WORLD NUCLEAR ASSOCIATION

Small Nuclear Power Reactors

(Updated November 2019)

- **There is strong interest in small and simpler units for generating electricity from nuclear power, and for process heat.**
- **This interest in small and medium nuclear power reactors is driven both by a desire to reduce the impact of capital costs and to provide power away from large grid systems.**
- **The technologies involved are numerous and very diverse.**

As nuclear power generation has become established since the 1950s, the size of reactor units has grown from 60 MWe to more than 1600 MWe, with corresponding economies of scale in operation. At the same time there have been many hundreds of smaller power reactors built for naval use (up to 190 MW thermal) and as neutron sources[a], yielding enormous expertise in the engineering of small power units. The International Atomic Energy Agency (IAEA) defines 'small' as under 300 MWe, and up to about 700 MWe as 'medium' – including many operational units from the 20th century. Together they have been referred to by the IAEA as small and medium reactors (SMRs). However, 'SMR' is used more commonly as an acronym for 'small modular reactor', designed for serial construction and collectively to comprise a large nuclear power plant. (In this paper the use of diverse pre-fabricated modules to expedite the construction of a single large reactor is not relevant.) A subcategory of very small reactors – vSMRs – is proposed for units under about 15 MWe, especially for remote communities.

Today, due partly to the high capital cost of large power reactors generating electricity via the steam cycle and partly to the need to service small electricity grids under about 4 GWe,[b] there is a move to develop smaller units. These may be built independently or as modules in a larger complex, with capacity added incrementally as required (see section below on Modular construction using small reactor units). Economies of scale are envisaged due to the numbers produced. There are also moves to develop independent small units for remote sites. Small units are seen as a much more manageable investment than big ones whose cost often rivals the capitalization of the utilities concerned.

An additional reason for interest in SMRs is that they can more readily slot into brownfield sites in place of decommissioned coal-fired plants, the units of which are seldom very large – more than 90% are under 500 MWe, and some are under 50 MWe. In the USA coal-fired units retired over 2010-12 averaged 97 MWe, and those expected to retire over 2015-25 average 145 MWe.

Small modular reactors (SMRs) are defined as nuclear reactors generally 300MWe equivalent or less, designed with modular technology using module factory fabrication, pursuing economies of series production and short construction times. This definition, from the World Nuclear Association, is closely based on those from the IAEA and the US Nuclear Energy Institute. Some of the already-operating small reactors mentioned or tabulated below do not fit this definition, but most of those described do fit it.

This paper focuses on advanced designs in the small category, *i.e.* those now being built for the first time or still on the drawing board, and some larger ones which are outside the mainstream categories dealt with in the Advanced Nuclear Power Reactors information paper. Note that many of the designs described here are not yet actually taking shape. Four main options are being pursued: light water reactors, fast neutron reactors, graphite-moderated high temperature reactors and various kinds of molten salt reactors (MSRs). The first has the lowest technological risk, but the second (FNR) can be smaller, simpler and with longer operation before refuelling. Some MSRs are fast-spectrum.

SMR development is proceeding in Western countries with a lot of private investment, including small companies. The involvement of these new investors indicates a profound shift taking place from government-led and -funded nuclear R&D to that led by the private sector and people with strong entrepreneurial goals, often linked to a social purpose. That purpose is often deployment of affordable clean energy, without carbon dioxide emissions.

A 2011 report for the US Department of Energy by the University of Chicago Energy Policy Institute pointed out that detailed engineering data for most small reactor designs were only 10-20% complete, only limited cost data was available, and no US design had advanced beyond the planning stages. In general, however, the report said that small reactors could significantly mitigate the financial risk associated with full-scale plants, potentially allowing small reactors to compete effectively with other energy sources.

Generally, modern small reactors for power generation, and especially SMRs, are expected to have greater simplicity of design, economy of series production largely in factories, short construction times, and reduced siting costs. Most are also designed for a high level of passive or inherent safety in the event of malfunction[8]. Also many are designed to be emplaced below ground level, giving a high resistance to terrorist threats. A 2010 report by a special committee convened by the American Nuclear Society showed that many safety provisions necessary, or at least prudent, in large reactors are not necessary in the small designs forthcoming. This is largely due to their higher surface area to volume (and core heat) ratio compared with large units. It means that a lot of the engineering for safety including heat removal in large reactors is not needed in the small reactors[9]. Since small reactors are envisaged as replacing fossil fuel plants in many situations, the emergency planning zone required is designed to be no more than about 300 m radius. The combined tables from this report are appended, along with notes of some early small water-, gas-, and liquid metal-cooled reactors.

Licensing is potentially a challenge for SMRs, as design certification, construction and operation licence costs are not necessarily less than for large reactors. Several developers have engaged with the Canadian Nuclear Safety Commission's (CNSC's) pre-licensing vendor design review process, which identifies fundamental barriers to licensing a new design in Canada and assures that a resolution path exists. The pre-licensing review is essentially a technical discussion, phase 1 of which involves about 5000 hours of staff time, considering the conceptual design and charged to the developer. Phase 2 is twice that, addressing system-level design.

A World Nuclear Association 2015 report on SMR standardization of licensing and harmonization of regulatory requirements[12], said that the enormous potential of SMRs rests on a number of factors:

- Because of their small size and modularity, SMRs could almost be completely built in a controlled factory setting and installed module by module, improving the level of construction quality and efficiency.
- Their small size and passive safety features lend them to countries with smaller grids and less experience of nuclear power.
- Size, construction efficiency and passive safety systems (requiring less redundancy) can lead to easier financing compared to that for larger plants.
- Moreover, achieving 'economies of series production' for a specific SMR design will reduce costs further.

The World Nuclear Association lists the features of an SMR, including:

- Small power and compact architecture and usually (at least for nuclear steam supply system and associated safety systems) employment of passive concepts. Therefore there is less reliance on active safety systems and additional pumps, as well as AC power for accident mitigation.
- The compact architecture enables modularity of fabrication (in-factory), which can also facilitate implementation of higher quality standards.
- Lower power leading to reduction of the source term as well as smaller radioactive inventory in a reactor (smaller reactors).
- Potential for sub-grade (underground or underwater) location of the reactor unit providing more protection from natural (*e.g.* seismic or tsunami according to the location) or man-made (*e.g.* aircraft impact) hazards.
- The modular design and small size lends itself to having multiple units on the same site.

- Lower requirement for access to cooling water – therefore suitable for remote regions and for specific applications such as mining or desalination.
- Ability to remove reactor module or in-situ decommissioning at the end of the lifetime.

A 2009 assessment by the IAEA under its Innovative Nuclear Power Reactors & Fuel Cycle (INPRO) programme concluded that there could be 96 small modular reactors (SMRs) in operation around the world by 2030 in its 'high' case, and 43 units in the 'low' case, none of them in the USA. (In 2011 there were 125 small and medium units – up to 700 MWe – in operation and 17 under construction, in 28 countries, totaling 57 GWe capacity.) The IAEA has a programme assessing a conceptual multi-application small light water reactor (MASLWR) design with integral steam generators, focused on natural circulation of coolant, and in 2003 the US DOE published a report on this MASLWR conceptual design. Several of the integral PWR designs below have some similarities.

There are a number of small modular reactors coming forward requiring fuel enriched at the top end of what is defined as low-enriched uranium (LEU) – 20% U-235. The US Nuclear Infrastructure Council (NIC) has called for some of the downblending of military HEU to be only to about 19.75% U-235, so as to provide a small stockpile of fuel which would otherwise be very difficult to obtain (since civil enrichment plants normally cannot go above 5%). A reserve of 20 tonnes has been suggested. The NIC said that the only supply of fuel for many advanced reactors under development would otherwise be foreign-enriched uranium. "Without a readily available domestic supply of higher enriched LEU in the USA, it will be extremely difficult to conduct research on advanced reactors, potentially driving American innovators overseas."

US support for SMRs

In January 2012 the DOE called for applications from industry to support the development of one or two US light-water reactor designs, allocating $452 million over five years through the SMR Licensing Technical Support (LTS) programme. Four applications were made, from Westinghouse, Babcock & Wilcox, Holtec, and NuScale Power, the units ranging from 225 down to 45 MWe. The DOE announced its decision in November 2012 to support the B&W 180 MWe mPower design, to be developed with Bechtel and TVA. Through the five-year cost-share agreement, the DOE would invest up to half of the total project cost, with the project's industry partners at least matching this. The total would be negotiated between DOE and B&W, and DOE had paid $111 million by the end of 2014 before announcing that funds were cut off due to B&W shelving the project. However B&W is not required to repay any of the DOE money, and the project, capped at $15 million per year, is now under BWX Technologies. The company had spent more than $375 million on the mPower programme to February 2016.

In March 2012 the DOE signed agreements with three companies interested in constructing demonstration small reactors at its Savannah River site in South Carolina. The three companies and reactors are: Hyperion (now Gen4 Energy) with a 25 MWe fast reactor, Holtec with a 160 MWe PWR, and NuScale with its 45 MWe PWR (since increased to 60 MWe). The agreements concerned the provision of land but not finance. The DOE was in discussion with four further small reactor developers regarding similar arrangements, aiming to have in 10-15 years a suite of small reactors providing power for the DOE complex. (Over 1953-1991, Savannah River was where a number of production reactors for weapons plutonium and tritium were built and run.)

In March 2013 the DOE called for applications for second-round funding, and proposals were made by Westinghouse, Holtec, NuScale, General Atomics, and Hybrid Power Technologies, the last two being for EM2 and Hybrid SMR, not PWRs. Other (non-PWR) small reactor designs will have modest support through the Reactor Concepts RD&D programme. A late application "from left field" was from National Project Management Corporation (NPMC) which includes a cluster of regional partners in the state of New York, South Africa's PBMR company, and National Grid, the UK-based grid operator with 3.3 million customers in New York, Massachusetts and Rhode Island.*

* The project is for an HTR of 165 MWe, apparently the earlier direct-cycle version of the shelved PBMR, emphasising its 'deep burn' attributes in destroying actinides and achieving high burn-up at high temperatures. The PBMR design was a contender with Westinghouse backing for the US Next-Generation Nuclear Power (NGNP) project, which has stalled since about 2010.

In December 2013 the DOE announced that a further grant would be made to NuScale on a 50-50 cost-share basis, for up to $217 million over five years, to support design development and NRC certification and licensing of its initially 45 MWe small reactor design, subsequently increased to 60 MWe. In mid-2013 NuScale launched

the Western Initiative for Nuclear (WIN) – a broad, multi-western state collaboration – to study the demonstration and deployment of multi-module NuScale SMR plants in the western USA. WIN includes Energy Northwest (ENW) in Washington and Utah Associated Municipal Power Systems (UAMPS). It is now called the Carbon-Free Power Project. A demonstration NuScale SMR built as part of Project WIN is projected to be operational by 2024, at the DOE's Idaho National Laboratory (INL), with UAMPS as the owner and ENW the operator. This would be followed by a full-scale 12-module plant (720 MWe) there owned by UAMPS, run by Energy Northwest, and costing $5000/kW on an overnight basis, hence about $3.0 billion. To the end of 2016 NuScale had received $167 million from the DOE under the SMR Licensing Technical Support programme, with another $50 million expected in 2017, and the DOE said it was committed to provide $16.6 million cost-share on the NuScale-UAMPS agreement for site characterization and preparation of the COL application.

In January 2014 Westinghouse announced that was suspending work on its small modular reactors in the light of inadequate prospects for multiple deployment. The company said that it could not justify the economics of its SMR without government subsidies, unless it could supply 30 to 50 of them. It was therefore delaying its plans, though small reactors remain on its agenda. In 2016 however, the company was much more positive about SMRs. See also UK Support subsection below. However, in March 2017 BWXT suspended work on the mPower design, after Bechtel withdrew from the project.

The Small Modular Reactor Research and Education Consortium (SmrREC) has been set up by Missouri University of Science and Technology to investigate the economics of deploying multiple SMRs in the country. SmrREC has constructed a comprehensive model of the business, manufacturing and supply chain needs for a new SMR-centric nuclear industry.

A mid-2015 article sets out US SMR developments.

Early in 2016 developers and potential customers for SMRs set up the SMR Start consortium to advance the commercialization of SMR reactor designs. Members of the consortium include Bechtel, BWX Technologies, Dominion, Duke Energy, Energy Northwest, Fluor, GE Hitachi Nuclear Energy, Holtec, NuScale, Ontario Power, PSEG Nuclear, Southern Nuclear, Tennessee Valley Authority (TVA) and UAMPS. The organization will represent the companies in interactions with the US Nuclear Regulatory Commission (NRC), Congress and the executive branch on small reactor issues. US industry body the Nuclear Energy Institute (NEI) is assisting in the formation of the consortium, and is to work closely with the organization on policies and priorities relating to small reactor technology.

