuation mechanisms and occasional early-stage operator interventions. Design provisions such as redundancy and diversity make such failures rare. The progress made in improving safety is demonstrated, for example, by the decrease in estimates of core damage frequency (CDF) resulting from the failure of decay heat removal after internal or external events. Current CDF estimates vary from 10^{-4} to 10^{-5} for "old" plants to as low as 10^{-6} for advanced and some retrofitted plants; in each case, the figures are per reactor-year [6]. The likelihood of large radioactive releases after early containment failure is at least one order of magnitude smaller, depending on containment design.

[2] Actinides are elements with atomic numbers from 89 (actinium) to 103 (lawrencium) and include neptunium (93), plutonium (94) and americium (95); neptunium and elements beyond plutonium are called minor actinides.

[3] On average, a large LWR generating about 10 TWh annually will produce 30 tons of radioactive heavy metal, including 1.4 tons of fission products and 350 kg of recyclable plutonium; the total volume is 15 m3.

[4] These include the bulk of "Generation II" plants, like the retrofitted Swiss NPPs, and evolutionary "Generation III" designs.

The other issue of concern is radioactive waste burden, although the volumes involved are small. There are three different fuel cycle concepts: In the "open cycle", spent fuel is unloaded at the end of its useful life of three to seven years, and sent for extended interim storage before ideally being placed in deep geological repositories. Alternatively, spent fuel can be reprocessed to extract fissile material such as the remaining uranium and plutonium before it goes for disposal and can also be used in mixed oxide (MOX) fuel elements ("partially closed cycle"). In the "fully closed cycle", uranium, plutonium, and (long-lived) minor actinides are extracted, used as fuel and burned (transmuted) in dedicated-design advanced fast reactors. Most LWRs use the open cycle since it is considered favourable in terms of proliferation[5] issues, as no separation of fissile material – particularly weapons-grade plutonium – takes place. In contrast, closed fuel cycle concepts allow for better exploitation of fuel and fuel reserves, while significantly reducing the radiotoxicity of waste and the associated stewardship requirement. However, the essential task of reprocessing and selectively separating long-lived isotopes is challenging, costly, lacks acceptance and is prohibited in many countries.

All fuel cycles require safe, long-term disposal of radioactive waste, although to differing extents. As yet, there is no operational deep geological repository anywhere in the world and progress is still slow. However, Finland has taken the lead, a licence having been granted in 2015, and construction is ongoing at the Olkiluoto site. Disposal process is expected to start by 2024/25.

Although current LWRs are extremely safe and reliable, future use of this technology is still impeded by major public acceptability obstacles. Such obstacles encompass basic safety and proliferation concerns and, notably, a pronounced aversion to "low probability – high consequence accidents" and the perceived risk of cancer at even low doses of invisible radiation.

Technology developments

Development work, mainly involving large, water-cooled reactors, has taken place or is ongoing [7] for the purpose of improving safety and robustness, increasing efficiency, flexibility and competitiveness, and extending lifetime:

- Evolutionary Generation III designs with enhanced active safety systems and passive features to preclude radioactive releases in the very unlikely event of the systems failing.

- Revolutionary Generation III+ designs that follow a paradigm shift towards fully passive systems that require only natural forces and inherent safety features, and thus rule out the station blackout events that initiate the serious accident sequences which are the statistically dominant cause of the nuclear incidents that have occurred to date.

Generation III/III+ plants are already in operation, under construction or ready for near-term deployment. Furthermore, innovative Generation IV concepts are under development [8]. These are mostly fast-spectrum (rather than slow thermal) reactors using "exotic" coolants, i.e., liquid metal (sodium, lead) or molten salt. They are capable of breeding more fuel than they consume or even of burning (transmuting) actinides. Deployment is expected in ten to twenty years from now.

There is a worldwide revival of interest in small and medium (typically up to 300 MWe) modular reactors (SMRs, including low-power microreactors) for electricity production and other purposes, based on diverse reactor technologies [6]. Some of the concepts have completed development, been pre-certified and are in the early construction phase [9].

[5] Proliferation refers to the spread of nuclear weapons, nuclear weapons technology, or fissile material to countries that do not already possess them.

Evolutionary and revolutionary next generation designs

The EPR developed by EDF and Framatome in collaboration with Siemens and German utilities is a key evolutionary Generation III design with a power output of roughly 1650 MWe and a service life of 60 years. Enhanced active safety systems are provided to further reduce the likelihood of core melt accidents (CDF about 10^{-6}/reactor-year). Core melt mitigation is robust and includes a core catcher for corium retention together with a dedicated containment spray and heat removal system and other passive features to prevent early release of radioactive material from the containment (Fig. 1). EPRs have been in commercial operation in China (Taishan 1&2) since 2018 and in Finland (Olkiluoto) since early 2023. One EPR is in the final (delayed) construction phase in France (Flamanville), while two are being built in the UK (Hinkley Point).

