swiss physical society

Nr. 62
Oktober 2020

SPG MITTEILUNGEN
COMMUNICATIONS DE LA SSP

Progress in Physics (75)

Novel reactor concepts: Asset in a future de-carbonized energy mix?

Wolfgang Kröger, Andrej Stankovski, ETH Zürich, Chair of Entrepreneurial Risks

Progress in Physics (75)

Novel reactor concepts: Asset in a future de-carbonized energy mix?

Wolfgang Kröger, Andrej Stankovski, ETH Zürich, Chair of Entrepreneurial Risks

1. Background and motivation

By the end of 2018 [1] the global primary energy consumption totaled to 166,379 TWh, has doubled within the last 50 years and increased by 2.9 % compared to 2017. Almost 40 % are converted into electricity which corresponds to a 16 % share of the final energy demand. Scenario analyses predict a massive growth of primary energy, mainly driven by developing countries, to cope with the expected increase of world population and expand energy access and economic opportunities to billions of people. The electricity sector is expected to grow disproportionally, by a factor of 2.5 till 2050 [2], notably to penetrate non-traditional domains, i.e. e-mobility, digitalization, buildings.

This challenging trajectory is confronted by the requirement to deeply de-carbonize the energy system, currently relying at about 85 % on fossil fuels [1]. The electricity production, based at 64 % on coal, gas and oil, contributes almost 30 % to the global CO_2 emissions of 34 gigatons (increased by 2 % compared to 2017). Therefore, the electricity sector needs a new mix and roughly doubled share of low-carbon generation assets by 2050 to meet the “2 °C climate target”, while other sustainability indicators like use of land and other resources, affordability, waste production, factorial and perceived risks must be kept in mind.

Most scenario-based projections (see also [3]) and strategies focus on expanded use of renewable energy sources. Besides hydro with a share of roughly 15 %, wind and solar contributed 9.3 % of the global power production (18.7 % in Europe) in 2018, with a 14.5 % annual growth, slightly below its historical average. However, there are growing concerns about whether (a) renewable generation will grow sufficiently fast, (b) variable energy sources alone will be sufficiently secure and (c) the required infrastructure including seasonal storage, upgraded grids and flexible backups can be provided.

Currently, nuclear power contributes 10.15 % to global electricity production – 23 % in Europe. The share increased from about 2 % in 1971 to 18 % in 1998, decreased afterwards but grew in 2018 by 2.4 %, the fastest growth since 2010, to which China contributed almost three quarters [1]. However, its prospects are dim in many parts of the world, with costs [4], lack of public acceptance and some unresolved issues including disposal of radioactive wastes as key problems [3]. Future shares of electricity production by nuclear energy are ambiguous, vary from zero [5] to a grow by 28 % till 2040 [2] – the latter corresponds to additional 510 GWe, and questions deployment readiness as well as industrial and regulatory capabilities.

2. Characteristics of nuclear energy and status of use

The use of nuclear power has proven to be a mature technology. In 2019 [6], there was a fleet of 450 reactor units with 398.9 GWe total net installed capacity in operation, distributed throughout 31 countries. The clear majority (80%) of all operating units are light water reactors (LWR), which use low enriched uranium (3-5% U-235). Experience accumulated to roughly 17000 reactor-years; the mean capacity factor was 80 %. There are 53 units under construction with 54.7 GWe in 20 countries, the majority of which in China (10). New builds in the Western world are rare and, like the European Pressurized Water Reactor (EPR) in Finland and France, confronted with tripled cost and construction time overruns, while projects in Asia tend to stay within basic conditions.

Uranium has incomparably high energy density: The energy density of a mix of natural (non-fissile) U-238 and Pu-239 used in breeder reactors is approximately 80.620 GJ/kg, meaning that, while undergoing full breeding and fission, one kg of uranium is the equivalent of burning 3500 tons of black coal [3]. Considering just the current proven uranium reserves in the low- and higher-cost range extraction the world can produce enough uranium for the next 125 years, with the current yearly consumption of uranium of roughly 63000 tons. When considering the inferred and reasonably assured resources, the total reserves and operating times are estimated to double [7]. Furthermore, moving to advanced nuclear options including breeder reactors, using thorium as fuel and application of new mining and extraction technologies could place nuclear as a practically unlimited resource.

Current nuclear technology has very low greenhouse gas emissions, comparable to hydro and wind, less than PV roof when considering the whole life cycle. By 2050, with the deployment of next generation reactors, the emissions are estimated to decrease further [8].

Nuclear power is not without its drawbacks, both in the physical process and current technologies. The decay of short-lived fission products is accountable for heat production after reactor nuclear shutdown while long-lived fission products together with actinides after neutron absorption

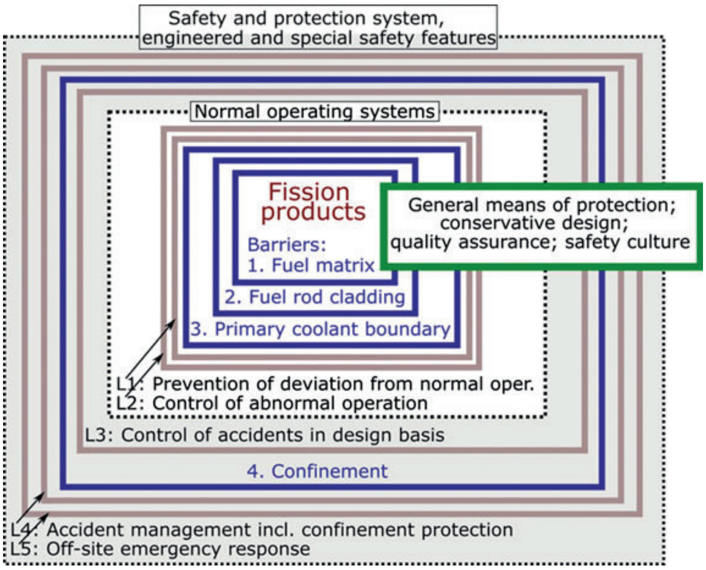


Fig. 1 Defense-in-depth: Four physical barriers (blue) and five levels of protection (brown), split into normal (white inner) and safety/protection (grey outer) operation layers, adapted from (IAEA 1999).