SMR Start has called for the DOE's LTS programme for SMRs to be extended to 2025 with an increase in funding. It pointed out: "Private companies and DOE have invested over $1 billion in the development of SMRs. However, more investment, through public-private partnerships is needed in order to assure that SMRs are a viable option in the mid-2020s. In addition to accomplishing the public benefit from SMR deployment, the federal government would receive a return on investment through taxes associated with investment, job creation and economic output over the lifetime of the SMR facilities that would otherwise not exist without the US government's investment."

In February 2016 TVA said it was still developing a site at Oak Ridge for a SMR and would apply for an early site permit (ESP, with no technology identified) for Clinch River in May with a view to building up to 800 MWe of capacity there. TVA has expanded discussions from B&W to include three other light-water SMR vendors. The DOE is supporting this ESP application financially from its SMR Licensing Technical Support Program, and in February 2016 DOE said it was committed to provide $36.3 million on cost-share basis to TVA.

Another area of small reactor development is being promoted by the DOE's Advanced Research Projects Agency – Energy (ARPA-E) set up under a 2007 act. This focuses on high-potential, high-impact energy technologies that are too early for private-sector investment. ARPA-E is now beginning a new fission programme to examine micro-reactor technologies, below 10 MWe. This will solicit R&D project proposals for such reactors, which must have very high safety and security margins (including autonomous operations), be proliferation resistant, affordable, mobile, and modular. Targeted applications include remote sites, backup power, maritime shipping, military instillations, and space missions.

The DOE in 2015 established the Gateway for Accelerated Innovation in Nuclear (GAIN) initiative led by Idaho National Laboratory (INL) "to provide the new nuclear energy community with access to the technical, regulatory and financial support necessary to move new nuclear reactor designs toward commercialization. GAIN is based on feedback from the nuclear community and provides a single point of access to the broad

range of capabilities – people, facilities, infrastructure, materials and data – across the Energy Department and its national laboratories." In January 2016 the DOE made grants of up to $40 million to X-energy for its Xe-100 pebble-bed HTR and to Southern for its molten chloride fast reactor (MCFR), being developed with TerraPower and Oak Ridge National Laboratory (ORNL).

In mid-2016 the DOE made GAIN grants of nuclear energy vouchers totalling $2 million including to Terrestrial Energy with Argonne National Laboratory, Transatomic Power with ORNL, and Oklo Inc with Argonne and INL for their respective reactor designs. A second round of GAIN voucher grants totalling $4.2 million was made in mid-2017, including to Terrestrial and Transatomic Power both with Argonne, Holtec's SMR Inventec for the SMR-160 at ORNL, Oklo Inc with Sandia and Argonne, and Elysium with INL and Argonne.

In April 2018, the DOE selected 13 projects to receive $60 million of cost-shared R&D funding for advance nuclear technologies, including the first awards under the US Industry Opportunities for Advance Nuclear Technology Development initiative.

In September 2018 the Nuclear Energy Innovation Capabilities Act and the Department of Energy Research and Innovation Act passed Congress. The first enables private and public institutions to carry out civilian research and development of advanced nuclear energy technologies. Specifically, the Act established the National Reactor Innovation Center to facilitate the siting of privately=funded advanced reactor prototypes at DOE sites through partnerships between the DOE and private industry. The second Act combines seven previously passed science bills to provide policy direction to the DOE on nuclear energy research and development.

In October 2018 the US DOE announced that it was proposing to convert metallic high-assay low-enriched uranium (HALEU), with enrichment levels between 5% and 20% U-235, into fuel for research and development purposes. This would be at Idaho National Laboratory's Materials and Fuels Complex and/or the Idaho Nuclear Technology and Engineering Center, to support the development of new reactor technologies with higher efficiencies and longer core lifetimes.

The US Nuclear Regulatory Commission (NRC) has released a draft white paper on its strategy for reviewing licensing applications for advanced non-light water reactor technologies. The NRC said it expects to finalise the draft paper by November, with submission of the first non-LWR application expected by December 2019. By mid-2019 the NRC had been formally notified by six reactor designers of their intention to seek design approval. These included three MSRs, one HTR, one FNR, and the Westinghouse eVinci heatpipe reactor.

UK support for SMRs

The UK government in 2014 published a report on SMR concepts, feasibility and potential in the UK. It was produced by a consortium led by the National Nuclear Laboratory (NNL). Following this, a second phase of work is intended to provide the technical, financial and economic evidence base required to support a policy decision on SMRs. If a future decision was to proceed with UK development and deployment of SMRs, then further work on the policy and commercial approach to delivering them would need to be undertaken, which could lead to a technology selection process for UK generic design assessment (GDA).

In March 2016 the UK Department of Energy & Climate Change (DECC) called for expressions of interest in a competition to identify the best value SMR for the UK. This relates to a government announcement in November 2015 that it would invest at least £250 million over five years in nuclear R&D including SMRs. DECC said the objective of the initial phase was "to gauge market interest among technology developers, utilities, potential investors and funders in developing, commercializing and financing SMRs in the UK." It said the initial stage would be a "structured dialogue" between the government and participants, using a published set of criteria, including that the SMR design must "be designed for manufacture and assembly, and ... able to achieve in-factory production of modular components or systems amounting to a minimum of 40% of the total plant cost."

In December 2017, the Department for Business, Energy & Industrial Strategy (BEIS), DECC's successor department, announced that the SMR competition had been closed. Instead, a new two-phase advanced modular reactor competition was launched, designed to incorporate a wider range of reactor types. Total funding for the Advanced Modular Reactor (AMR) Feasibility and Development (F&D) project is up to £44 million, and 20 bids had been received by the initial deadline of 7 February 2018. In September 2018 it was announced that the following eight organisations were awarded contracts up to £300,000 to produce feasibility studies for the first phase of the AMR F&D project: Advanced Reactor Concepts (ARC-100); DBD

(representing China's Institute of Nuclear and New Energy Technology's HTR-PM); LeadCold (SEALER-UK); Moltex Energy (Stable Salt Reactor); Tokamak Energy (compact spherical modular fusion reactor); U-Battery Developments (U-Battery); Ultra Safe Nuclear (Micro-Modular Reactor); and Westinghouse (Westinghouse LFR).

In March 2019 BEIS released a 2016 report on microreactors that defined them as having a capacity up to 100 MWt/30 MWe, and projecting a global market for around 570 units of an average 5 MWe by 2030, total 2850 MWe. It notes that they are generally not water-moderated or water cooled, but "use a compact reactor and heat exchange arrangement, frequently integrated in a single reactor vessel." Most are HTRs.

In 2015 Westinghouse had presented a proposal for a "shared design and development model" under which the company would contribute its SMR conceptual design and then partner with UK government and industry to complete, license and deploy it. The partnership would be structured as a UK-based enterprise jointly owned by Westinghouse, the UK government and UK industry. In October 2016 the company said it would work with UK shipbuilder Cammell Laird as well as the UK's Nuclear Advanced Manufacturing Research Centre (NAMRC) on a study to explore potential design efficiencies to reduce the lead times of its SMR.

NuScale has said that it aims to deploy its SMR technology in the UK with UK partners, so that the first of its 60 MWe units could be in operation by the mid-2020s. In September 2017 the company released its five-point UK SMR action plan. Rolls-Royce is reported to have submitted a detailed design to the government for a 220 MWe SMR unit (no details yet public).

Canadian support for SMRs

A June 2016 report for the Ontario Ministry of Energy focused on nine designs under 25 MWe for off-grid remote sites. All had a medium level of technology readiness and were expected to be competitive against diesel. Two designs were integral PWRs of 6.4 and 9 MWe, three were HTRs of 5, 8 and 16 MWe, two were sodium-cooled fast reactors (SFRs) of 1.5/2.8 and 10 MWe, one was a lead-cooled fast reactor (LFR) of 3-10 MWe, and one was an MSR of 32.5 MWe. Four were under 5 MWe (an SFR, LFR, and two HTRs). Ontario distinguishes 'grid scale' SMRs above 25 MWe from these (very) small-scale reactors.

The Canadian Nuclear Safety Commission (CNSC) has been conducting pre-licensing vendor design reviews – an optional service to assess a nuclear power plant design based on a vendor's reactor technology – for eight small reactors with capacities in the range of 3-300 MWe. Three further agreements for design review are being negotiated, including GE Hitachi's BWRX-300, StarCore's HTR and Westinghouse's eVinci. In November 2017 CNSC completed phase 1 for Terrestrial Energy's IMSR-400. In February 2019 it completed phase 1 for the Ultra-Safe Nuclear Corporation 5 MWe HTR, called a 'micro modular reactor' (MMR), and in March Global First Power submitted a site preparation licence application for an MMR at Chalk River. In October 2019 it completed phase 1 pre-licensing vendor design review for ARC Nuclear Canada's ARC-100 design.

In June 2017 Canadian Nuclear Laboratories (CNL) invited expressions of interest in SMRs. This resulted in many responses, including 19 for siting a demonstration or prototype reactor at a CNL-managed site. CNL aims to have a new SMR at its Chalk River site by 2026. Global First Power with its partners Ontario Power Generation and Ultra-Safe Nuclear Corporation was the first to get to the third stage of CNL's siting evaluation, with its MMR, a 5 MWe HTR. In February 2019 CNL announced that StarCore Nuclear and Terrestrial Energy had qualified to enter the due diligence (second) stage of its siting evaluation for their 14 MWe HTR and 195 MWe IMSR respectively.

In November 2018 the Canadian government released its SMR Roadmap, a 10-month nationwide study of SMR technology. The report concludes that Generation IV SMR development is a response to market forces for "smaller, simpler and cheaper" nuclear energy, and the large global market for this technology will be "driven not just by climate change and clean energy policies, but also by the imperatives of energy security and access."

Chinese support for SMRs

The most advanced small modular reactor project is in China, where Chinergy is starting to build the 210 MWe HTR-PM, which consists of twin 250 MWt high-temperature gas-cooled reactors (HTRs) which build on the experience of several innovative reactors in the 1960s to 1980s.

However, China is also developing small district heating reactors of 100 to 200 MWt capacity which may have a strong potential evaluated at around 400 units. The heat market is very large in northern China, now almost exclusively served by coal, causing serious pollution, particularly by dust, particulates, sulfur, and nitrogen oxides.

Overall SMR research and development in China is very active, with vigorous competition among companies encouraging innovation.

Other countries

Urenco has called for European development of very small – 4 MWe – 'plug and play' inherently-safe reactors based on graphite-moderated HTR concepts. It is seeking government support for a prototype "U-Battery" which would run for 5-10 years before requiring refuelling or servicing.

Already operating in a remote corner of Siberia are four small units at the Bilibino co-generation plant. These four 62 MWt (thermal) units are an unusual graphite-moderated boiling water design with water/steam channels through the moderator. They produce steam for district heating and 11 MWe (net) electricity each, remote from any grid. They are the world's smallest commercial power reactors and have performed well since 1976, much more cheaply than fossil fuel alternatives in the severe climate of this Arctic region, but are due to be retired by 2023.

Looking ahead, and apart from its barge-mounted ones, Rosatom is not positive about small reactors generally.

Also in the small reactor category are the Indian 220 MWe pressurised heavy water reactors (PHWRs) based on Canadian technology, and the Chinese 300-325 MWe PWR such as built at Qinshan Phase I and at Chashma in Pakistan, and now called CNP-300. The Nuclear Power Corporation of India (NPCIL) is now focusing on 540 MWe and 700 MWe versions of its PHWR, and is offering both 220 and 540 MWe versions internationally. These small established designs are relevant to situations requiring small to medium units, though they are not state of the art technology.

Another significant line of development is in very small fast reactors of under 50 MWe. Some are conceived for areas away from transmission grids and with small loads; others are designed to operate in clusters in competition with large units.

Other, mostly larger new designs are described in the information page on Advanced Nuclear Power Reactors.