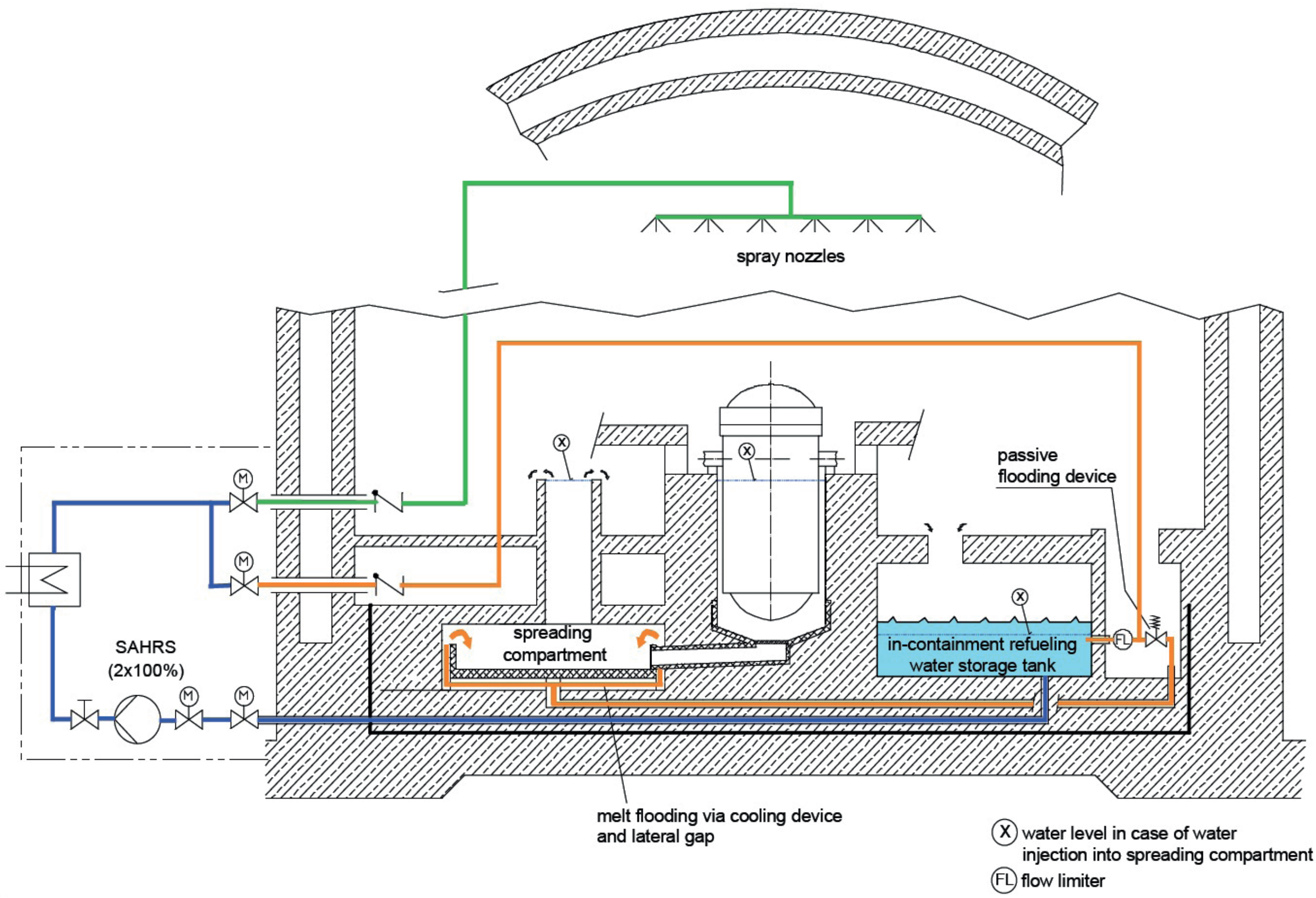


Fig. 1: EPR advanced containment design with core melt (corium) retention and cooling systems [12].

Another example of advanced evolutionary designs is the APR-1400 (MWe) developed by KEPCO. Two units are in operation in South Korea, three in the UAE, while four in South Korea and one in the UAE are under construction. The four units in the UAE were built within 10 years at a total expected cost of USD 24 billion.

Westinghouse's fully passive, 1100-MWe AP 1000 represents a revolutionary Generation III+ design. It utilises natural forces such as natural circulation and convection to provide safety related functions, ensuring that the reactor will safely shut down and remain cooled without operator action even under station blackout conditions (low CDF 10^{-7}/reactor-year) for at least 72 hours. Four units are in operation in China, while two are under construction in the USA (Vogtle) with in-service dates of 2023/24.