call for ultra-long confinement times. This leads to major design challenges and implementation of safety functions as regards to fission product confinement, reactivity control and decay heat removal, under all conceivable circumstances as well as for management and long-term storage of nuclear waste. Current safety principles like defense-in-depth (Fig. 1) and proven technologies address these issues successfully.

However, certain aspects are still problematic, such as reliance on active safety systems, early operator actions, vulnerable structural metallic material, and little grace time (one to two hours) in case safety systems fail. Major safety improvements are demonstrated by decreasing core damage frequency (CDF) estimates – from 10^{-4} to 10^{-5} for operating LWR to as low as 10^{-6} for advanced and some retro-fitted plants, each per reactor-year [3][23]. The likelihood of large radioactive releases is roughly by one order of magnitude smaller, depending on the containment design. However, they cannot be excluded and provoke public fear.

The other issue of concern is radioactive waste burden. LWR follow one of three fuel cycle concepts, "once-through", "partially closed" and "fully closed" [3]. In the once-through cycle, spent fuel (SF) is sent for extended interim storage and emplacement in deep geological repositories. On the other hand, SF can be reprocessed to extract fissile material such as uranium and plutonium before disposal (partially closed cycle). In the fully-closed fuel cycle, uranium, plutonium, and other minor actinides (long-lived radionuclides) are extracted and used as fuel in advanced fast reactors. The once-through cycle is the most favorable in terms of proliferation issues as no separation of fissile material, Pu in particular, takes place. In contrast closed fuel cycle concepts allow for better exploitation of fuel reserves, and bring down amounts of low-level nuclear waste.

All fuel cycle concepts require a safe and long-term disposal of radioactive wastes. However, due to inherent uncertainties, strong opposition and strict regulatory/safety requirements, the advancements are still slow, and there is no operating deep geological repository around the world, yet. Nevertheless, Finland is in the lead, granting license and starting construction at Olkiluoto site in 2015 with the disposal process expected to start by 2024.

There are major barriers to make future, potentially expanded, use of nuclear power acceptable to the public such as general safety concerns and risk aversion, in particular, including the (i) unequal treatment of extra-ordinarily low probabilities and high consequences of potential accidents and (ii) the perceived cancer dread of even low doses of radiation.

3. Challenges and means to overcome barriers

3.1 Key requirements

To overcome risk aversion-related barriers, we recommend a fundamental shift from reactor designs that depend on properly functioning (active) safety systems, requiring AC power and reliable actuation mechanisms, towards designs that incorporate passive and inherent safety features. Furthermore, nuclear plants should be less sensitive to adequate protection against natural events and malicious manmade physical or cyber-based attacks; they should warrant higher tolerability to human errors, lack of safety culture and socio-political instability within the operational environment. Fuel cycle concepts should allow more efficient use of resources and alleviate requirements to high-level waste disposal. The following key requirements, aiming at a deterministic exclusion of serious conditions and states, are put forward (see [3] for details):

1) *Reactivity control*, i.e. elimination of potential reactivity induced accidents, by
   a) weak/negative reactivity coefficients,
   b) small reactivity surplus at startup with fresh fuel.
2) *Assurance of heat removal* to ultimate heat sink and retention of fission products, by
   a) low power density and power size (to avoid exceeding critical temperature limits),
   b) resistant fuel cladding and structural material that will not melt or react chemically,
   c) sufficient heat storage capability and inherent/passive heat transfer mechanisms in case of loss of normal (forced) cooling.
3) *Securing structural integrity* to avoid loss of core cooling capability/confinement of radioactive inventory by
   a) low primary circuit pressure or rupture proof components (reactor pressure vessel),
   b) radiation resistant, chemically and physically robust core structures,
   c) underground siting for protection against extreme external impact, including weapons' attack.
4) *Use of non-reactive, non-toxic materials/fluids* or avoid direct contact of reacting substances.
5) *Avoidance/incineration of long-lived radioisotopes*, by
   a) a switch to thorium with drastically smaller generation of long-lived minor actinides,
   b) waste burner core designs,
   c) striving for long-term stable, high burn-up SF as an open fuel cycle option.
6) *Enhanced intrinsic proliferation resistance* characteristics, basically by applying established principles, means and strategies by avoided use of highly enriched uranium (HEU) and off-line reprocessing of SF if there is no strategy to minimize the time during which weapons-grade material, notably plutonium, is in separated form and to avoid accumulating a stockpile.

3.2. Building blocks

To achieve these ambitious requirements, key design features for advanced nuclear reactors and related systems can be identified. They include neutron spectra and coolants, furthermore fuels, fuel claddings and core structural materials, power densities and power sizes, and siting options. A look at the fission probabilities ("cross sections") of selected actinides demonstrates the attractiveness of fast *neutrons* compared to moderated neutrons that dominate the spectrum of today's LWR. While thermal fission cross sections of fissile U-233 and U-235 and Pu-239 are significantly larger than those for fast fission, their important fission-to-absorption ratio is of the same order but significantly higher for other selected isotopes, in particular atoms heavier than uranium. Large fission-to-absorption ratios are favorable to avoid or minimize the formation of radioactive waste and minor actinides, in particular. Eliminating these isotopes from spent nuclear fuel would reduce drastically the stewardship times of the long-lived wastes (up to a factor 100).