Small reactors operating

Name	Capacity	Type	Developer
CNP-300	300 MWe	PWR	SNERDI/CNNC, Pakistan & China
PHWR-220	220 MWe	PHWR	NPCIL, India
EGP-6	11 MWe	LWGR	at Bilibino, Siberia (cogen, soon to retire)

Small reactor designs under construction

Name	Capacity	Type	Developer
KLT-40S	35 MWe	PWR	OKBM, Russia
RITM-200	50 MWe	integral PWR	OKBM, Russia
CAREM-25	27 MWe	integral PWR	CNEA & INVAP, Argentina
HTR-PM	210 MWe	twin HTR	INET, CNEC & Huaneng, China
ACPR50S	60 MWe	PWR	CGN, China

Small reactors for near-term deployment – development well advanced

Name	Capacity	Type	Developer
VBER-300	300 MWe	PWR	OKBM, Russia

Name	Capacity	Type	Developer
NuScale	60 MWe	integral PWR	NuScale Power + Fluor, USA
SMR-160	160 MWe	PWR	Holtec, USA + SNC-Lavalin, Canada
ACP100/Linglong One	125 MWe	integral PWR	NPIC/CNPE/CNNC, China
SMART	100 MWe	integral PWR	KAERI, South Korea
BWRX-300	300 MWe	BWR	GE Hitachi, USA
PRISM	311 MWe	sodium FNR	GE Hitachi, USA
ARC-100	100 MWe	sodium FNR	ARC with GE Hitachi, USA
Integral MSR	192 MWe	MSR	Terrestrial Energy, Canada
BREST	300 MWe	lead FNR	RDIPE, Russia

Small reactor designs at earlier stages (or shelved)

Name	Capacity	Type	Developer
EM2	240 MWe	HTR, FNR	General Atomics (USA)
VK-300	300 MWe	BWR	NIKIET, Russia
AHWR-300 LEU	300 MWe	PHWR	BARC, India
CAP200 LandStar-V	220 MWe	PWR	SNERDI/SPIC, China
SNP350	350 MWe	PWR	SNERDI, China
ACPR100	140 MWe	integral PWR	CGN, China
IMR	350 MWe	integral PWR	Mitsubishi Heavy Ind, Japan
Westinghouse SMR	225 MWe	integral PWR	Westinghouse, USA*
mPower	195 MWe	integral PWR	BWXT, USA*
Rolls-Royce SMR	220+ MWe	PWR	Rolls-Royce, UK
PBMR	165 MWe	HTR	PBMR, South Africa*
HTMR-100	35 MWe	HTR	HTMR Ltd, South Africa
Xe-100	75 MWe	HTR	X-energy, USA
MCFR	large?	MSR/FNR	Southern Co, USA
SVBR-100	100 MWe	Lead-Bi FNR	AKME-Engineering, Russia
Westinghouse LFR	300 MWe	Lead FNR	Westinghouse, UK
TMSR-SF	100 MWt	MSR	SINAP, China
PB-FHR	100 MWe	MSR	UC Berkeley, USA
Integral MSR	192 MWe	MSR	Terrestrial Energy, Canada
Moltex SSR-U	150 MWe	MSR/FNR	Moltex, UK
Moltex SSR-W global	150 MWe	MSR	Moltex, UK
Thorcon MSR	250 MWe	MSR	Martingale, USA
Leadir-PS100	36 MWe	lead-cooled	Northern Nuclear, Canada

Very small reactor designs being developed (up to 25 MWe)

Name	Capacity	Type	Developer
U-battery	4 MWe	HTR	Urenco-led consortium, UK
Starcore	10-20 MWe	HTR	Starcore, Quebec
USNC MMR-5&10	5 MWe	HTR	UltraSafe Nuclear, USA
Gen4 module	25 MWe	Lead-bismuth FNR	Gen4 (Hyperion), USA
Sealer	3-10 MWe	Lead FNR	LeadCold, Sweden

Name	Capacity	Type	Developer
eVinci	A few MWe	Heatpipe	Westinghouse, USA

See also IAEA webpage on Small and Medium Sized Reactors (SMRs) Development, Assessment and Deployment and also UxC listing of SMRs.

** Well-advanced designs understood to be on hold or abandoned.*

Military developments of small power reactors from 1950s

US experience

About five decades ago the US Army built eight reactors, five of them portable or mobile. PM1 successfully powered a remote air/missile defence radar station on a mountain top near Sundance, Wyoming for six years to 1968, providing 1 MWe. At Camp Century in northern Greenland the 10 MWt, 1.56 MWe plus 1.05 GJ/hr PM-2A was assembled from prefabricated components, and ran from 1960-64 on high-enriched uranium fuel. Another was the 9 MWt, 1.5 MWe (net) PM-3A reactor which operated at McMurdo Sound in Antarctica from 1962-72, generating a total of 78 million kWh and providing heat. It used high-enriched uranium fuel and was refuelled once, in 1970. MH-1A was the first floating nuclear power plant operating in the Panama Canal Zone from 1968-77 on a converted Liberty ship. It had a 45 MWt/10 MWe (net) single-loop PWR which used low-enriched uranium (4-7%). It used 541 kg of U-235 over ten years and provided power for nine years at 54% capacity factor. ML-1 was a smaller and more innovative 0.3 MWe mobile power plant using pressurised nitrogen to drive a closed cycle gas turbine, tested over 1962-66. It fitted into a standard shipping container and was truck-mobile.

All these were outcomes of the Army Nuclear Power Program (ANPP) for small reactor development – 0.1 to 40 MWe – which ran from 1954-77. ANPP became the Army Reactor Office (ARO) in 1992. More recently (2010) the DEER (Deployable Electric Energy Reactor) was being commercialised by Radix Power & Energy for forward military bases or remote mining sites. See later subsection.

A 2018 report from the US Army analysed the potential benefits and challenges of mobile nuclear power plants (MNPPs) with very small modular reactor (vSMR) technology. This followed a 2016 report on Energy Systems for Forward/Remote Operating Bases. The purpose is to reduce supply vulnerabilities and operating costs while providing a sustainable option for reducing petroleum demand and consequent vulnerability. MNPPs would be portable by truck or large aircraft and returned to the USA for refuelling after 10-20 years. They would load-follow and run on low-enriched uranium (<20%), probably as TRISO (tristructural-isotropic) fuel in high-temperature gas-cooled reactors (HTRs).

In January 2019 the Department of Defense (DOD) solicited proposals for a "small mobile reactor" design which could address electrical power needs in rapid response scenarios. These would make domestic infrastructure resilient to an electrical grid attack and change the logistics of forward operating bases, both by making more energy available and by simplifying fuel logistics needed to support existing, mostly diesel-powered, generators. They would also enable a more rapid response during humanitarian assistance and disaster relief operations. "Small mobile nuclear reactors have the potential to be an across-the-board strategic game changer for the DOD by saving lives, saving money, and giving soldiers in the field a prime power source with increased flexibility and functionality."

Each reactor should be an HTR with high-assay low-enriched uranium (HALEU) TRISO fuel and produce a threshold power of 1-10 MWe for at least three years without refuelling. It must weigh less than 40 tonnes and be sized for transportability by truck, ship, and C-17 aircraft. Designs must be "inherently safe", ensuring that a meltdown is "physically impossible" in various complete failure scenarios such as loss of power or cooling, and must use ambient air as their ultimate heat sink, as well as being capable of passive cooling. The reactor must be capable of being installed to the point of "adding heat" within 72 hours and of completing a planned shutdown, cool down, disconnect and removal of transport in under seven days.

Russian experience

The Joint Institute for Power Engineering and Nuclear Research (Sosny) in Belarus built two Pamir-630D truck-mounted small air-cooled nuclear reactors in 1976, during the Soviet era. The entire plant required several trucks. This was a 0.6 MWe HTR reactor using 45% enriched fuel and driving a gas turbine with nitrogen tetraoxide through the Brayton cycle. After some operational experience the Pamir project was scrapped in 1986. It had been preceded by the 2 MWe TES-3, a PWR mounted on an extended heavy tank chassis. The prototype started up in 1961, operated to 1965, and was abandoned in 1969.

Since 2010 Sosny has been involved with Luch Scientific Production Association (SRI SIA Luch) and Russia's N.A. Dollezhal Research and Development Institute of Power Engineering (NIKIET or RDIPE) to design a small transportable nuclear reactor. The new design will be an HTR concept similar to Pamir but about 2.5 MWe.

A small Russian HTR which was being developed by NIKIET is the Modular Transportable Small Power Nuclear Reactor (MTSPNR) for heat and electricity supply of remote regions. It is described as a single circuit air-cooled HTR with closed cycle gas turbine. It uses 20% enriched fuel and is designed to run for 25 years without refuelling. A twin unit plant delivers 2 MWe and/or 8 GJ/h. It is also known as GREM. No recent information is available, but an antecedent is the Pamir, from Belarus. More recently NIKIET has described the ATGOR – a transportable HTR with up to six parallel commercial gas-turbine engines with two independent heat sources (a nuclear reactor and a start-up diesel fuelled combustor).

Another NIKIET project is the 6 MWt, 1 MWe Vityaz modular integral light water reactor with two turbine generators, which is transportable as four modules of up to 60 tonnes.

In 2015 it was reported that the Russian defence ministry had commissioned the development of small mobile nuclear power plants for military installations in the Arctic. A pilot project being undertaken by Innovation Projects Engineering Company (IPEC) is a mobile low-power nuclear unit to be mounted on a large truck, tracked vehicle or a sledged platform. Production models will need to be capable of being transported by military cargo jets and heavy cargo helicopters, such as the Mil Mi-26. They need to be fully autonomous and designed for years-long operation without refuelling, with a small number of personnel, and remote control centre. It is assumed but not confirmed that these reactors will be the MTSPNR.

Light water reactors

These are moderated and cooled by ordinary water and have the lowest technologicalrisk, being similar to most operating power and naval reactors today. They mostly use fuel enriched to less than 5% U-235 with no more than a six-year refuelling interval, and regulatory hurdles are likely least of any small reactors.

US experience of small light water reactors (LWRs) has been of small military power plants, mostly PWRs – see above.

Some successful small reactors from the main national programme commenced in the 1950s. One was the Big Rock Point BWR of 67 MWe which operated for 35 years to 1997.

The US Nuclear Regulatory Commission is starting to focus on small light-water reactors using conventional fuel, such as B&W, Westinghouse, NuScale, and Holtec designs including integral types (B&W, Westinghouse, NuScale). Beyond these in time and scope, "the NRC intends to take full advantage of the experience and expertise" of other nations which have moved forward with non light-water designs, and it envisages "having a key role in future international regulatory initiatives."

Of the following designs, the KLT, VBER and Holtec SMR have conventional pressure vessels plus external steam generators (PV/loop design). The others mostly have the steam supply system inside the reactor pressure vessel ('integral' PWR design). All have enhanced safety features relative to current LWRs. All require conventional cooling of the steam condenser.

In the USA major engineering and construction companies have taken active shares in two projects: Fluor in NuScale, and Bechtel in B&W mPower.

Three new concepts are alternatives to conventional land-based nuclear power plants. Russia's floating nuclear power plant (FNPP) with a pair of PWRs derived from icebreakers is well on the way to commissioning, with the KLT-40S reactors described below and in the Nuclear Power in Russia paper. The next generation is expected to use RITM-200M reactors. China has a similar project for its ACP100 SMR as a FNPP, whilst MIT is

developing a floating plant moored offshore with a reactor of about 200 MWe in the bottom part of a cylindrical platform. France's submerged Flexblue power plant, using a 50-250 MWe reactor, was an early concept but is now cancelled.

KLT-40S

Russia's KLT-40S from OKBM Afrikantov is derived from the KLT-40 reactor well proven in icebreakers and now – with low-enriched fuel – proposed for wider use in desalination and, on barges, for remote area power supply. Here a 150 MWt unit produces 35 MWe (gross) as well as up to 35 MW of heat for desalination or district heating (or 38.5 MWe gross if power only). Burn-up is 45 GWd/t. Units are designed to run 3-4 years between refuelling with on-board refuelling capability and used fuel storage. All fuel assemblies are replaced in each such refuelling. At the end of a 12-year operating cycle the whole plant is taken to a central facility for overhaul and storage of used fuel. Operating plant lifetime is 40 years. Two units will be mounted on a 20,000 tonne barge to allow for outages (70% capacity factor). It may also be used in Kaliningrad.

Although the reactor core is normally cooled by forced circulation (four-loop), the design relies on convection for emergency cooling. Fuel is uranium aluminium silicide with enrichment levels of up to 20%, giving up to four-year refuelling intervals. A variant of this is the KLT-20, specifically designed for floating nuclear plants. It is a two-loop version with the same enrichment but with a ten-year refuelling interval.

The first floating nuclear power plant, the *Akademik Lomonosov*, commenced construction in 2007. Due to insolvency of the shipyard the plant is now expected to be operational in 2019. (See also *Floating nuclear power plants* section in the information page on Nuclear Power in Russia.)

RITM-200M

OKBM Afrikantov has developed a compact reactor – RITM-200M – to replace the KLT reactors and to serve in floating nuclear power plants or Optimised Floating Power Unit (OFPU) as they are now called by OKBM. This is an integral 175 MWt/50 MWe PWR with four coolant loops and external main circulation pumps. It has inherent safety features, using low-enriched (<20%) fuel in 199 fuel assemblies. OFPUs will be returned to base for servicing every 10-12 years and no onboard used fuel storage is required. Operational lifetime is 40 years, with possible extension to 60 years. Twin reactor plants in containment have a mass of 2600 tonnes and occupy 6.8 m × 14.6 m × 16.0 m high, requiring a much smaller barge than the KLT-40S units. It is derived from the RITM-200 power plants in the LK-60 icebreakers. A major challenge is the reliability of steam generators and associated equipment which are much less accessible when inside the reactor pressure vessel.