Highly innovative technical concepts

Highly innovative reactor and fuel cycle concepts differ by purpose, associated neutron spectrum and coolant, as well as by fuel cycle strategies (ranging from open to closed cycles with offsite or onsite reprocessing) and other features. Concept development and refinement are driven by key countries such as the USA, China, India, and Russia and relevant industries. Most of the designs they propose are capable of using a variety of fuels, including spent fuel from LWRs, or of burning (transmuting) actinides, thereby completing the fuel cycle, increasing uranium utilisation significantly compared to current LWRs and/or reducing husbandry times for long-lived waste [10]. Moreover, most new designs aim for lifetimes of 60 years and claim to be inherently safe and highly resistant to proliferation.

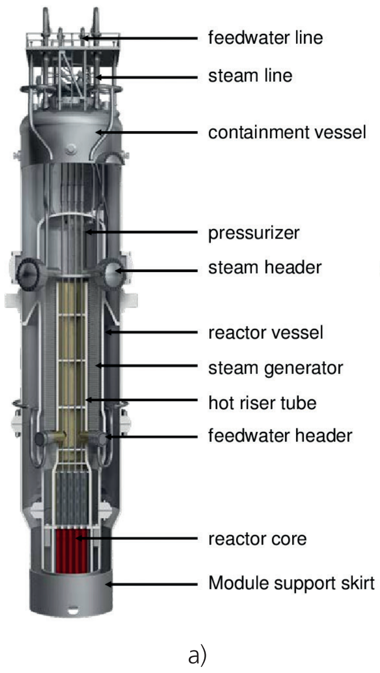
Of the multitude of concepts based on proven thermal reactor technologies, including GE-Hitachi's BRX-300 and the UK's Rolls-Royce SMR, two designs are discussed in greater detail below: the VOYGR light water reactor and the HTR-PM gas-cooled reactor. All the concepts mentioned above are small to medium sized modular reactors, termed SMRs, and most of them are suitable for series production and shipping in key parts.

NuScale's VOYGR pressurised-water reactor concept, was developed in the USA and leverages extensive experience of operating current LWRs by applying it to smaller and simpler configurations and varying the number of 77 MWe power modules. The concept claims to have many technological advantages over conventional large-scale PWRs:

- In hypothetical (beyond design-basis) core damage scenarios, the low fission product inventory will result in a small release of radioactive substances. Since doses will be below safe limits at the site boundaries, emergency planning zones will not be required.

- Compact steam generators incorporated into the small containment permit heat exchange by natural circulation, eliminating the need for reactor coolant pumps (Fig. 2 a).

- Modules are submerged in the cooling pool (Fig. 2 b). This provides a passive heat sink and eliminates the need for emergency core cooling systems requiring additional water since it can adequately provide long-term core cooling via natural circulation. As a result, the concept is impervious to station blackout and provides indefinite grace periods.



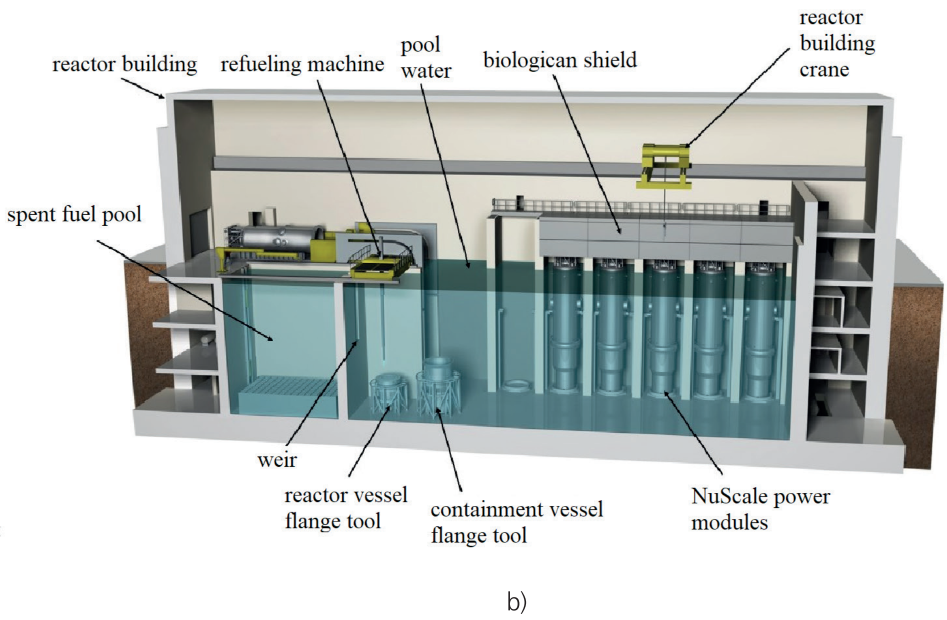
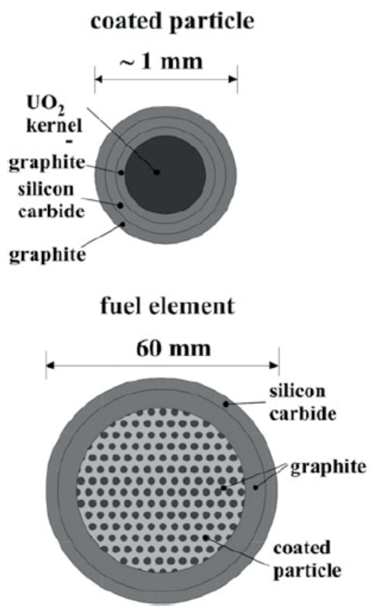


Fig. 2: Schematic view of the VOYGR plant concept – a) 77 MWe power module, b) cut-away of the power plant; up to 12 modules can be submerged in one cooling pool inside the reactor building for a total output of 924 Mwe [13].