Fast neutron spectra, together with adequate coolants, allow for high neutron economy and reactor designs that are favorable to produce as much or more fissile material than consumed ("breeder reactor") and/or incinerate radioactive waste ("waste or actinides burner"). However, the cores of fast reactors are not in the state of highest reactivity under steady-state operational conditions; changes of physical parameters could lead to disruptive power excursions.

Considered *coolants*, i.e. liquid metals like sodium, lead or lead/bismuth, molten salt (fluorides or chlorides) and gas (helium) are briefly characterized here, for details see [3]. All liquid metals and salts feature good heat storage and transfer capabilities and no need for pressurization for operation in a single-phase mode. But high density and mass may lead to high static loads, notably for lead. All liquids and gas allow for core outlet temperatures of about 510 °C (molten sodium) to almost 600 °C (molten lead, molten salt) or even 850/950 °C (helium), significantly higher than for water. This results in thermodynamic efficiencies for power production clearly above 40 % (rather than 33 % for LWR) and potential use for chemical heat applications.

Current reactors base their *fuel* on metal oxide (UO_2) rather than metals themselves, because the melting point is much higher (2850 °C) and it cannot burn, although its thermal conductivity is very low. Ceramic fuels have the advantage of high heat conductivities and melting points (2700 - 2800 °C) but are more prone to swelling than oxide fuels. Uranium-carbide, most notably in the form of coated micro particles together with ceramic (or graphite) structural material, are regarded as attractive fuel for certain future reactors. Liquid fuels, i.e. dissolved in molten salts, offer numerous operational advantages due to inherently stable self-adjusting reactor dynamics, rapid drain ability into dump-tanks and continuous release of xenon gas that acts as a neutron absorber.

Making fuel, fuel cladding and structural material more resistant to temperature rise and resulting core damage is a promising way to increase the robustness of nuclear reactors against potential accidents. A huge program on "accident tolerant fuel", coordinated by Westinghouse, is focused on high temperature resistant enriched U_3SiC fuel pellets and protecting claddings from oxidation by coating.

Moreover, *thorium* (namely Th-232) is becoming a promising fuel option, for which all uranium fuel cycles apply. Thorium is three to four times more abundant than uranium and has superior physical properties in metallic and oxide states (high melting points, high thermal conductivity, small expansion coefficient). It has more specific energy (200 times more than natural uranium), and produces less nuclear wastes with shorter lifetimes [9]. Th-232 does not undergo fission itself but, on capturing a neutron, it leads to U-233 as final fissile product of the reaction chain. U-233 could be misused for weapon production and, as its forerunner Pa-233 can be separated effectively, the Th-232 fuel is not regarded proliferation proof. Thorium-based technologies are still at early phases with little commercial experience.

Steel alloys dominate the *material for reactor* (pressure) *vessels*; "absolutely" rupture proof pre-stressed concrete reactor pressure vessels are technically feasible.

Nuclear fission enables reactors with high power density and power rating: typical power densities vary from 70 for current LWR to about 290 MW/m^3 for conceptual designs of sodium cooled fast reactors, while those of liquid lead or salt cooled fast reactors are less than half that high and those of gas-cooled thermal reactors are small, in principle. Power ratings follow the economy of scale with 4800 MWth (1600 MWe) of modern large size LWR as a reference point. In principle, high power density and power rating make the reactors more susceptible to loss of coolant/decay heat removal accidents. In other words, limiting the power densities and power rating, together with other means, could provide flexibility to increase the robustness of nuclear reactors.

There is a revival of interest in small and simpler units for electricity production and other purposes. The incentive to develop small (up to 300 MWe) modular reactors (SMR) comes from different sources. There is a strong belief [10] that SMR would

- open additional market sectors, e.g., heat for chemical processes, and, based on enhanced safety characteristics, allow for site flexibility;
- better adapt to low growth rates of energy demand, are more suitable to replace aging fossil-fired plants;
- lower upfront capital cost and ease financing and earlier revenues;
- allow for greater simplicity of design, enable economy of serial production largely in factories and, thus, shorter construction times.

As the inventory of fission products is proportional to the power level, a smaller amount could be released into the environment by smaller-sized reactors under loss of confinement conditions, in principle. However, some question the economic competitiveness of SMR and raise concerns regarding adequacy of the current regulatory system and license ability of some (first-of-its-kind) designs.

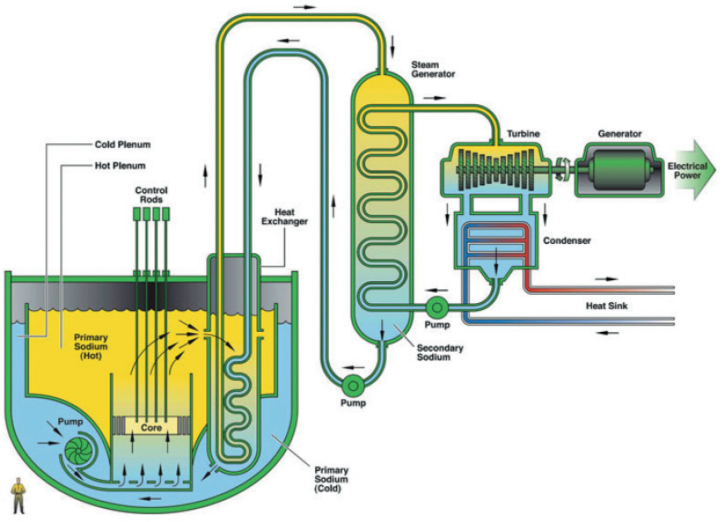
Site characteristics are relevant for ensuring that societal risks due to severe nuclear accidents are acceptably low and remote sites are deemed most suitable. However, driven by scarcity of actual remote sites and aspired use of nuclear reactors beyond power production sites closer to consumer centers may have to be permitted. Accordingly, the combination of small, inherently "super-safe" reactors and underground siting has been proposed, the latter allows to protect the plant against extreme external physical impacts.