Onshore installation of the RITM-200M is envisaged, with two or more modules of 175 MWt/50 MWe, fuel enriched to almost 20% and 5-7 year fuel cycle.

CNP-300

This is based on the early Qinshan 1 reactor in China as a two-loop PWR, with four operating in Pakistan. It is 1000 MWt, 325 MWe with a design operating lifetime of 40 years. Fuel enrichment is 2.4-3.0%, with refuelling at 12-month intervals. It was designed by Shanghai Nuclear Energy Research & Design Institute (SNERDI).

SNP350

The SNP350 is SNERDI's development of the CNP-300, upgraded in many respects to meet latest performance, economy, and safety requirements. It is 1035 MWt, 350 MWe gross, with design operating lifetime of 60 years and digital I&C systems.

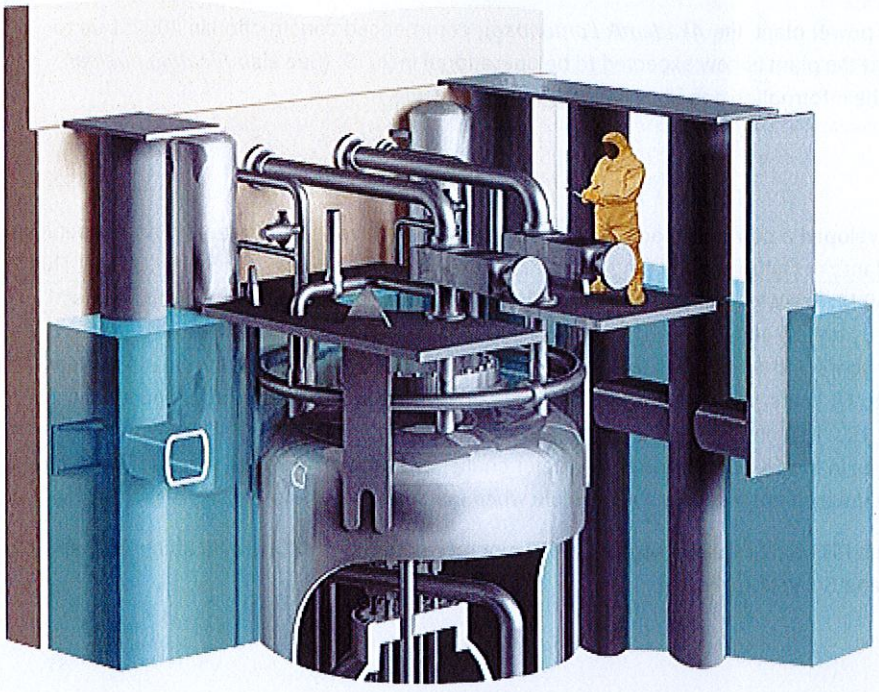
NuScale

A smaller unit is the NuScale Power Module, a 200 MWt, 60 MWe gross integral PWR with natural circulation. In December 2013 the US Department of Energy (DOE) announced that it would support accelerated development of the design for early deployment on a 50-50 cost share basis. An agreement for

$217 million over five years was signed in May 2014 by NuScale Power. In September 2017, following acceptance of the company's design certification application (DCA) by the US Nuclear Regulatory Commission (NRC) earlier in the year, NuScale applied for the second part of its loan guarantee with the US DOE.

It will be factory-built with a three-metre diameter pressure vessel and convection cooling, with the only moving parts being the control rod drives. It uses standard PWR fuel enriched to 4.95% in normal PWR fuel assemblies (but which are only 2 m long), with 24-month refuelling cycle. Installed in a water-filled pool below ground level, the 4.6 m diameter, 22 m high cylindrical containment vessel module weighs 650 tonnes and contains the reactor with steam generator above it. A standard power plant would have 12 modules together giving about 720 MWe. An overhead crane would hoist each module from its pool to a separate part of the plant for refuelling. Design operational lifetime is 60 years. It has full passive cooling in operation and after shutdown for an indefinite period, without even DC battery requirement. The NRC concluded in January 2018 that NuScale's design eliminated the need for class 1E backup power – a current requirement for all US nuclear plants. It claims good load-following capability, in line with EPRI requirements and also black start capability.

The UK's National Nuclear Laboratory (NNL) has confirmed that the reactor can run on MOX fuel. It also said that a 12-module NuScale plant with full MOX cores could consume 100 tonnes of reactor-grade plutonium in about 40 years, generating 200 TWh from it. This would be in line with Areva's proposal for using the UK plutonium stockpile, especially since Areva is already contracted to make fuel for the NuScale reactor.



NuScale Power Module (NuScale)

The company had estimated in 2010 that overnight capital cost for a 12-module, 540 MWe NuScale plant would be about $4000 per kilowatt, this in 2014 had risen to $5078/kWe net, with LCOE expected to be $100/MWh for first unit (or $90 for NOAK). In June 2018, the company announced that its reactor can generate 20% more power than originally planned. Subject to NRC approval, this would lower the overnight capital cost to about $4200 per kilowatt, and lower the LCOE by 18%.

The NuScale Power company was spun out of Oregon State University in 2007, though the original development was funded by the US Department of Energy. After NuScale experienced problems in funding its development, Fluor Corporation paid over $30 million for 55% of NuScale in October 2011. With the support of Fluor, NuScale expects to bring its technology to market in a timely manner. The DOE sees this as a "near-term LWR design." In August 2013 Rolls-Royce joined the venture to support an application for DOE funding, and in March 2014 Enercon Services took undisclosed equity to become a partner and assist with design certification and COL applications.

NuScale lodged an application for US design certification in January 2017, and in July 2017 the NRC confirmed that its highly integrated protection system (HIPS) architecture was approved. NuScale has been engaged with the NRC since 2008, having spent some $130 million on licensing to November 2013. It expects the NRC review to take 40 months, so the first unit could be under construction in 2020 and in operation about 2023. A COL application is planned for early 2018. The company also expects to apply for generic design assessment in the UK in a similar timeframe. At the end of April 2018, NuScale announced that the NRC had completed the first and most intensive phase of the review for its SMR design certification. In September 2018 NuScale selected BWX Technologies as the first manufacturer of its SMR after an 18-month selection process.

In March 2012 the US DOE signed an agreement with NuScale regarding constructing a demonstration unit at its Savannah River site in South Carolina.

In mid-2013 NuScale launched the Western Initiative for Nuclear (WIN) – a broad, multi-western state collaboration* – to study the demonstration and deployment of a multi-module NuScale Small Modular Reactor (SMR) plant in the western USA. WIN includes Energy Northwest (ENW) in Washington and Utah Associated Municipal Power Systems (UAMPS). A demonstration NuScale SMR built as part of Project WIN is projected to be operational by 2024, at the DOE's Idaho National Laboratory (INL), with UAMPS as the owner and ENW the operator. This would be followed by a full-scale 12-module plant (720 MWe) owned by UAMPS and run by Energy Northwest and costing $5000/kW on overnight basis, hence about $3.0 billion. Energy Northwest comprises 27 public utilities, and had examined small reactor possibilities before choosing NuScale and becoming part of the **UAMPS Carbon-Free Power Project**.

* Washington, Oregon, Idaho, Wyoming, Utah and Arizona.

NuScale is investigating cogeneration options including desalination (with Aquatech), oil recovery from tar sands and refinery power (with Fluor), hydrogen production by high-temperature steam electrolysis (with INL) and flexible back-up for a wind farm (with UAMPS and Energy Northwest).

Holtec SMR-160

Holtec International has a subsidiary – SMR-160 LLC – to commercialize a 160 MWe factory-built reactor concept called the Holtec Inherently Safe Modular Underground Reactor (HI-SMUR). This has two external horizontal steam generators, and uses fuel similar to that in larger PWRs, including MOX. The 32 full-length fuel assemblies are in a fuel cartridge, which is loaded and unloaded as a single unit from the 31-metre high pressure vessel. Holtec claims a one-week refuelling outage every 42 months. It has full passive cooling in operation and after shutdown for an indefinite period, and also a negative temperature coefficient so that it shuts down at high temperatures. The reactor will be offered with optional heat sink to atmosphere, using dry cooling. The whole reactor system will be installed below ground level, with used fuel storage. A 24-month construction period is envisaged for each $800 million unit ($5000/kW). Operational life claimed is 80 years.

Licensing of the SMR-160 in the USA will initially use an NRC process which involves a construction permit followed by an operating licence, and later continuing to design certification under other licensing rules. Holtec originally expected to submit an application for design certification to the NRC late in 2016, but then aimed for licence application by the end of 2018, either in the USA or Canada. The detailed design phase was from August 2012, and in August 2015 Mitsubishi Electric Power Products and its Japanese parent became a partner in the project, to undertake the digital I&C design* and help with licensing. This was formalised in September 2016 and the cooperation was boosted in mid-2017. In July 2017 a partner agreement with SNC-Lavalin based in Ontario was formalised, involving engineering support and licensing. The design is in phase 1 of pre-licensing vendor design review with the CNSC.

* all of Japan's PWRs and 14 Chinese PWRs use Mitsubishi Electric's I&C technology.

In March 2012 the US DOE signed an agreement with Holtec regarding constructing a demonstration SMR-160 unit at its Savannah River Site in South Carolina. In 2013 NuHub, a South Carolina economic development project, and the state itself supported Holtec's bid for DOE funding for the SMR-160, as did partners PSEG and SCE&G – which would operate the demonstration plant. Apart from the SCE&G demonstration plant, Holtec was negotiating to supply an SMR-160 to PSEG for its Hope Creek/Salem site in New Jersey, for which PSEG has sought an early site permit (ESP). After failing to get DOE funding, both PSEG and SCE&G reaffirmed their

support for the SMR-160. In January 2016 Holtec said that development continued with support from Mitsubishi and PSEG Power. In October 2016 Holtec said it was considering standardizing on a 160 MWe steam turbine from Turboatom in Ukraine. Electrical components will be from Mitsubishi Electric.

In February 2018, GE Hitachi Nuclear Energy, Global Nuclear Fuel, Holtec and SMR Inventec signed a memorandum of understanding, with the initial focus on fuel development and control rod drive mechanisms for the SMR-160.

In February 2019 Holtec announced new agreements with Exelon – to join the support team with Mitsubishi and SNC-Lavalin – and Ukraine's Energoatom. Energoatom plans to establish a consortium with Holtec and Ukraine's national nuclear consultant, State Scientific and Technical Centre for Nuclear and Radiation Safety (SSTC-NRS), to explore the environmental and technical feasibility of qualifying a 'generic' SMR-160 system that can be built and operated at any candidate site in the country.

mPower

In mid-2009, Babcock & Wilcox (B&W) announced its mPower reactor, a 500 MWt, 180 MWe integral PWR designed to be factory-made and railed to site[i]. It was a deliberately conservative design, to more readily gain acceptance and licensing. In November 2012 the US Department of Energy (DOE) announced that it would support accelerated development of the design for early deployment, with up to $226 million, and it paid $111 million of this.

The reactor pressure vessel containing core of 2x2 metres and steam generator is thus only 3.6 metres diameter and 22 m high, and the whole unit 4.5 m diameter and 23 m high. It would be installed below ground level, have an air-cooled condenser giving 31% thermal efficiency[ii], and passive safety systems. The power was originally 125 MWe, but by about 2014, 195 MWe was quoted when water-cooled. A 155 MWe air-cooled version was also planned. The integral steam generator is derived from marine designs, as is the control rod set-up. Convection would be assisted by eight small canned-motor coolant pumps. It has a "conventional core and standard fuel" (69 fuel assemblies, each standard 17x17, < 20 t)[i] enriched to almost 5%, with burnable poisons, to give a four-year operating cycle between refuelling, which will involve replacing the entire core as a single cartridge. Core power density is lower than in a large PWR, and burn-up is about 35 GWd/t. (B&W draws upon over 50 years of experience in manufacturing nuclear propulsion systems for the US Navy, involving compact reactors with long core life.) A 60-year service life is envisaged, as sufficient used fuel storage would be built onsite for this.

The mPower reactor is modular in the sense that each unit is a factory-made module and several units would be combined into a power station of any size, but most likely a 380 MWe twin-unit plant and using approx 200 MWe turbine generators (also shipped as complete modules), constructed in three years. BWXT Nuclear Energy's present manufacturing capability in North America could produce these units.

B&W Nuclear Energy Inc set up B&W Modular Nuclear Energy LLC (now BWXT mPower Inc) to market the design, in collaboration with Bechtel which joined the project as a 10% equity partner to design, license and deploy it. The company expects both design certification and construction permit in 2018, and commercial operation of the first two units in 2022. Overnight cost for a twin-unit plant was put by B&W at about $5000/kW.