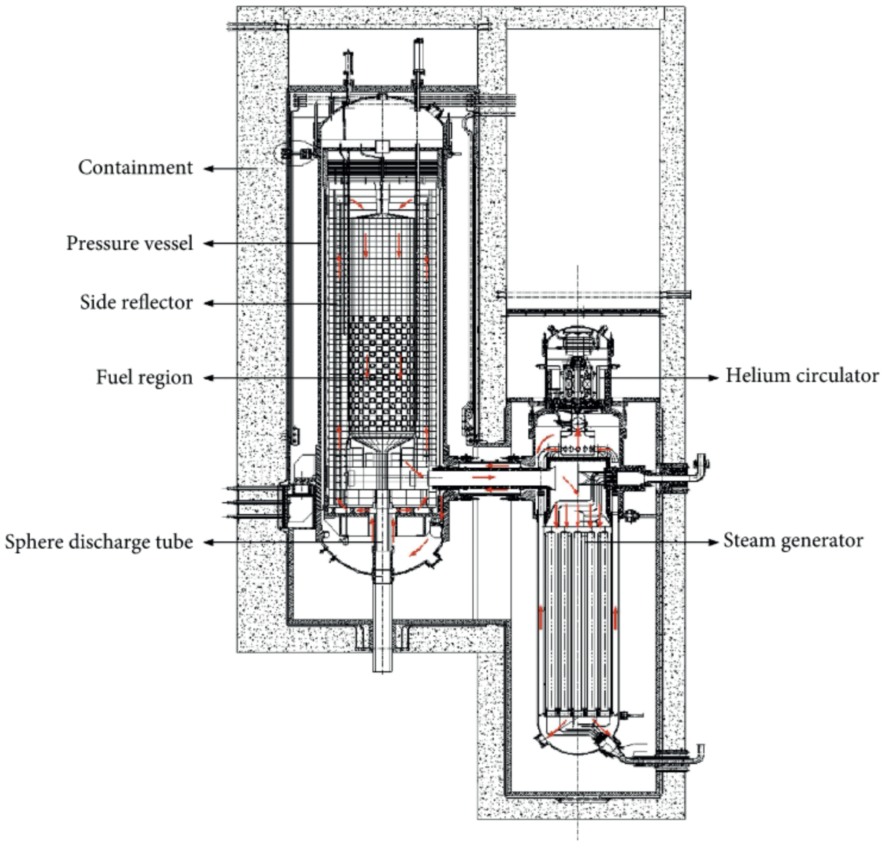
The VOYGR is fuelled with UO_2 pellets enriched to 4.95 percent U-235 and operates at 13.8 MPa with natural primary circulation. Multiple modules can achieve a power output that rivals the generation capacities of conventional PWRs yet offers enhanced inherent safety features. The project has received regulatory standard design approval in the USA and design work has recently been completed on a six-module system. Equipment manufacturing for this system is in progress and the first commercial plant is now scheduled to come on-stream in Idaho by 2029.

Modern high temperature gas-cooled reactor (HTR) designs use graphite as a moderator and low-pressure (about 7 MPa) helium as a coolant. The high operating temperatures of min. 750°C result in a high thermal efficiency of about 40 percent and could also open new applications for nuclear power beyond electricity production. The ceramic-pebble fuel consists of thousands of robust multi-coated particles embedded in a graphite matrix (Fig. 3 a). The relatively low power level and power density coupled with a high heat capacity graphite moderator and effective fission product retention are deemed to make these reactors inherently safe. However, the concept is not without weaknesses: potential unrestricted air or water ingress could cause graphite corrosion.

Multiple prototypes employing HTR pebble-bed technology have gone into operation, including the AVR and THTR-300 in Germany. Construction work on an HTR-PM (pebble-bed modular) reactor with continuous refuelling (Fig. 3 b) started in China late 2012. An operating licence was granted in August 2021, criticality was reached one month later and the plant was operating at full power by the end of 2022. The plant features two 250 MWt modules operating at 7.8 MPa and connected to power a single 210 MWe turbogenerator. The reactor makes full use of features outlined above to provide a high degree of inherent safety. HTR-PM currently uses an open fuel cycle concept.



a)



b)

Fig. 3: Schematic view of a) multi-coated particle and fuel element, b) HTR–PM layout [15]. Coated particles consist of a uranium kernel enriched to 8.5 percent U-235, a porous graphite layer to accommodate for fuel expansion, an inner and outer dense pyrolytic graphite layer, and a silicon carbide layer in between for fission product retention up to 1600 °C.