4. Reactor concepts under development

In what follows, we aim to provide information about reactor concepts and associated states of development by looking into the R&D pipeline. Besides next generation thermal reactors, many prominent reactor concepts are fast reactors that allows them to breed more fissile fuel than they consume or even burn wastes. Most of their proposed designs can use various fuels including spent fuel (SF) from LWR, hence closing the fuel cycle and increases the utilization of uranium significantly compared to current LWR [11]. Most new concepts claim to be inherently safe and highly resistant to proliferation.

4.1 Sodium and lead cooled fast reactors

Heralded as one of the more promising next generation fast breeder reactor concepts, liquid metal cooled reactors (Fig. 2) have a high neutron economy and offer a variety of advantages over conventional. Sodium cooled reactors (*SFR*) in particular, have been in development for more than 60 years. The usual design employs a pool or loop type reac-



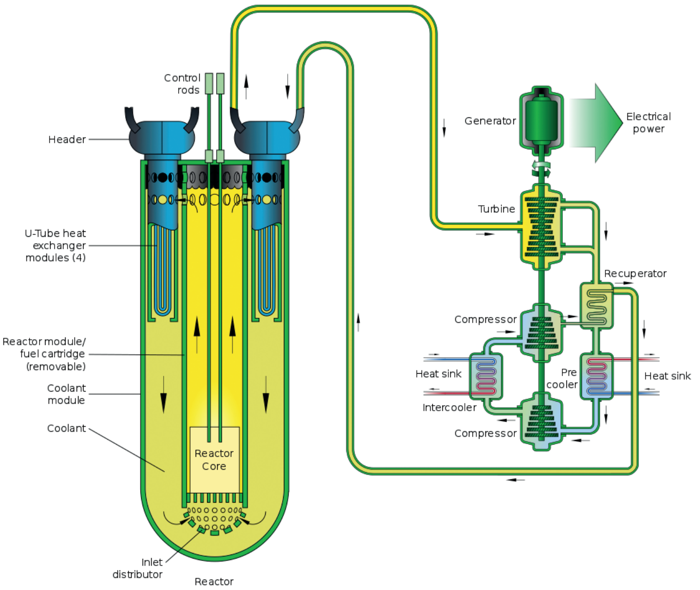


Fig. 2 Schematic view of a pool type - left: SFR and right: LFR, with core outlet temperatures higher than 500 °C [12].

tor filled with molten sodium, an intermediate sodium circuit and a secondary steam generator circuit [3]. Metal oxide fuel (MOX) potentially containing minor actinides is considered as the primary option for larger SFR (600 - 1500 MWe), while metal alloy fuel with minor actinides can also be used for designs in the range of 50 - 600 MWe. All designs use a parfait blanket of fertile material (U-238 and potentially Th-232) in order to increase breeding efficiency. Combined with re-processing techniques which cannot extract plutonium (aqueous re-processing for MOX fuel and pyro-metallurgical for metal alloy fuel), the modern SFR designs are proliferation resistant in this respect. The primary disadvantages of these reactors are the positive void and temperature coefficients (more pronounced in larger cores) and the exothermic reactivity of sodium with water and air.

Lead-cooled reactors (*LFR*) use molten lead or lead-bismuth (Pb-Bi) eutectic as a coolant and share many of the positive characteristics of the SFR. Unlike SFR, the coolant is not chemically reactive with water, making the intermediate coolant loop unnecessary, has a higher boiling point and the positive temperature coefficient is only slightly pronounced due to its neutronic properties [3]. In contrast, the higher melting temperature of the coolant (freezing concerns), Po-210 build-up, corrosive reaction with steel and coolant price (for Pb-Bi) are listed as some of the disadvantages.

Approximately ten liquid metal reactors are expected to be deployed in the near future, out of which PRISM and BREST-OD-300 appear the most promising.

PRISM (Power Reactor Innovative Small Module) is a generation IV SFR under development by GE Hitachi Nuclear Energy. The design comes with two reactor modules, each of 311 MWe power output, using uranium-plutonium-zirconium alloy fuel, which utilizes SF from LWR [13]. Based on the experimental breeder reactor (EBR-II), the design is proven to be both mature and reliable, with additional unique safety features such as negative temperature coefficient (small core size), passive decay heat removal via natural air circulation, and digital instrumentation and control. PRISM is in an advanced stage and as of 2019 has entered the US Versatile Test Reactor program, which aims to build a fast-breeder reactor by 2026 [14].

BREST-OD-300 is a generation IV, 300 MWe LFR developed by RDIPE in Russia. It is a pool-type reactor with passive decay heat removal using natural air circulation. The fuel used is uranium-plutonium mononitride (PuN-UN) mainly comprised of SF from LWR. The design is claimed to be resistant to loss-of-coolant and heat removal accidents, while the small operating reactivity margin prevents power excursions in normal operating conditions [15]. The reactor is in an advanced stage and construction was approved in 2016, with the first plant expected to be operating by 2025 [16]. A larger 1200 MWe version is planned to be built if operation of BREST-OD-300 proves to be successful.