In November 2013 B&W said it would seek to bring in further equity partners by mid-2014 to take forward the licensing and construction of an initial plant.* B&W said it had invested $360 million in Generation mPower with Bechtel, and wanted to sell up to 70% of its stake in the joint venture, leaving it with about 20% and Bechtel 10%. In April 2014 B&W announced that it was cutting back funding on the project to about $15 million per year, having failed to find customers or investors. DOE then terminated further funding. B&W planned to retain the rights to manufacture the reactor module and nuclear fuel for the mPower plant. In December 2014 B&W finished laying off staff working on the project, and early in 2016 reduced funding further.

With more than $375 million having been spent on the mPower program, in March 2016 BWXT and Bechtel reached agreement on "accelerated development" of the mPower project, so that Bechtel would take over leadership of the project and attempt for a year to secure funding for SMR development from third parties, including the DOE. If Bechtel succeeded in this, then BWXT and Bechtel would negotiate and execute a new agreement, with Bechtel taking over management of the mPower program from BWXT. If Bechtel decided to

terminate the project, it would be paid $30 million by BWXT, which is what happened in March 2017. The project was then shelved, leaving both BWXT and Bechtel free to be involved in the supply chain or management of other SMR projects.

* When B&W launched the mPower design in 2009, it said that Tennessee Valley Authority (TVA) would begin the process of evaluating Clinch River at Oak Ridge as a potential lead site for the mPower reactor, and that a memorandum of understanding had been signed by B&W, TVA and a consortium of regional municipal and cooperative utilities to explore the construction of a small fleet of mPower reactors. It was later reported that the other signatories of the agreement were FirstEnergy and Oglethorpe Power[3]. In February 2013 B&W signed an agreement with TVA to build up to four units at Clinch River, with design certification and construction permit application to be submitted to NRC in 2015. In August 2014 the TVA said it would file an early site permit (ESP) application instead of a construction permit application for one or more small modular reactors at Clinch River, possibly by the end of 2015. In February 2016 TVA said it was still developing a site at Oak Ridge for a SMR and would apply for an early site permit (ESP, with no technology identified) in May with a view to building up to 800 MWe of capacity there.

BWRX-300

GE Hitachi Nuclear Energy has a 300 MWe very small BWR design (originally VSBWR), envisaged as single units. GEH has announced this as the BWRX-300 "which further simplifies the NRC-licensed ESBWR" from which it is derived. The BWRX-300 incorporates a range of cost-saving features, including natural circulation systems, smaller, dry containment, and more passive operational control systems. The estimated capital cost is $2250/kWe for series production after initial units are built. The design aims to limit onsite operational staff numbers to 75 employees to achieve an estimated O&M cost of $16/MWh. In May 2018 the US utility Dominion Energy agreed to help fund the project.

In July 2018 GEH announced $1.9 million in funding from the US Department of Energy to lead a team including Bechtel, Exelon, Hitachi-GE Nuclear Energy and the Massachusetts Institute of Technology to examine ways to simplify the reactor design, reduce plant construction costs, and lower operation and maintenance costs for the BWRX-300. In particular the team aims to identify ways to reduce plant completion costs by 40-60% compared with other SMR designs in development and to be competitive with gas. "As the tenth evolution of the boiling water reactor, the BWRX-300 represents the simplest, yet most innovative BWR design since GE began developing nuclear reactors in 1955." In May 2019 the BWRX-300 was submitted to Canada's CNSC for a pre-licensing vendor design review. In October 2019 GEH signed an agreement with Estonia's Fermi Energia to examine the economic feasibility of constructing a BWRX-300 there.

IRIS

Westinghouse's IRIS (International Reactor Innovative & Secure) is a reactor design which was developed over more than two decades. A 1000 MWt, 335 MWe capacity was proposed, although it could be scaled down to 100 MWe. IRIS is a modular pressurised water reactor with integral primary coolant system and circulation by convection. Fuel is similar to present LWRs and (at least for the 335 MWe version) fuel assemblies would be identical to those in AP1000. Enrichment is 5% with burnable poison and fuelling interval of up to four years (or longer with higher enrichment and MOX fuel). US design certification was at the pre-application stage, but is now listed as 'inactive', and the concept has evolved into the Westinghouse SMR.

Westinghouse SMR

The Westinghouse small modular reactor is an 800 MWt/225 MWe class integral PWR with passive safety systems and reactor internals including fuel assemblies based closely on those in the AP1000 (89 assemblies 2.44m active length, <5% enrichment). The steam generator is above the core fed by eight horizontally-mounted axial-flow coolant pumps. The reactor vessel will be factory-made and shipped to site by rail, then installed below ground level in a containment vessel 9.8 m diameter and 27 m high. The reactor vessel module is 25 metres high and 3.5 metres diameter. It has a 24-month refueling cycle and 60-year service life. Passive safety means no operator intervention is required for seven days in the event of an accident. Daily load following can be performed from 100% to 20% power at a rate of 5% change per minute; in continuous load following, the plant can perform load changes of ±10% power at a rate of 2% per minute.

In May 2012 Westinghouse teamed up with General Dynamics Electric Boat to assist in the design and Burns & McDonnell to provide architectural and engineering support. A design certification application was expected by NRC in September 2013, but the company has stepped back from lodging one while it re-assesses the market for small reactors. The company has started fabricating prototype fuel assemblies.

The DOE earlier saw this as a "near-term LWR design". In March 2015 Westinghouse announced that the NRC had approved its safety evaluation report for the SMR design, which it said was a significant step towards design certification. However, while the company continues efforts to seek customer interest, it is not proceeding with the NRC yet.

In April 2012 Westinghouse set up a project with Ameren Missouri to seek DOE funds for developing the design, with a view to obtaining design certification and a combined construction and operation licence (COL) from the Nuclear Regulatory Commission (NRC) for up to five SMRs at Ameren's Callaway site, instead of an earlier proposed large EPR there. The initiative – NexStart SMR Alliance – had the support of other state utilities and the state governor, as well as Savannah River, Exelon and Dominion. However, this agreement expired about the end of 2013, and both companies stepped back from the project as DOE funds went to other SMR projects.

In May 2013 Westinghouse announced that it would work with China's State Nuclear Power Technology Corporation (SNPTC) to accelerate design development and licensing in the USA and China of its SMR. SNPTC would ensure that the Westinghouse SMR design met standards for licensing in China and would lead the licensing effort in that country. The status of this collaboration is uncertain.

In October 2015 Westinghouse presented a proposal for a "shared design and development model" under which the company would contribute its SMR conceptual design and then partner with UK government and industry to complete, license and deploy it. This would engage UK companies such as Sheffield Forgemasters in the reactor supply chain.

VVER-300 (V-478)

This is a 850 MWt, 300 MWe two-loop PWR design from Gidropress, based on the VVER-640 (V-407) design. It is little reported.

VBER-150, VBER-300

A larger Russian factory-built and barge-mounted unit (requiring a 12,000 tonne vessel) is the VBER-150, of 350 MWt, 110 MWe. It is modular and is derived by OKBM from naval designs, with two steam generators. Uranium oxide fuel enriched to 4.7% has burnable poison; it has low burn-up (31 GWd/t average, 41.6 GWd/t maximum) and eight-year refuelling interval.

OKBM Afrikantov's larger VBER-300 PWR is a 917 MWt, 325 MWe unit, the first of which is planned to be built in Kazakhstan. It was originally envisaged in pairs as a floating nuclear power plant, displacing 49,000 tonnes. As a cogeneration plant it is rated at 200 MWe and 1900 GJ/hr. The reactor is designed for 60-year life and 90% capacity factor. It has four external steam generators and a cassette core with 85 standard VVER fuel assemblies enriched to 4.95% and 50 GWd/tU burn-up with a 72-month fuel cycle. Versions with three and two steam generators are also envisaged, of 230 and 150 MWe respectively. Also, with more sophisticated and higher-enriched (18%) fuel in the core, the refuelling interval can be pushed from two years out to five years (6 to 15 years fuel cycle) with burn-up to 125 GWd/tU. A 2006 joint venture between Atomstroyexport and Kazatomprom set this up for development as a basic power source in Kazakhstan, then for export[8]. It is also envisaged for use in Russia, mainly as cogeneration unit. It is considered likely for near-term deployment.

The company also offers 200-600 MWe designs based on a standard 100 MWe module and explicitly based on naval units.

VK-300

Another larger Russian reactor with completed detailed design is NIKIET's VK-300 integral boiling water reactor of 750 MWt, 250 MWe, being developed specifically for cogeneration of both power and district heating or heat for desalination (150 MWe plus 1675 GJ/hr) by the N.A. Dollezhal Research and Development Institute of

Power Engineering (RDIPE or NIKIET) together with several major research and engineering institutes. It has evolved from the 50 MWe (net) VK-50 BWR at Dimitrovgrad[f], but uses standard components wherever possible, and has 313 fuel elements similar to the VVER. Cooling is passive, by convection, and all safety systems are passive. Fuel enrichment is 4% and burn-up is 41 GWd/tU with a 72-month refuelling interval. It is capable of producing 250 MWe if solely electrical. Design operating lifetime is 60 years.

In September 2007 it was announced that six would be built at Kola or Archangelsk and at Primorskaya in the far east, to start operating 2017-20,[4] but no more has been heard of this plan. A feasibility study was undertaken for Arkhangelsk nuclear cogeneration plant with four units. As a cogeneration plant it was intended for the Mining & Chemical Combine at Zheleznogorsk, but MCC is reported to prefer the VBER-300. The design was completed in 2013.

VKT-12

A smaller Russian BWR design is the 12 MWe transportable VKT-12, described as similar to the VK-50 prototype BWR at Dimitrovgrad, with one loop. It has a ceramic-metal core with uranium enriched to 2.4-4.8%, and 10-year refuelling interval. The reactor vessel is 2.4m inside diameter and 4.9 m high. This is reported to be shelved.

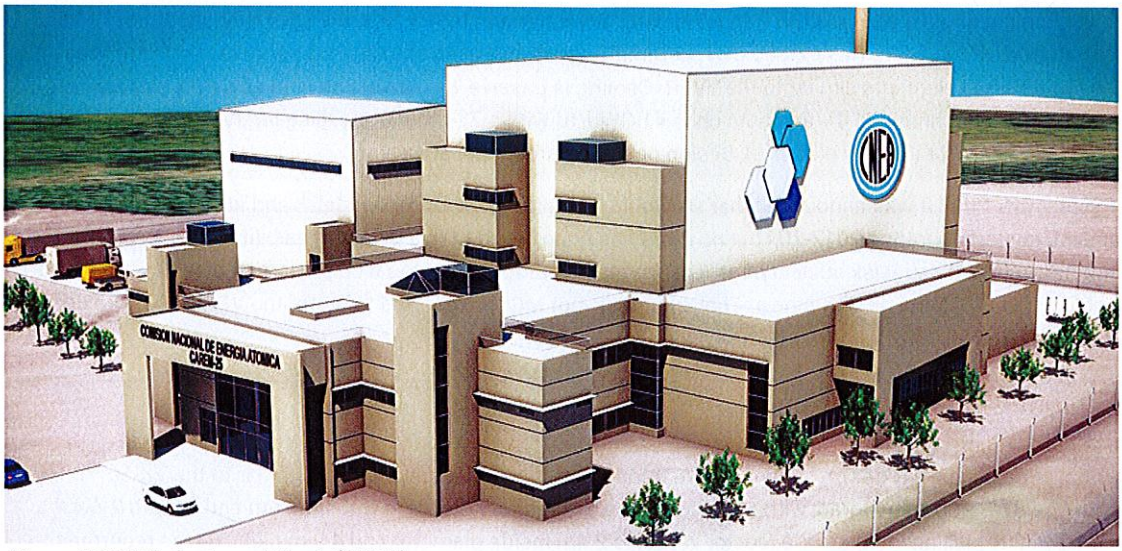
ABV, ABV-6M

A smaller Russian PWR unit under development by OKBM Afrikantov is the ABV multipurpose power source. It is readily transported to the site, with rapid assembly and operation for 10-12 years between refuelling, which is carried out offsite at special facilities. There is a range of sizes from 45 MWt (ABV-6M) down to 18 MWt (ABV-3), giving 4-18 MWe outputs. (The IAEA 2011 write-up of the ABV-6M quotes 14 MWt or 6 MWe in cogeneration mode.) The units are compact, with integral steam generator and natural circulation in the primary circuit. They will be factory-produced and designed as a universal power source for floating nuclear plants – the ABV-6M would require a 3500 tonne barge; the ABV-3, 1600 tonne for twin units. The Volnolom FNPP consists of a pair of reactors (12 MWe in total) mounted on a 97-metre, 8700 tonne barge plus a second barge for reverse osmosis desalination (over 40,000 m^3/day of potable water).