Sodium cooled fast reactors (SFR) are heralded as one of the most promising next-generation reactor concepts. Their excellent neutron economy enables them to breed fissile material, and with outlet temperatures in the range of 500 °C, thermal efficiency is 37 percent. SFRs are usually designed with a pool- or loop-type reactor filled with molten sodium and helium at atmospheric pressure as the cover gas, an intermediate sodium circuit and a secondary steam generator circuit (Fig. 4 a). Designs and fuel composition can vary by mission. For example, uranium-plutonium-zirconium metal alloy fuel can be used in small and medium-sized designs to burn spent fuel from LWRs, which helps alleviate the issue of nuclear waste. In combination with pyro-metallurgical reprocessing techniques, which cannot extract plutonium, modern SFR designs are deemed to be proliferation-resistant. In addition, sodium exhibits excellent heat conduction properties, which are valuable for passive heat removal. The primary disadvantages of SFRs are their sensitivity to potential power excursions (exponential outbursts of nuclear fission chain reactions, which are pronounced in larger cores) and sodium's exothermic reactivity with water and air. Various countries and organisations are collaborating within the Gen-IV International Forum to develop an SFR system rated at 50–1500 MWe [8].

Approximately ten liquid metal reactors are expected to be deployed soon, with the extremely advanced Terrapower reactor and PRISM emerging as the most prominent concepts. The **PRISM** design (Fig. 4 b) involves two 311 MWe reactor modules that use uranium-plutonium-zirconium alloy fuel and burn spent fuel from LWRs. Other missions and associated fuel compositions and configurations could include actinide recycling, fuel breeding with a U-238 breeding blanket and even weapons material consumption. The core outlet temperature is about 500–550 °C. The vessel auxiliary cooling system is capable of maintaining reactor temperatures at well below design limits by using natural circulation to remove heat from the reactor module, i.e., air flowing naturally around the lower containment vessel all times. The design is considered mature [9] with additional unique safety features such as negative reactivity response to temperature rise due to the small core size and passive decay heat removal.

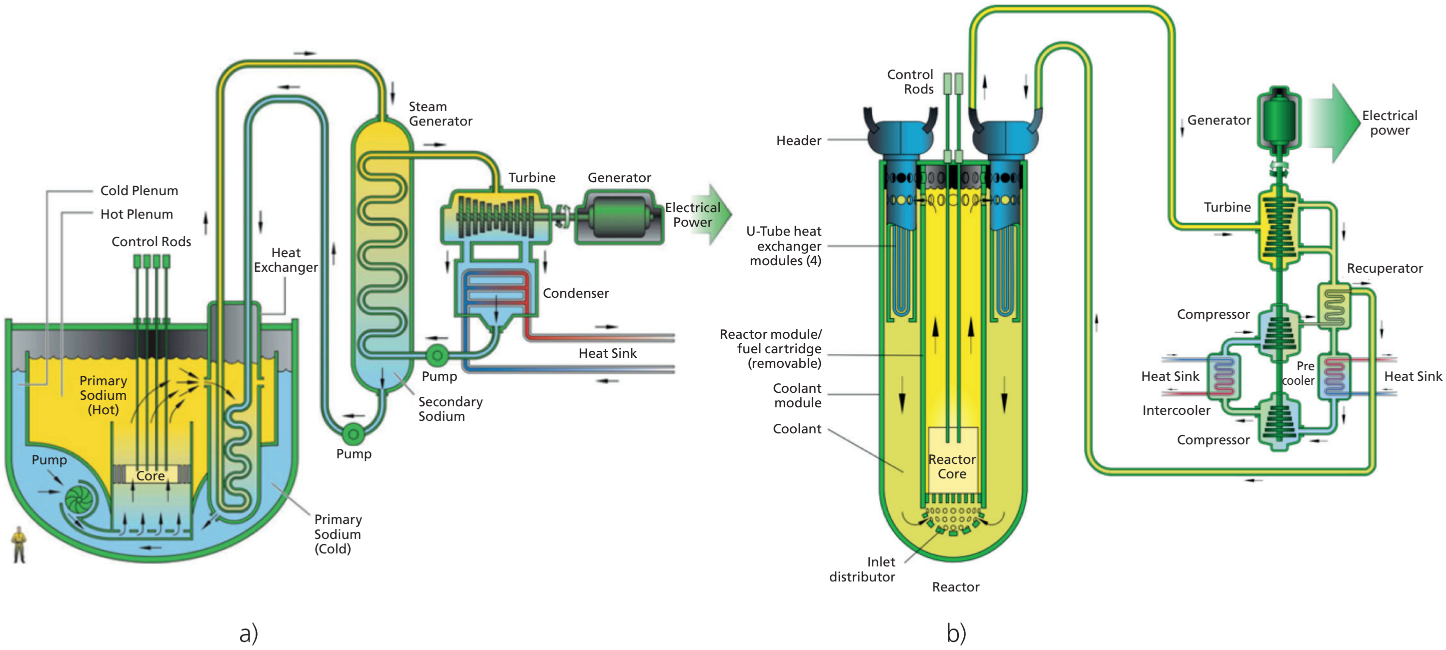


Fig. 4: Schematic view a) large 1500 MWe SFR and b) 311 MWe PRISM module; both pool type with intermediate sodium loop [8].