4.2 Molten salt-cooled thermal and fast reactors

Molten salt reactor (*MSR*) designs have been of interest since the 1960s, with one experimental reactor (MSRE) in the USA, operable from 1965 to 1969. The main coolant is a molten salt mixture which can have different properties depending on the salt used (fluoride, chloride), while lithium salts with higher boiling points are preferable (> 1400 °C) as they allow operating at higher temperatures (750 - 900 °C). These reactors can operate with thermal or fast neutron spectra and use solid fuel or fuel dissolved into the coolant, which is the preferable option [3]. Both uranium or thorium-based fuel can be used, optionally with added minor actinides, with the reactor operating as a breeder or a waste burner. The next generation designs envision an unpressurized breeder or burner MSR with fuel dissolved in the coolant. The coolant is constantly circulated through the core and chemical processing plant, in which volatile fission products are separated and the fuel concentration is controlled (Fig. 3). In case of overheating, a freeze plug melts and dumps the coolant into tanks, which immediately stops the fission reaction. The decay heat from the tanks is passively cooled, making the design safe in station blackout scenarios. Main drawbacks of MSR are the corrosive properties of the coolant and potential criticality spikes.

There are multiple MSR under development, with the Danish SWaB (Seaborg Waste Burner) as one of the most promising concepts, designed as a modular reactor which uses SF and thorium. The reactor has a reliable passive overflow system which would dump the fuel in both overheating and prompt criticality scenarios [17]. Even in the worst-case scenarios, such as meltdown due to failure of the system to dump the fuel, the company claims that a redundant dump tank and a secondary barrier would prevent fission products

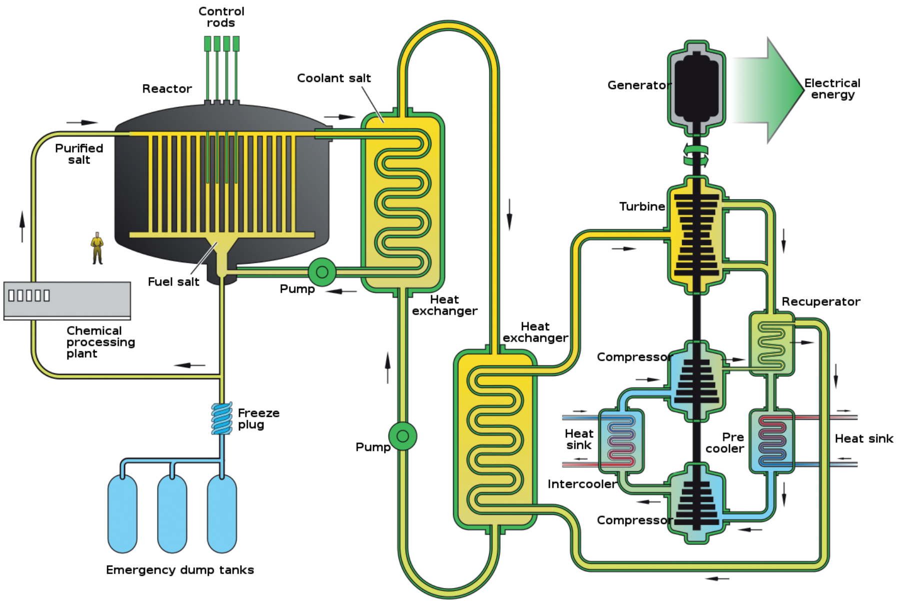


Fig. 3 Schematic view of MSR with online reprocessing, intermediate molten salt circuit and a steam cycle [12].

release to the environment. Although promising, the design is still in a very early stage of development.

4.3 High temperature gas-cooled thermal reactors

Modern high temperature gas-cooled reactor (*HTR*) designs focus on using graphite as moderator and helium as coolant (with inert properties). The high operating temperatures could also open new perspectives for nuclear power, such as cogeneration and hydrogen production [3][18]. The fuel in the form of ceramic pebbles is comprised of thousands of TRISO coated particles embedded in a graphite matrix. The TRISO coated particles consist of a lightly enriched (< 20 %) uranium kernel, a porous pyrolytic graphite layer to accommodate for fuel expansion, an inner and outer dense pyrolytic graphite layer and a silicon carbide (SiC) layer in between for fission products retention (Fig. 4a). HTR offers a range of advantages, such as pronounced negative temperature reactivity coefficient, continuous refueling, fission products retention up to fuel temperatures of about 1600 °C. Together with use of heat storage and convection capabilities, these reactors are deemed inherently safe. However, the concept is not without disadvantages: standard measuring equipment cannot be placed inside the pebble bed core and reprocessing of the ceramic fuel elements is very difficult, raising concerns about the increasing amount of nuclear waste. Multiple prototypes employing this technology were taken into operation, such as the AVR (Germany, 1966), THTR-300 (Germany, 1983) and HTR-10 (China, 2003).

The HTR-PM (pebble-bed modular) reactor (Fig. 4b) is currently under construction in Shindao Bay, China, and expected to become operational in 2020. The design specifies that two 250 MWth reactors, intended to operate at temperatures of 750 °C, will be connected to power a single 210 MWe turbine [18]. The reactor relies on inherent safety features and use of passive cooling systems for decay heat removal, practically eliminating the danger of station blackout events (large grace period). The main vulnerability of the design is that potential unrestricted air or water ingress could cause graphite corrosion.