The smallest land-based version has reactor module 13 m long and 8.5 m diameter, with a mass of 600 t. The land-based ABV-6M module is 44 m long, 10 m diameter and with mass of 3000 t. The core is similar to that of the KLT-40 except that enrichment is 16.5% or 19.7% and average burn-up 95 GWd/t. It would initially be fuelled in the factory. The service lifetime is about 40 years.

CAREM

The CAREM-25 reactor prototype being built by the Argentine National Atomic Energy Commission (CNEA), with considerable input from INVAP[g], is an older design modular 100 MWt (27 MWe gross) integral pressurized water reactor, first announced in 1984. It has 12 steam generators within the pressure vessel and is designed to be used for electricity generation or as a research reactor or for water desalination (with 8 MWe in cogeneration configuration). CAREM has its entire primary coolant system within the reactor pressure vessel (11m high, 3.5m diameter), self-pressurized and relying entirely on convection (for modules less than 150 MWe). The final full-sized export version will be 100 MWe or more, with axial coolant pumps driven electrically. Fuel is standard 3.1 or 3.4% enriched PWR fuel in hexagonal fuel assemblies, with burnable poison, and is refuelled annually.



How a CAREM plant would look (CNEA)

The 25 MWe prototype unit is being built next to Atucha, on the Parana River in Lima, 110 km northwest of Buenos Aires, and the first larger version (probably 100 MWe) is planned in the northern Formosa province, 500 km north of Buenos Aries, once the design is proven. Some 70% of CAREM-25 components will be local manufacture. The pressure vessel is being manufactured by Industrias Metalurgicas Pescarmona SA (IMPSA).

The IAEA lists it as a research reactor under construction since April 2013, though first concrete was poured in February 2014, marking official start of construction. It is proceeding slowly but is due online in 2019.

In March 2015 Argentina's INVAP and state-owned Saudi technology innovation company Taqnia set up a joint venture company, Invania, to develop nuclear technology for Saudi Arabia's nuclear power program, apparently focused on CAREM for desalination.

SMART from KAERI

On a larger scale, South Korea's SMART (System-integrated Modular Advanced Reactor) is a 330 MWt pressurised water reactor with integral steam generators and advanced safety features. It is designed by the Korea Atomic Energy Research Institute (KAERI) for generating electricity (up to 100 MWe) and/or thermal applications such as seawater desalination. Design life is 60 years, fuel enrichment 4.8%, with a three-year refuelling cycle. It has 57 fuel assemblies very similar to normal PWR ones but shorter, and it operates with a 36-month fuel cycle. All the active safety features of the original design were substituted by early 2016 with passive versions. Residual heat removal is passive. It received standard design approval (SDA) from the Korean regulator in mid-2012. A single unit can produce 90 MWe plus 40,000 m^3/day of desalinated water.

In March 2015 KAERI signed an agreement with Saudi Arabia's King Abdullah City for Atomic and Renewable Energy (KA-CARE) to assess the potential for building SMART reactors in that country, and in September 2015 further contracts were signed to that end. The cost of building the first SMART unit in Saudi Arabia was estimated at $1 billion. Through to November 2018 pre-project engineering will be undertaken jointly including FOAK engineering design and preparations for building two units.

MRX

The Japan Atomic Energy Research Institute (JAERI) designed the MRX, a small (50-300 MWt) integral PWR reactor for marine propulsion or local energy supply (30 MWe). The entire plant would be factory-built. It has conventional 4.3% enriched PWR uranium oxide fuel with a 3.5-year refuelling interval and has a water-filled containment to enhance safety. Little has been heard of it since the start of the Millennium.

Nuward NP-300

TechnicAtome with Naval Group and CEA in France have developed the NP-300 PWR design from submarine power plants and aimed it at export markets for power, heat and desalination. It has passive safety systems and could be built for applications of 100 to 300 MWe or more with up to 500,000 m^3/day desalination. As of mid-2018, a 570 MWt / 170 MWe version was proposed as SMR to be in a metallic compact containment submerged in water, each module in a separate pool.

TechnicAtome makes the K15 naval reactor of 150 MWt, running on low-enriched fuel. A land-based equivalent – *Réacteur d'essais à terre* (RES) – was built at Cadarache from 2003 with several delays and achieved criticality in October 2018. It is essentially a PWR test reactor for the Navy.

It earlier seemed that some version of this reactor might be used in the Flexblue submerged nuclear power plant being proposed by DCNS in France, but now cancelled. The concept eliminates the need for civil engineering, and refuelling or major service can be undertaken by refloating it and returning to the shipyard.

NHR-200

The Chinese NHR-200 (Nuclear Heating Reactor), developed by Tsingua University's Institute of Nuclear Energy Technology (now the Institute of Nuclear and New Energy Technology), is a simple 200 MWt integral PWR design for district heating or desalination. It is based on the NHR-5 which was commissioned in 1989, and runs at lower temperature than the above designs[h]. Used fuel is stored around the core in the pressure vessel.

In 2008, the Chinese government was reported to have agreed to build a multi-effect distillation (MED) desalination plant using this on the Shandong peninsula, but no more has been heard of that project, and INET is focused on the HTR-PM being built in Shandong.

ACP100/Linglong One

The Nuclear Power Institute of China (NPIC), under China National Nuclear Corporation (CNNC), has designed a multi-purpose small modular reactor, the ACP100 or Linglong One. China Nuclear Power Engineering Co (CNPE) is also promoting it. It has passive safety features, notably decay heat removal, and will be installed underground. It has 57 fuel assemblies 2.15m tall and integral steam generators (287°C), so that the whole steam supply system is produced and shipped a single reactor module. Its 385 MWt produces about 125 MWe, and power plants comprising two to six of these are envisaged, with 60-year design operating lifetime and 24-month refuelling. Or each module can supply 1000 GJ/hr, giving 12,000 m^3/day desalination (with MED). Industrial and district heat uses are also envisaged, as well as floating nuclear power plant (FNPP) applications. Capacity of up to 150 MWe is envisaged. In April 2016 the IAEA presented CNNC with its report from the Generic Reactor Safety Review process.

In October 2015 the Nuclear Power Institute of China (NPIC) signed an agreement with UK-based Lloyd's Register to support the development of a floating nuclear power plant (FNPP) using the ACP100S reactor, a marine version of the ACP100. Following approval as part of the 13th Five-Year Plan for innovative energy technologies, CNNC signed an agreement in July 2016 with China Shipbuilding Industry Corporation (CSIC) to prepare for building its ACP100S demonstration floating nuclear plant, for 2019 operation.

CNNC New Energy Corporation, a joint venture of CNNC (51%) and China Guodian Corp, was planning to build two ACP100 units in Putian county, Zhangzhou city, at the south of Fujian province, near Xiamen, as a demonstration plant. This would be the CNY 5 billion ($788 million) phase 1 of a larger project. Preliminary design was completed in 2014, based on larger ACP/CNP units. Construction time is expected to be 36-40 months. Early in 2017 the site for the first ACP100 units was changed to Changjiang, on Hainan, with a larger reactor to be built at Putian. Preliminary work began in July 2019, with first concrete expected 2019/2020. It involves a joint venture of three companies for the pilot plant: CNNC as owner and operator; the Nuclear Power Institute of China (NPIC) as the reactor designer; and China Nuclear Engineering Group being responsible for plant construction.

The company signed a second ACP100 agreement with Hengfeng county, Shangrao city in Jiangxi province, and a third with Ningdu county, Ganzhou city in Jiangxi province in July 2013 for another ACP100 project costing CNY 16 billion. Further inland units are planned in Hunan and possibly Jilin provinces. Export potential is considered to be high, with full IP rights. In 2016 China Nuclear Engineering & Construction Corporation (CNEC) submitted an expression of interest to the UK government based on its ACP100+ design.

CAP200/LandStar-V, CAP150, CAP50

CAP200 or LandStar-V multiple application SMR is a PWR, with SNPTC provenance, being developed from the CAP1000 in parallel with the CAP1400 by SNERDI, using proven fuel and core design. It is 660 MWt/220 MWe and has two external steam generators (301°C). It is pitched to replace coal plants and supply process heat and district heating, with a design operating lifetime of 60 years. With 24-month refuelling, burn-up of 42 GWd/t is expected, the 89 fuel assemblies being the same as those of the CAP1400 but shorter. It has both active and passive cooling, and natural circulation is effective for up to 20% power. In an accident scenario, no operator intervention is required for seven days. It will be installed below grade in a 32 m deep caisson structure, with seismic design basis 600 Gal, even in soft ground. In 2017 the first-of-a-kind cost was estimated at $5000/kW and $160/MWh, dropping to $4000/kW in series.

The OceanStar-V version would be on a barge, as a floating nuclear power plant.

The CAP150 is an earlier version, 450 MWt/150 MWe, with eight integral steam generators. It is claimed to have "a more simplified system and more safety than current third generation reactors." Seismic design basis is 300 Gal. In mid-2013 SNPTC quoted approximately $5000/kW capital cost and 9 c/kWh, so significantly more than the CAP1400.

A related SNERDI project is the CAP50 reactor for floating nuclear power plants. This is to be 200 MWt and relatively low-temperature (250°C), so only about 40 MWe with two external steam generators and five-year refuelling.

ACPR100, ACPR50S

China General Nuclear Group (CGN) has two small ACPR designs: an ACPR100 and ACPR50S, both with passive cooling for decay heat and 60-year design life. Both have standard type fuel assemblies and fuel enriched to <5% with burnable poison giving 30-month refueling. The ACPR100 is an integral PWR, 450 MWt, 140 MWe, having 69 fuel assemblies. Reactor pressure vessel is 17m high and 4.4 m inside diameter, operating at 310°C. It is designed as a module in larger plant and would be installed underground. The applications for these are similar to those for the ACP100.

CGN's floating reactor concept

The offshore ACPR50S is 200 MWt, 60 MWe with 37 fuel assemblies and four external steam generators. Reactor pressure vessel is 7.4m high and 2.5 m inside diameter, operating at 310°C. It is designed for mounting on a barge as floating nuclear power plant (FNPP). Following approval as part of the 13th Five-Year Plan for innovative energy technologies, CGN announced construction start on the first FNPP at Bohai shipyard in November 2016 for trial operation in 2019, supplying power and desalination.

Flexblue

This was a conceptual design from DCNS (now Naval Group, state-owned), Areva, EdF and CEA from France. It is designed to be submerged, 60-100 metres deep on the sea bed up to 15 km offshore, and returned to a dry dock for servicing. The reactor, steam generators and turbine-generator would be housed in a submerged 12,000 tonne cylindrical hull about 100 metres long and 12-15 metres diameter. Each hull and power plant would be transportable using a purpose-built vessel. Reactor capacity ranged 50-250 MWe, derived from DCNS's latest naval designs, but with details not announced. The project is now cancelled. In 2011DCNS said it could start building a prototype Flexblue unit in 2013 in its shipyard at Cherbourg for launch and deployment in 2016, possibly off Flamanville.

UNITHERM

This is an integral 30 MWt, 6.6 MWe PWR conceptual design from Russia's Research and Development Institute of Power Engineering (RDIPE or NIKIET). It has three coolant loops, with natural circulation, and claims self-regulation with burnable poisons in unusual metal-ceramic fuel design, so needs no more than an annual maintenance campaign and no refueling during a 25-year life. The mass of one unit with shielding is 180 tonnes, so it can be shipped complete from the factory to site.

SHELF

This is a Russian 6 MWe, 28 MWt PWR concept with turbogenerator in a cylindrical pod about 15 m long and 8 m diameter, sitting on the sea bed like Flexblue. The SHELF module uses an integral reactor with forced and natural circulation in the primary circuit, in which the core, steam generator, motor-driven circulation pump and control and protection system drive are housed in a cylindrical pressure vessel. It uses low-enriched fuel of UO_2 in aluminium alloy matrix. Fuel cycle is 56 months. The reactor is based on operating prototypes, and would be serviced infrequently. It is intended as energy supply for oil and gas developments in Arctic seas, and land-based versions have been envisaged. It is at concept design stage with NIKIET which estimates that a further five years would be required in order to finalise the design, licensing, construction and commissioning.

KARAT-45

This is a 45 MWe tank-type BWR as a stand-alone cogeneration plant. The design includes natural circulation in its core cooling system for heat removal in all operational modes and incorporates passive safety systems. A larger version is 100 MWe.

IMR

Mitsubishi Heavy Industries has a conceptual design of the Integral Modular Reactor (IMR), a PWR of 1000 MWt, 350 MWe. It has design life of 60 years, 4.8% fuel enrichment and fuel cycle of 26 months. It has natural circulation for primary cooling. The project has involved Kyoto University, the Central Research Institute of the Electric Power Industry (CRIEPI), and the Japan Atomic Power Company (JAPC), with funding from METI. The target year to start licensing is 2020 at the earliest.