Other innovative technical concepts [9] involve **lead-cooled fast reactors** (LFRs) which use molten lead or lead-bismuth (Pb-Bi) eutectic as a coolant and share many of the positive characteristics of SFRs. However, the coolant is not chemically reactive with water, which makes an intermediate coolant loop unnecessary, has a higher boiling point and is less susceptible to power excursions due to its neutronic properties. In contrast, the major disadvantages include the higher melting temperature of the coolant, which raises concerns over freezing, its corrosive reaction with steel and the high price of Pb-Bi. The Russian-developed **BREST-OD-300** MWe is a pool-type LFR with passive decay heat removal using natural air circulation. The fuel used is 14.5 percent enriched uranium-plutonium mononitride consisting mainly of spent LWR fuel. Reactor construction was approved in 2016, concrete for the foundation slab was poured in August 2021 and the slab was delivered to the site one year later. Operation was expected to start in 2025, but has recently been delayed to 2026.

Molten salt cooled reactors (MSRs) can operate with thermal or fast neutron spectra and have power densities similar to LWRs. The main coolant is a molten salt mixture, the properties of which can vary depending on the salt used. Lithium salts with boiling points in excess of 1400 °C are preferred as they allow operating temperatures of 700–900 °C. MSRs use solid fuel or fuel dissolved in the coolant, the latter preferred for next-generation unpressurised breeder or waste burner designs. Uranium- and thorium-based fuels can both be used, optionally with added minor actinides. The coolant is constantly circulated through the core and chemical processing plant, which separates volatile fission products and controls fuel concentration. If the reactor overheats a freeze plug melts and dumps the coolant into tanks, which immediately stops the fission reaction. The decay heat from the tanks is removed passively, which makes the design safe in station blackout scenarios. The main drawbacks of MSRs are the corrosive properties of the coolant and potential criticality spikes.

A number of MSR concepts are at the early development stage. One of these is the **"Waste Burner"** designed by Seaborg Technologies of Denmark. The Waste Burner is a 100 MWe compact modular thermal reactor (CSMR) which uses spent fuel and thorium mixed in a molten fluoride salt that also acts as the coolant. The reactor has inherent/passive safety features including a reliable overflow system to dump the fuel. The start-up company aims to complete detailed design and start construction work by 2026.

Accelerator-driven systems (ADSs) are novel concepts comprised of a subcritical reactor and an external neutron source, usually a high-intensity proton accelerator. The proton beam is aimed at a metal target and produces neutrons by spallation. Fission chain reactions are stopped by turning off the accelerator. The reactor is designed as a lead- or lead-bismuth-cooled fast breeder reactor. These characteristics make ADSs perfect for burning (transmuting) minor actinides which greatly reduces nuclear waste husbandry times. However, the fact that there is no facility for the industrial-scale reprocessing of minor actinides indicates that the concept is several decades away from commercial readiness. One of the most advanced concepts is **MYRRHA** (Fig. 5), an actinide burner developed by the Belgian Centre for Nuclear Research. The system is expected to be commissioned by 2036, the superconducting cavity having become ready by end of 2022. Design and construction of the first Linac section up to 100 MeV will be completed by 2026 and this will be extended to 600 MeV by 2033.

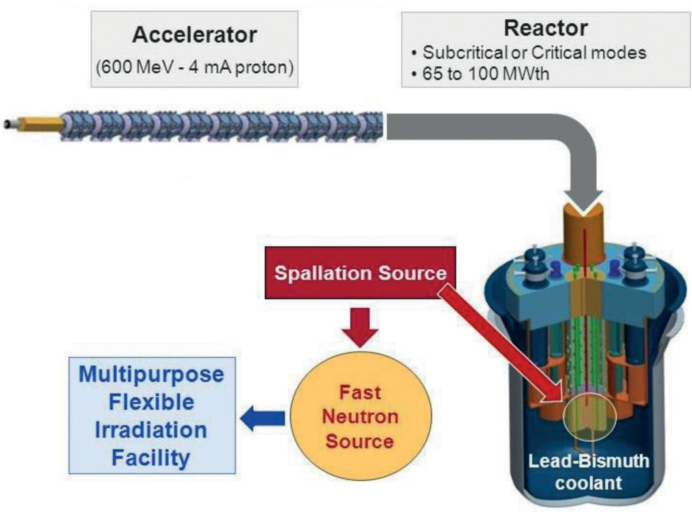


Fig. 5: Schematic view of MYRRHA (Multi-purpose Hybrid Research Reactor for High-tech Applications) [4].