4.4 Accelerator-driven subcritical systems

Accelerator-driven systems (*ADS*) are novel concepts comprised of a subcritical reactor and an external neutron source, usually a high-intensity proton accelerator [3]. The proton beam is focused on a metal target and produces neutrons by spallation. As the reactor is incapable of self-sustaining fission reactions, the chain reaction stops by turning off the accelerator. Therefore, these systems do not require the installation of control rods and eliminate the possibility of reactivity induced accidents. The reactor is conceptualized as a lead or lead-bismuth (Pb-Bi) cooled fast breeder reactor, introduced before. These characteristics make the ADS perfect for the burning of minor actinides (transmutation) which greatly reduces the husbandry times of nuclear waste.

One of the more promising concepts currently in development is MYRRHA (Fig. 5), a proposed actinide burner developed by the Belgian Centre for Nuclear Research. The design couples a subcritical (multiplication factor 0.95) Pb-Bi cooled fast reactor with a proton accelerator, focused on a liquid Pb-Bi spallation target. With a total budget of 1.6 billion euros, the system is expected to be commissioned by 2036 [19].

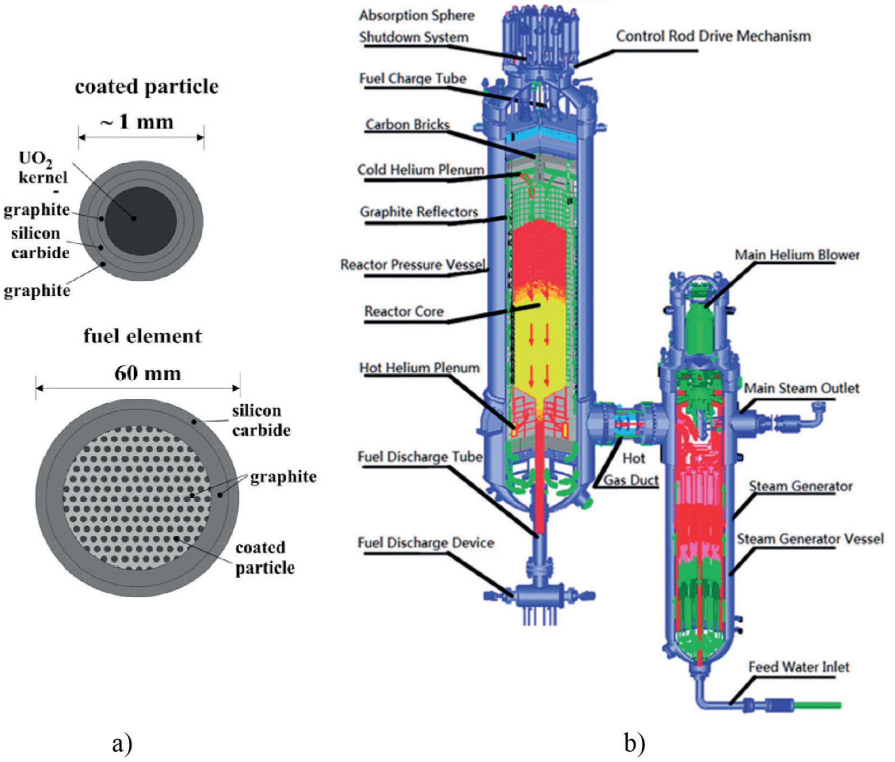


Fig. 4 Schematic view of HTR - a) TRISO coated particle and fuel element and b) HTR-PM reactor design [18].

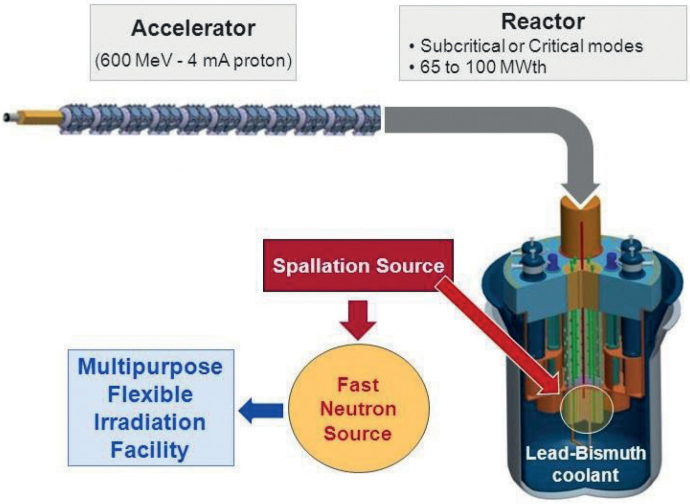


Fig. 5 Schematic view of MYRRHA (Multi-purpose Hybrid Research Reactor for High-tech Applications) [3].

4.5 Small-medium sized, modular reactor concepts

Following the expected benefits of small modular reactors (*SMR*) different concepts are currently under development worldwide (Fig. 6). They include smaller versions of all reactor types, including reactors with thermal and fast neutron spectrum; the most promising "revolutionary" designs discussed before are often considered as SMR.

Additional designs of interest are LWR-based SMR, which have the lowest technological and regulatory risk. The NuScale project in the USA appears to be in a well-advanced stage and initial deployment is expected in 2026. The 60 MWe reactors are based on mature PWR designs, with technological advancements which claim to make the reactor inherently safe, such as small size, small fuel and fission product inventory (1/20 of normal PWRs), containment immersed in the cooling pool, etc. [21]. Additionally, up to 12 reactors can be submerged in one cooling pool, still allowing power generation of 720 MWe.

Another interesting concept are the floating SMR, built at shipbuilding facilities and towed to designated areas where they could provide electricity, district heating and seawater desalination, especially in developing countries. The first plant of this kind is Akademik Lomonosov, recently commissioned in Russia. This plant is powered by two 35 MWe PWR, based on the KLT-40 marine propulsion reactor, with passive decay heat removal, modernized active safety systems and instrumentation [22].