Rolls-Royce SMR

Rolls-Royce has been working since 2015 on a small reactor of 220 to 440 MWe, the output "depending on configuration". It is to be factory-built, transportable to site (16 m high, 4 m diameter pressure vessel), with 60-year design life. It is a four-loop PWR with close-coupled steam generators. Ten UK companies have been

collaborating, including Amec Foster Wheeler, Nuvia and Arup, together with the Nuclear Advanced Manufacturing Research Centre. Early in 2016 Rolls-Royce submitted a detailed design to the UK government for a 220 MWe SMR unit and also a paper to the Department of Business, Energy and Industrial Strategy, outlining its plan to develop a fleet of 7 GWe of SMRs in the UK with a new consortium.

Rolls-Royce has designed three generations of naval reactors since the 1950s and also operates a small test reactor. It led the development of a small integral reactor (SIR) of 330 MWe in the 1980s.

TRIGA

The TRIGA Power System is a PWR concept based on General Atomics' well-proven research reactor design. It is conceived as a 64 MWt, 16.4 MWe pool-type system operating at a relatively low temperature. The secondary coolant is perfluorocarbon. The fuel is uranium-zirconium hydride enriched to 20% and with a little burnable poison and requiring refuelling every 18 months. Used fuel is stored inside the reactor vessel.

FBNR

The Fixed Bed Nuclear Reactor (FBNR) is an early conceptual design from the Federal University of Rio Grande do Sul, Brazil. It is a PWR with pebble fuel, 134 MWt, 70 MWe, with "flexible fuel cycle". Other reports have it as 40 MWe.

SMART from Dunedin

The SMART (Small Modular Adaptable Reactor Technology) from Dunedin Energy Systems in Canada is a 30 MWt, 6 MWe battery-type unit, installed below grade. It is replaced by a new one when it is returned to a processing facility for refuelling; at 83% capacity factor this would be every 20 years. It drives a steam turbine. Emergency cooling is by convection. Cost is about 29c/kWh, according to Dunedin.

DEER from Radix

The DEER (Deployable Electric Energy Reactor) was being developed by Radix Power & Energy Corporation in the USA, in collaboration with Brookhaven Technology Group, Brookhaven National Laboratory, Parsons Corporation, Dunedin Energy Systems, and University of California, Berkeley. The DEER is a PWR and would be portable and sealed, able to operate in the range of 10-50 MWe. DEER-1 was to use fuel based on that in Triga research reactors, with a ten-year cycle, and DEER-2 was to use TRISO fuel, for forward military bases or remote mining sites. No recent information is available.

Chinese district heat reactors

Three Chinese designs are solely for district heat at 90-110°C, for northern provinces, especially Heilongjiang. Reducing winter air pollution is the main driver of their development. CGN's NHR-200 passed regulatory review in the 1990s; CNNC's DHR-400 or 'Yanlong' is a 400 MWt pool-type reactor; and SPIC's LandStar-1 is similar to the Yanlong but 200 MWt.

Heavy water reactors

PHWR-220

These are the oldest and smallest of the Indian pressurized heavy water reactor (PHWR) range, with a total of 16 now on line, 800 MWt, 220 MWe gross typically. Rajasthan 1 was built as a collaborative venture between Atomic Energy of Canada Ltd (AECL) and the Nuclear Power Corporation of India (NPCIL), starting up in 1972. Subsequent indigenous PHWR development has been based on these units, though several stages of evolution can be identified: PHWRs with dousing and single containment at Rajasthan 1-2, PHWRs with suppression pool and partial double containment at Madras, and later standardized PHWRs from Narora onwards having double containment, suppression pool, and calandria filled with heavy water, housed in a water-filled calandria vault.

They are moderated and cooled by heavy water, and the natural uranium oxide fuel is in horizontal pressure tubes, allowing refueling on line (maintenance outages are scheduled after 24 months). Burn-up is about 15 GWd/t.

AHWR-300 LEU

The Advanced Heavy Water Reactor developed by the Bhaba Atomic Research Centre (BARC) is designed to make extensive use of India's abundant thorium as fuel, but a low-enriched uranium fuelled version is pitched for export. This will use low-enriched uranium plus thorium as a fuel, largely dispensing with the plutonium input of the version for domestic use. About 39% of the power will come from thorium (via in situ conversion to U-233, cf two thirds in domestic AHWR), and burn-up will be 64 GWd/t. Uranium enrichment level will be 19.75%, giving 4.21% average fissile content of the U-Th fuel. It will have vertical pressure tubes in which the light water coolant under high pressure will boil, circulation being by convection. Nominal 300 MWe, 284 MWe net. It is at the basic design stage.

High-temperature gas-cooled reactors

These use graphite as moderator (unless fast neutron type) and either helium, carbon dioxide or nitrogen as primary coolant. The experience of several innovative reactors built in the 1960s and 1970s, notably those in Germany, has been analyzed, especially in the light of US plans for its Next Generation Nuclear Plant (NGNP) and China's launching its HTR-PM project in 2011. Lessons learned and documented for NGNP include the use of TRISO fuel, use of a reactor pressure vessel, and use of helium cooling (UK AGRs are the only HTRs to use CO2 as primary coolant). However US government funding for NGNP has now virtually ceased, and the technology lead has passed to China.

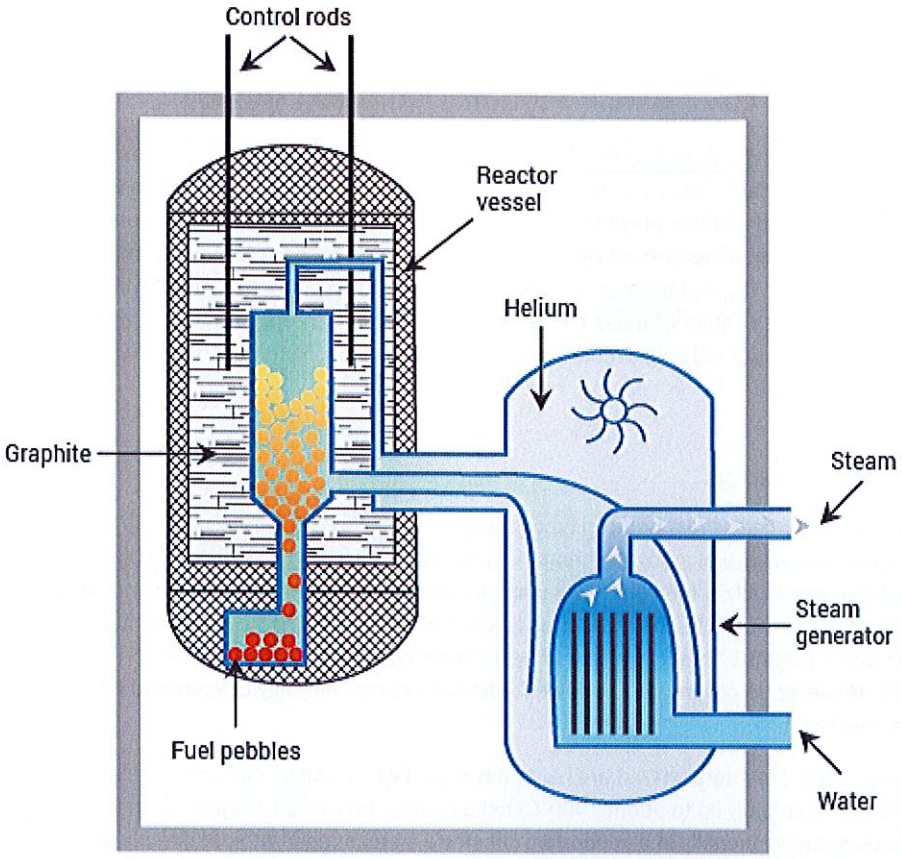
New high-temperature gas-cooled reactors (HTRs) are being developed which will be capable of delivering high temperature (700-950°C and eventually up to about 1000°C) helium either for industrial application via a heat exchanger, or to make steam conventionally in a secondary circuit via a steam generator, or directly to drive a Brayton cycle* gas turbine for electricity with almost 50% thermal efficiency possible (efficiency increases around 1.5% with each 50°C increment). One design uses the helium to drive an air compressor to supercharge a CCGT unit. Improved metallurgy and technology developed in the last decade makes HTRs more practical than in the past, though the direct cycle means that there must be high integrity of fuel and reactor components. All but one of those described below have neutron moderation by graphite, one is a fast neutron reactor.

* There is little interest in pursuing the direct Brayton cycle for helium at present due to higher technological risk. Attrition of fuel tends to give rise to graphite dust with radioactivity in the coolant circuit.

Fuel for these reactors is in the form of TRISO (tristructural-isotropic) particles less than a millimetre in diameter. Each has a kernel (*ca.* 0.5 mm) of uranium oxycarbide (or uranium dioxide), with the uranium enriched up to 20% U-235, though normally less. This is surrounded by layers of carbon and silicon carbide, giving a containment for fission products which is stable to over 1600°C.

There are two ways in which these particles are arranged: in blocks – hexagonal 'prisms' of graphite, or in billiard ball-sized pebbles of graphite, each with about 15,000 fuel particles and 9g uranium. There is a greater volume of used fuel (20 times) than from the same capacity in a light water reactor, due to the fact that the fuel pebbles are mainly graphite – less than one percent is uranium. However, the used fuel is overall less radiotoxic and produces less decay heat due to higher burn-up. The HTR moderator is graphite.

A High-Temperature Reactor (HTR)



HTRs can potentially use thorium-based fuels, such as highly-enriched or low-enriched uranium with Th, U-233 with Th, and Pu with Th. Most of the experience with thorium fuels has been in HTRs (see information paper on Thorium).

With negative temperature coefficient of reactivity (the fission reaction slows as temperature increases) and passive decay heat removal, the reactors are inherently safe. HTRs therefore are put forward as not requiring any containment building for safety. They are sufficiently small to allow factory fabrication, and will usually be installed below ground level.

Three HTR designs in particular – PBMR, GT-MHR and Areva's SC-HTGR – were contenders for the Next Generation Nuclear Plant (NGNP) project in the USA (see *Next Generation Nuclear Plant* section in the information page on US Nuclear Power Policy). In 2012 Areva's HTR was chosen. However, the only HTR project currently proceeding is the Chinese HTR-PM.

Hybrid Power Technologies have a hybrid-nuclear Small Modular Reactor (SMR) coupled to a fossil-fuel powered gas turbine.

HTTR, GTHTR

Japan Atomic Energy Research Institute's (JAERI's) High-Temperature Test Reactor (HTTR) of 30 MWt started up at the end of 1998 and first reached full power with a reactor outlet coolant temperature of 850°C in December 2001. In 2004 it achieved 950°C outlet temperature, and in 2009 it ran at 950°C for 50 days. Its fuel is in prisms and its main purpose is to develop thermochemical means of producing hydrogen from water.

Based on the HTTR, JAERI is developing the Gas Turbine High Temperature Reactor (GTHTR) of up to 600 MWt and 275 MWe per module. It uses improved HTTR fuel elements with 14% enriched uranium achieving high burn-up (112 GWd/t). Helium at 850°C drives a horizontal turbine at 47% efficiency to produce up to 300 MWe. The core consists of 90 hexagonal fuel columns 8 metres high arranged in a ring, with reflectors. Each

column consists of eight one-metre high elements 0.4 m across and holding 57 fuel pins made up of fuel particles with 0.55 mm diameter kernels and 0.14 mm buffer layer. In each two-yearly refuelling, alternate layers of elements are replaced so that each remains for four years.

Early in 2019 the Japan Atomic Energy Agency (JAEA) formed a joint venture with Penultimate Power UK to build a 10 MWe SMR there based on the HTTR, for power and process heat. Plans include scaling up the design to 100 MWe and building a factory in the UK for multiple plants.

HTR-10

China's HTR-10, a 10 MWt high-temperature gas-cooled experimental reactor at the Institute of Nuclear & New Energy Technology (INET) at Tsinghua University north of Beijing started up in 2000 and reached full power in 2003. It has its fuel as a 'pebble bed' (27,000 elements) of oxide fuel with average burn-up of 80 GWday/t U. Each pebble fuel element has 5g of uranium enriched to 17% in around 8300 TRISO-coated particles. The reactor operates at 700°C (potentially 900°C) and has broad research purposes. Eventually it will be coupled to a gas turbine, but meanwhile it has been driving a steam turbine.

In 2004, the small HTR-10 reactor was subject to an extreme test of its safety when the helium circulator was deliberately shut off without the reactor being shut down. The temperature increased steadily, but the physics of the fuel meant that the reaction progressively diminished and eventually died away over three hours. At this stage a balance between decay heat in the core and heat dissipation through the steel reactor wall was achieved, the temperature never exceeded a safe 1600°C, and there was no fuel failure. This was one of six safety demonstration tests conducted then. The high surface area relative to volume, and the low power density in the core, will also be features of the full-scale units (which are nevertheless much smaller than most light water types.)