Special case: Small modular reactor (SMR) concepts

More than 80 SMRs are under development in various countries (Fig. 6) for all the principal reactor technology lines: water-cooled, either land- or marine-based, gas-cooled, liquid metal or molten salt cooled. Some of them are at a very advanced stage of development, with deployment expected within this decade or in the early 2030s including those which have been discussed above[6] [9]. There is a strong body of opinion [11] that SMRs could

- open up additional market sectors, for example industrial heat applications, including hydrogen production,
- adapt more effectively to low energy demand growth rates, fulfil the need for flexible power generation for a wider range of users, demonstrate greater suitability for low-capacity power networks,
- permit greater simplicity of design, unlock economies of scale, primarily in factories, and thus shorten construction times, reduce upfront capital costs, simplify financing and yield earlier revenues, etc.

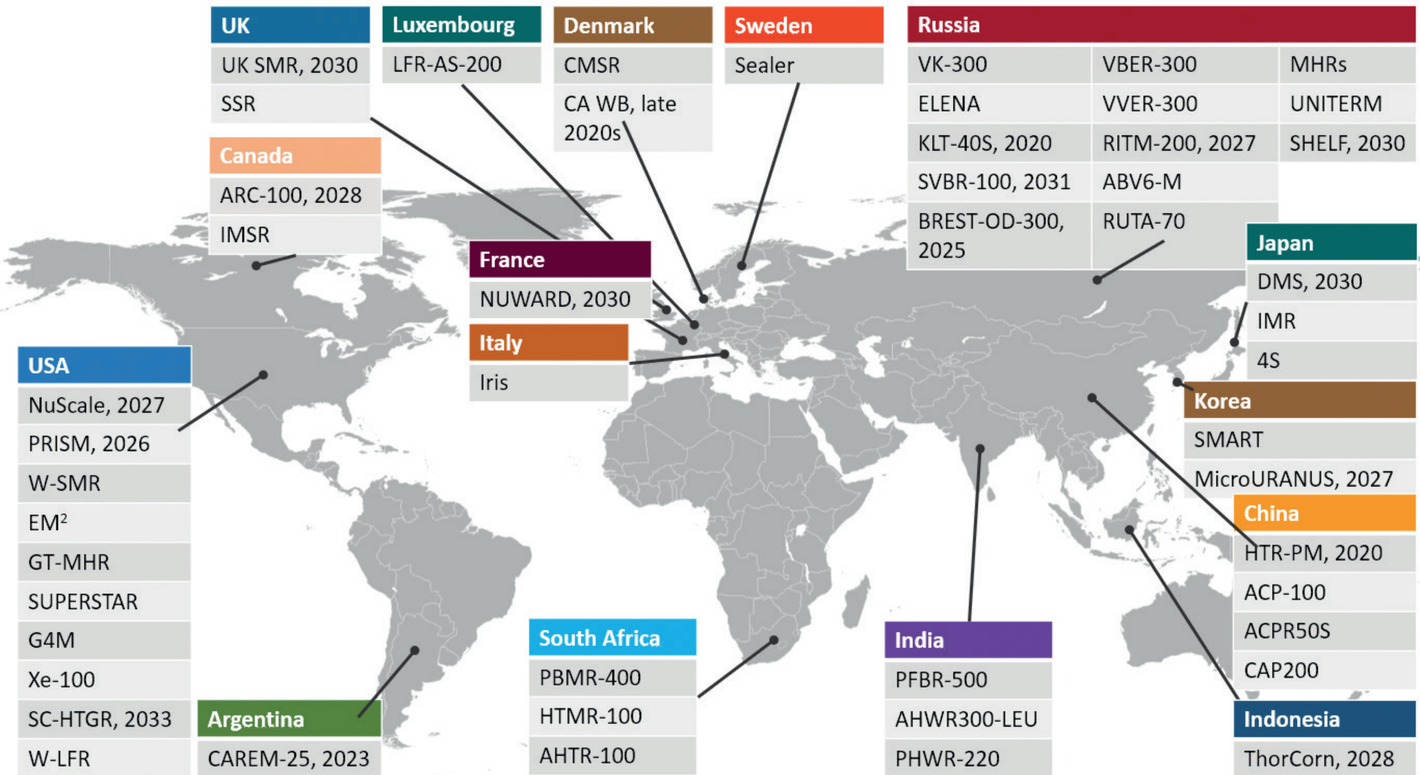


Fig. 6: World map of small and medium modular reactors under development [14].

As the inventory of fission products is proportional to the power level, SMRs could, in principle, release a smaller amount into the environment under loss of confinement conditions. In view of their excellent inherent safety characteristics, these reactors are often called super-safe and underground siting has been proposed for some designs to protect plants against extreme external physical impacts, including weapon attacks. However, some question the economic competitiveness of SMRs and raise concerns regarding the adequacy of the current regulatory system.

[6] Two SMR designs are in operation (Russian water-cooled KLT 40S, HTR-PM), two are under construction (CAREM in Argentina, Chinese ACP100) and three have completed detailed design (including VOYGR); most concepts are aiming for deployment by the end of this decade.