5. Evaluation of selected candidate concepts against key requirements

The results of a concept-by-concept comparison indicate a high potential for far-reaching improvements compared to the most advanced LWR (Generation III+) as the benchmark. As can be can be seen from Table 1, none of the best versions, i.e. small sized in general, of the candidate concepts fully meet all requirements convincingly, yet [3][23]. Thermal helium cooled reactors (HTR-PM) come closest, promising inherent robustness against severe accidents and largely avoiding long-lived radio-isotopes when using thorium fuel. With respect to burning waste, molten salt fast reactors promise to do best but appear most susceptible to reactivity-induced accidents, as are all liquid metal cooled fast reactors are, albeit to different degrees. The only exception are the accelerator-driven systems (ADS), which are inherently resistant to RIA due to their subcritical core design. There is also a potential of new concept specific accidents, such as overcooling/freezing of coolant, chemical reactions following coolant outflows after leaks or air/water ingress into hot graphite cores, which deserve special attention.

All concepts seem to have limited capabilities to achieve the goal of reducing proliferation risk or even to maintain the current level, mainly due to partially elevated and/or significantly increased enrichment or significantly heightened by the need for off-site reprocessing.

It is also important to note that revolutionary designs and technologies often start from scratch and introduce new man-machine interfaces and tend to represent a jump in complexity. The molten salt cooled systems with dissolved fuel, fission products, and off-gas systems may serve as example; some features of coolants, e.g., production of activation products, chemical toxicity, non-transparency, freezing at high temperatures, may require complex operations and maintenance procedures [4].

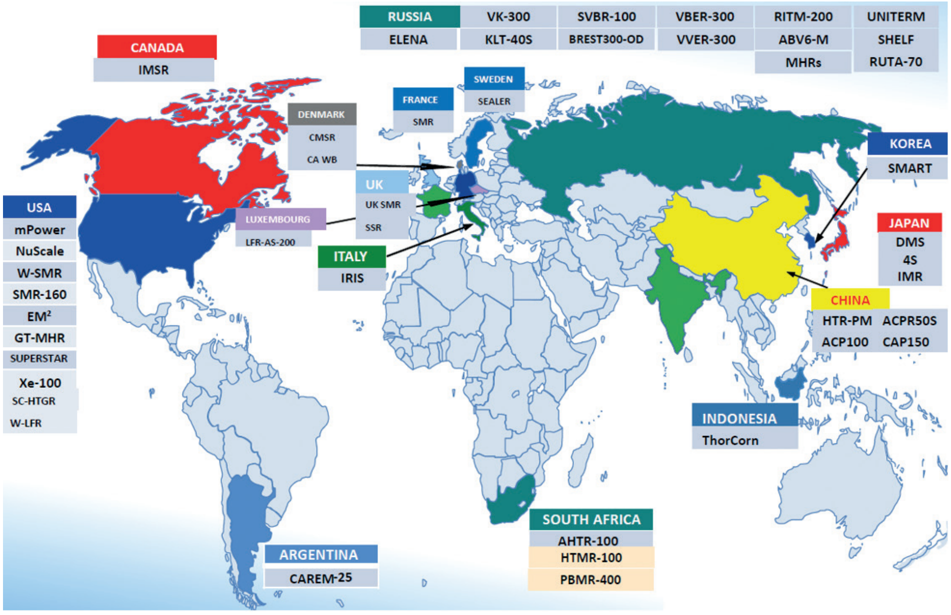


Fig. 6 World map of small and medium reactor designs under development [20].

6. Conclusions

The global demand of energy, of electricity in particular, is expected to grow, simultaneously confronted by the requirement of de-carbonization. Most countries base their future strategies on "renewables" while there are growing concerns that renewables alone will be adequate and sufficient. Diversification and use of low-carbon energy sources according to their merits seem to be a prudent principle. Nuclear energy has the potential to become an asset in a future energy mix. However, its prospects are dim in many parts of the world and major barriers including risk aversion must be overcome to make its use acceptable to the public which current technologies barely achieve.

Therefore, we set up key requirements

Table 1 Ranking from excellent (5) to neutral to very poor (1) of candidate reactor concepts against key requirements with the generation III+ EPR as the benchmark

Key requirements	***Candidate reactor concepts –*** *varying coolant, selected designs in brackets*					
	Water – thermal (large EPR)	Sodium – fast (PRISM)	Molten Salt – fast (SaWB)	Helium – thermal (HTR-PM)	Lead – fast (BREST-OD-300)	ADS (MYRRHA)
Elimination of Reactivity Induced Accidents	**4**	**2**	**1**	**5**	**2 - 3**	**5**
Resistance to Loss of Active Core Cooling	**1**	**2**	**3**	**5**	**2 - 3**	**3**
- avoid exceeding critical temperatures	1	n.a.	n.a.	5	n.a.	n.a.
- avoid high fission product inventory	1	4 [1]	5 [2]	4 [1]	4 [1]	4 [1]
- provide sufficient heat storage & transfer capacity	4	5	4	4	5	5
Structural Integrity	**2**	**4**	**4**	**5**	**4**	**4**
- avoid high operating pressure	1	4 [3]	5	4	4 [3]	4 [3] [4]
[suitability of underground siting]	[2]	[?]	[5] [4]	[5] [4]	[4]	
Use Non-chemically Reactive / Non-Toxic Materials	**4**	**1** [5]	**2** [5] (non-stable)	**5**	**4**	**4**
Avoid Long-lived Radioisotopes	**1**	**4**	**5**	**4**	**5**	**5**
Enhance Proliferation Resistance	**4**	**2**	**2**	**3**	**2**	**2**
- avoid high enriched uranium	5	2 [6]	2 [6]	2-3	2 [6]	2 [6]