Concluding remarks, outlook

Global energy demand, particularly for electricity, is expected to grow, yet is faced with the urgent need to decarbonise. Most countries have based their future energy strategies on renewables, despite concerns that renewable energy sources alone will not be sufficient. Diversification and use of all low-carbon energy sources according to their merits seems to be a prudent principle, including a contribution from nuclear energy using sufficiently secured, easily storable fuel resources. Nuclear technology has made or is making significant advances, including extended lifetimes of 60 years, at global scale, which will further improve safety and robustness and increase efficiency, load flexibility and competitiveness. Such advances indicate strong potential for far-reaching improvements compared to current-generation LWRs.

New large reactor concepts are available, already in operation in some cases or under construction. Some evolutionary designs use enhanced active safety systems combined with passive core melt mitigation features. By contrast, revolutionary reactor types display a fundamental shift towards designs that fully incorporate passive and inherent safety features.

Some of the highly innovative designs – mostly those using coolants other than water or thermal or fast neutron spectra – vary by size and purpose: Fast liquid metal- or molten salt-cooled fast reactors allow for fuel breeding and/or spent fuel/actinide burning, either to further extend the limits of fuel resources or to drastically reduce waste disposal requirements. Associated advanced cycle concepts, including promising reprocessing technologies, are under development. Most such concepts face delays and are at a low readiness level.

In general, the outlook for small to medium sized modular concepts (SMR) is favourable. Most of them, like the water-cooled VOYGR and gas-cooled HTR-PM, both of which have thermal neutron spectra, incorporate inherent safety features for decay heat removal from the reactor, thereby virtually excluding major core meltdown or core damage states respectively. As the standard design has been completed, the standard licence and construction work has started or full power operation has begun, these designs incorporate moderate technological risks and a high readiness level. However, uncertainties remain regarding technological development and implementation, and their economic competitiveness is often questioned.

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Nuclear technology development lines

Key figures, impact on waste disposal and proliferation issues

Generation	**II retrofitted** **benchmark: NPP Gösgen**	**III** **evolutionary**	**III+** **revolution-ary**	**IV** **highly innovative (chosen concepts belong to the SMR family)**				
Reactor type **Power [MWe]**	PWR 1010	EPR 1600	AP 1000 1100	VOYGR 12 x 77	HTR-PM 210	PRISM 2 x 310	BREST-OD 300	CMSR 100
Neutron spectrum **Field of application**	thermal fuel burner	thermal fuel burner	thermal fuel burner	thermal fuel burner	thermal fuel burner	thermal U breeder/ SNF burner	fast SNF/actinides burner	thermal SNF/waste burner
Coolant	water	water	water	water	gas (helium)	sodium	lead/ lead-bismuth	molten salt (fluoride)
Fuel **Enrichment [%]**	UO_2 low (4.6-4.95)	UO_2 (MOX) low (3–5)	UO_2 low (2.3–4.8)	UO_2 low (4.95)	U coated kernels low/mode-rate (8.5)	U-Pu-Zr alloy, SNF n.a.	(U-Pu) N moderate (≤ 14.5)	U/Th solid, min. actinides n.a.
Primary loop pressure [MPa] **Core outlet temp. [°C]**	high (15.5) 325	high 325	high 325	moderate (13.8) ?	low (7.8) ≥ 750	low ~ 500	low 535	low 700–900
Safety concept / systems **CDF [per reactor-year]**	active 2 x 10^{-6}	enhanced active, passive 10^{-6}	fully passive 2.4 x 10^{-7}	fully passive n.a.	passive/ inherent features n.a.	fully passive n.a.	passive n.a.	passive n.a.
Status [number of plants], readiness	in operation	in operation (3), under construction (1+2)	in operation (4), under construction (2)	construction started, operational 2029	in operation	under development	construction started, operational 2026	conceptual design, construction start 2026
Waste disposal requirements	benchmark	=	=	=	(+)	+	++	++
Proliferation resistence	benchmark	=	=	=	(-)	-	--	-

NPP: nuclear power plant   SNF: spent nuclear fuel from LWRs   CDF: core damage frequency   n.a.: not available/not applicable

Waste disposal-related: = virtually constant, (+) slightly improved, +/++ improved/considerably improved

Proliferation resistance-related: = virtually constant, (-) slight decrease (due to higher enrichment), -/-- decrease (due to higher enrichment or reprocessing / both)

Making Switzerland's energy systems carbon-neutral while safeguarding supply is a major challenge for the country. The **Swiss Academy of Engineering Sciences** SATW is supporting developments by partnering with a network of renowned experts from science and business to identify important new technologies, provide comprehensive information and objective explanations for government and society, and assess the potential of innovative solutions.

SATW's Energy group investigates new technologies capable of delivering a safe and sustainable energy supply and publishes its findings in a series of fact sheets. The views expressed here are those of the author and do not reflect the official position of SATW and its members.

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