[1] due to small power size
[2] in case of dispersed fuel & due to small power size
[3] not pressurized but high static load
[4] foreseen
[5] intermediate cycle (IHX) foreseen
[6] close to / above HEU lower limit

and recommend a fundamental shift towards designs that incorporate passive and inherent safety features, are less sensitive to stable operating conditions and apply fuel cycle concepts that are more sustainable and reduce husbandry times of nuclear wastes to historical time-scales. Novel reactor designs with coolants different from water, thermal or fast spectrum, the latter allowing for fuel breeding and waste burning, and fuel cycle concepts are under development which indicate a high potential for far-reaching improvements compared to the most advanced current designs. However, none of the best versions of the candidate concepts fully meet all requirements convincingly, yet, while small sized concepts deem favorable, in general, while thermal helium cooled reactors (HTR-PM) come closest, promising inherent robustness against severe accidents and largely avoiding long-lived radio-isotopes when using thorium fuel. Boosted R&DD appear necessary, aiming at further improving some essential characteristics and features of evaluated concepts and mastering some jumps in complexity as well as to shorten commercial deployment times to ten to twenty years from now.

References

[1] BP (2019) BP Statistical Review of World Energy 2019, 68th edition.https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2019-full-report.pdf

[2] OECD-IEA (2019) World Energy Outlook 2019. https://www.iea.org/reports/world-energy-outlook-2019

[3] Sornette, D., Kröger, W. and Wheatley, S. (2019) New Ways and Needs for Exploiting Nuclear Energy. Springer.

[4] Buongiorno, J., Corradini, M., John, P., & Petti, D. (2018). The Future of Nuclear Energy in a Carbon-Constrained World. Massachusetts Institute of Technology, 26.

[5] Greenpeace (2015) The Energy [R]evolution 2015. http://www.greenpeace.org/international/en/campaigns/climate-change/energyrevolution/

[6] IAEA (2019) Preliminary Nuclear Power Facts and Figures for 2019. https://www.iaea.org/newscenter/news/preliminary-nuclear-powerfacts-and-figures-for-2019

[7] OECD-NEA and IAEA (2018) Uranium 2018: Resources, Production and Demand. NEA No. 7413. https://www.oecd-nea.org/ndd/pubs/2018/7413-uranium-2018.pdf

[8] Hirschberg, S. and Burgherr, P. (2015) Sustainability Assessment for Energy Technologies. Handbook of Clean Energy Systems.

[9] Kiplinger, J. L. and Ramos, O. Jr. (2011) Th-ING: A Sustainable Energy Source. https://www.lanl.gov/science/NSS/issue2_2011/story6full.shtml

[10] World Nuclear Association (WNA) (2020) Small Nuclear Power Reactors. https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/small-nuclear-power-reactors.aspx

[11] Tsvetkov, P., Waltar, A. and Todd, D. (2012) Sustainable Development of Nuclear Energy and the Role of Fast Spectrum Reactors. In Fast Spectrum Reactors (pp. 3 - 22). Springer, Boston, Massachusetts.

[12] Generation IV International Forum (2002) A Technology Roadmap for Generation IV Nuclear Energy Systems.

[13] Tripplet, B. S., Loewen, E. P. and Dooies, B. J. (2010) PRISM: A Competitive Small Modular Sodium-Cooled Reactor. Nuclear Technology, 178:2, 186-200. https://doi.org/10.13182/NT178-186

[14] GE Hitachi (2018) GE Hitachi and PRISM Selected for U.S. Department of Energy's Versatile Test Reactor Program. https://www.genewsroom.com/press-releases/ge-hitachi-and-prism-selected-us-department-energys-versatile-test-reactor-program

[15] IAEA BREST-OD-300. https://aris.iaea.org/PDF/BREST-OD-300.pdf

[16] Nuclear Engineering International (2019) Titan-2 Contracted to Build Russia's Brest 300 Reactor. https://www.neimagazine.com/news/newstitan-2-contracted-to-build-russias-brest-300-reactor-7527297/

[17] Seaborg Technologies (2015) Seaborg Wasteburner. Molten Salt Reactor. Whitepaper SEAB-WP-2015-001. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.712.5069&rep=rep1&type=pdf

[18] Zhang, Z. et al. (2016) The Shandong Shidao Bay 200 MWe High-Temperature Gas-Cooled Reactor Pebble-Bed Module (HTR-PM) Demonstration Power Plant: An Engineering and Technological Innovation. Engineering 2 (2016) 112–118. Elsevier. https://doi.org/10.1016/J.ENG.2016.01.020

[19] MYRRHA Project (2020) MYRRHA Phased implementation. https://www.myrrha.be/myrrha-project/

[20] Reitsma, F. (2019) The Status of Different SMR Technologies and the Role of The IAEA to Support its Member States in SMR Technology Development - IAEA Atoms for Peace and Development presentation. https://wins.org/wp-content/uploads/2018/11/3.-Frederik-Reitsma_IAEA_SMRs_WINS_Reitsma_5March2019.pdf

[21] Black, G. and Peterson, S. (2019) Economic Impact Report: Construction and Operation of a Small Modular Reactor Electric Power Generation Facility at the Idaho National Laboratory Site, Butte County, Idaho. Idaho Policy Institute, Boise State University.

[22] IAEA (2013) KLT-40S. https://aris.iaea.org/PDF/KLT-40S.pdf

[23] Kröger, W., Sornette, D. and Ayoub, A. (2020) Towards Safer and More Sustainable Ways for Exploiting Nuclear Power. World Journal of Nuclear Science and Technology. doi:10.4236/wjnst.2020.103010