HTR-PM

Construction of a larger version of the HTR-10, China's HTR-PM, was approved in principle in November 2005, with preparation for first concrete in mid-2011 and full construction start in December 2012. It is also based on the German HTR-Modul design of 200 MWt. Originally envisaged as a single 200 MWe (450 MWt) unit, this will now have twin reactors, each of 250 MWt driving a single 210 MWe steam turbine.*

* The size was reduced to 250 MWt from earlier 458 MWt modules in order to retain the same core configuration as the prototype HTR-10 and avoid moving to an annular design like South Africa's PBMR (see section on PBMR below).

Each reactor has a single steam generator with 19 elements (665 tubes). The fuel as 60 mm diameter pebbles is 8.5% enriched (520,000 elements in the two reactors) giving 90 GWd/t discharge burn-up. Core outlet temperature is 750°C for the helium, steam temperature is 566°C and core inlet temperature is 250°C. It has a thermal efficiency of 40%. Core height is 11 metres, diameter 3 m in a 25 m high, 5.7 m diameter reactor vessel. There are two independent reactivity control systems: the primary one consists of 24 control rods in the side graphite reflector, the secondary one of six channels for small absorber spheres falling by gravity, also in the side reflector. Pebbles are released into the top of the core one by one with the reactor operating. They are correspondingly removed from the bottom, broken ones are separated, the burn-up is measured, and spent fuel elements are screened out and transferred to storage.

China Huaneng Group, one of China's major generators, is the lead organization involved in the demonstration unit with 47.5% share; China Nuclear Engineering & Construction (CNEC) has a 32.5% stake and Tsinghua University's INET 20% – it being the main R&D contributor. Projected cost is US$ 430 million (but later units falling to US$1500/kW with generating cost about 5 ¢/kWh). Fuel pebbles were loaded in September 2017 and start-up was expected in 2018. The HTR-PM rationale is both eventually to replace conventional reactor technology for power, and also to provide for future hydrogen production. INET is in charge of R&D, and was aiming to increase the size of the 250 MWt module and also utilize thorium in the fuel.

The 210 MWe Shidaowan HTR-PM DPP demonstration plant at Rongcheng in Shandong province is to pave the way for commercial 600 MWe reactor units (6x250 MWt, total 655 MWe) with a single turbine, also using the steam cycle at 43.7% thermal efficiency. Plant operating lifetime is envisaged as 40 years with 85% load factor. The capital cost per kW is expected to be 75% of the small HTR-PM, and for subsequent units, 50%.

Meanwhile CNEC is promoting the technology for HTR-PM 600 plants using six 250 MWt modules. Eventually a series of HTRs, possibly with Brayton cycle directly driving the gas turbines, would be factory-built and widely installed throughout China.

Performance of both this and South Africa's PBMR design includes great flexibility in loads (40-100%) without loss of thermal efficiency, and with rapid change in power settings. Power density in the core is about one-tenth of that in a light water reactor, and if coolant circulation ceases the fuel will survive initial high temperatures while the reactor shuts itself down – giving inherent safety. Power control is by varying the coolant pressure, and hence flow. (See also section on Shidaowan HTR-PM in the information page on Nuclear Power in China and the Research and development section in the information page on China's Nuclear Fuel Cycle).

EM²

In February 2010, General Atomics announced its Energy Multiplier Module (EM²) fast neutron design, superseding its GT-MHR. The EM² is a 500 MWt, 240 MWe helium-cooled fast-neutron HTR operating at 850°C and fuelled with 20 tonnes of used PWR fuel or depleted uranium, plus 22 tonnes of low-enriched uranium (~12% U-235) as starter. Fuel rods have silicon carbide cladding, according to a company datasheet. Used fuel from this is processed to remove fission products (about 4 tonnes) and the balance is recycled as fuel for subsequent rounds, each time topped up with 4 tonnes of further used PWR fuel. (The means of reprocessing to remove fission products is not specified.) Each refuelling cycle may be as long as 30 years. With repeated recycling the amount of original natural uranium (before use by PWR) used goes up from 0.5% to 50% at about cycle 12. High-level wastes are about 4% of those from PWR on open fuel cycle. A 48% thermal efficiency is claimed, using Brayton cycle. EM² would also be suitable for process heat applications. The main pressure vessel can be trucked or railed to the site, and installed below ground level, and the high-speed (gas) turbine generator is also truck-transportable. The means of reprocessing to remove fission products is not specified. The company applied for the second round of DOE funding in 2013.

The company anticipates a 12-year development and licensing period, which is in line with the 80 MWt experimental technology demonstration gas-cooled fast reactor (GFR) in the Generation IV program[!]. GA has teamed up with Chicago Bridge & Iron, Mitsubishi Heavy Industries, and Idaho National Laboratory to develop the EM².

Urenco U-Battery

Urenco with others commissioned a study by TU-Delft and Manchester University on the basis of which it has called for European development of a very small 'plug and play' inherently-safe reactor called the U-Battery. This is based on graphite-moderated, helium cooled HTR concepts such as the UK's Dragon reactor (to 1975). The fuel block design is based on that of the Fort St Vrain reactor in the USA. It would use TRISO fuel with 17-20% enriched uranium and possibly thorium with a beryllium oxide reflector. The 10 MWt design can produce 750°C process heat or up to 4 MWe back-up and off-grid power. The consortium envisages up to six U-Batteries at one site.

This micro-SMR U-battery would run for five years before refuelling and servicing, a larger 20 MWt one would run for 10 years. The 10 MWt/4 MWe design, 1.8 m diameter, may be capable of being returned to the factory for refuelling. The U-Battery consortium, led by Urenco, is seeking government support for a prototype, with target operation in 2026. Wood, Laing O'Rourke, Cammell Laird and Kinectrics are involved.

In mid-2018 the consortium was one of eight organisations to be awarded a contract to produce a feasibility study as part of the UK government's Advanced Modular Reactor Feasibility and Development project. It has been accepted for pre-licensing vendor design review with the Canadian Nuclear Safety Commission (CNSC), from 2017. In July 2019 it became the first design to complete the first of the four phases of Canadian Nuclear Laboratories' review process for siting an SMR at Chalk River Laboratories in Ontario.

Russian HTR for Indonesia

In 2015 a consortium of Russian and Indonesian companies led by NUKEM Technologies had won a contract for the preliminary design of the multi-purpose 10 MWe HTR in Indonesia, which would be "a flagship project in the future of Indonesia's nuclear program". It will be a pebble-bed HTR at Serpong. Atomproekt is architect general, and OKBM Afrikantov the designer. SRI Luch is also involved with fuel design. The conceptual design was completed in December 2015, and will lead to BATAN calling for bids to construct the reactor, for both electricity and process heat.

X-energy

X-energy founded in 2009 in the USA is designing the Xe-100 pebble-bed HTR of 200 MWt, 75 MWe, and has been in talks with utilities, stressing that a plant will fit on a 4 ha site, below grade. The initial TRISO fuel in mid-2020s will utilize uranium oxycarbide (UCO), but longer-term thorium is intended as the primary fuel. Unlike other pebble bed HTRs, the fuel will only pass through once. Fairly rapid load-following from 25% to 100% is a feature of the helium-cooled design. Each four-pack would cost about $1 billion. Factory-made units would be transported to site by road and installed.

The company has been in discussion with several utilities, including South Carolina Electricity & Gas (SCEG), regarding replacing coal-fired capacity with the four-pack installations. Industrial process heat is also a likely application. X-energy is working in partnership with BWX Technology, Oregon State University, Teledyne-Brown Engineering, SGL Group, Idaho National Laboratory (INL), and Oak Ridge National Laboratory (ORNL) on the design. In January 2016 the US DOE awarded a Gateway for Accelerated Innovation in Nuclear (GAIN) grant to the project, worth $53 million. In September 2016 Burns & McDonnell Engineering joined the project as architectural and engineering partner, in parallel with the DOE five-year award. The company expected to complete the basic conceptual design by mid-2019 and hoped to deploy the first units by 2027. In November 2017 the company signed an agreement with Jordan Atomic Energy Commission to consider building the Xe-100 in Jordan.

In August 2016 X-energy signed an agreement to work with Southern Nuclear Operating Company to collaborate on development and commercialization of their respective small reactor designs. Southern is developing an MSR, the Molten Chloride Fast Reactor (MCFR). In September 2018, X-energy said that its design was about 50% complete, and that it hoped the full design would be finalized by 2022 or 2023.

X-energy has a TRISO pilot fuel fabrication facility at Oak Ridge National Laboratory, Tennessee and in November 2019 it agreed with Global Nuclear Fuel to set up commercial HALEU TRISO production at GNF's Wilmington plant. X-energy also has agreements with Centrus Energy in the USA to develop TRISO fabrication technology for uranium carbide fuel, and with NFI at Tokai in Japan, where NFI has 400 kgU/yr HTR fuel capacity.

StarCore HTR

This is a small (20 MWe) concept design of helium-cooled reactor from StarCore Nuclear in Quebec, designed for remote locations (displacing diesel and propane) and with remote control system via satellite. It is expandable to 100 MWe. The units would be installed below grade and in pairs. They are truck-transportable, with reactor vessels 2.5 m diameter and 6 m high. Fuel is TRISO in carbon prismatic matrix. Each reactor has a five-year refuelling schedule. The secondary cooling circuit is nitrogen, to a steam generator driving a turbine. The company offers a build-own-operate-decommission concept with a power purchase agreement for the life of the reactor, mentioning C$0.18 per kWh. The units are designed to deliver both electricity and potable water.

The company has applied to the CNSC to start the pre-licensing vendor design review process.

In April 2018, Canadian Nuclear Laboratories (CNL) launched its SMR review – a separate process to licensing – with a view to having an SMR constructed on its Chalk River site by 2026. In February 2019 CNL anounced that StarCore had completed the prequalification stage and been invited to enter the due diligence stage.

Ultra Safe Nuclear Corporation micro-modular reactor

Ultra Safe Nuclear Corporation (USNC), an American company with a subsidiary in South Korea, has a 'micro-modular reactor' (MMR) HTR with the fuel in prismatic graphite blocks and operating at 12 MWt/5 MWe in the MMR-5 version. There is also an MMR-10. It has a sealed transportable core. The Canadian representation is Global First Power (GFP) in collaboration with Ontario Power Generation (OPG).

Phase 1 of a pre-licensing vendor design review by the Canadian Nuclear Safety Commission (CNSC) was completed in February 2019, and GFP then submitted a site preparation licence application for Chalk River.

In April 2018, CNL launched its SMR review – a separate process to licensing – with a view to having an SMR constructed on its Chalk River site by 2026. GFP/OPG/USNC has completed the first and second stages of CNL's process, and has been invited to participate in the third and penultimate stage.

(USNC is also developing an accident-tolerant shutdown system for NASA in nuclear thermal propulsion systems.)

Hybrid SMR concept

The hybrid-nuclear Small Modular Reactor (SMR) design from Hybrid Power Technologies LLC produces massive quantities of compressed air, while the gas turbine, able to burn a variety of fossil fuels, generates electrical power. Helium from the 600 MWt graphite-moderated reactor drives a primary turbine coupled to an air compressor. The very high pressure air then supercharges a combined cycle gas turbine (CCGT) driving an 850 MWe generator at 85% efficiency. The reactor and compressor are in a full containment structure. (The actual HTR is equivalent to less then 300 MWe output, so that component is still 'small'.) The company applied for the second round of DOE funding in 2013.

Supercritical CO_2 direct cycle fast reactor concept

This is a Generation IV design based partly on the well-proven UK Advanced Gas-Cooled reactors (AGRs). The supercritical direct cycle gas fast reactor (SC-GFR) uses the supercritical CO2 coolant at 20 MPa and 650°C from a fast reactor of 200 to 400 MW thermal in Brayton cycle. A small long-life reactor core could maintain decay heat removal by natural circulation. A 2011 paper from Sandia Laboratories describes it. (S-CO2 is applicable to many different heat sources, including concentrated solar. It claims high efficiency with smaller and simpler power plants. With a helium-cooled HTR or sodium-cooled fast reactor, it would be the secondary circuit.)

Antares – Areva SC-HTGR

Another full-size HTR design is being put forward by Areva. It is based on the GT-MHR and has also involved Fuji. The reference design is 625 MWt with prismatic block fuel like the GT-MHR. Core outlet temperature is 750°C for the steam-cycle HTR version (SC-HTGR), though an eventual very high temperature reactor (VHTR) version is envisaged with 1000°C and direct cycle. The present concept uses an indirect cycle, with steam in the secondary system, or possibly a helium-nitrogen mix for the VHTR, removing the possibility of contaminating the generation, chemical or hydrogen production plant with radionuclides from the reactor core. It was selected in 2012 for the US Next Generation Nuclear Plant, with two-loop secondary steam cycle, the 625 MWt probably giving 285 MWe per unit, but the primary focus being the 750°C helium outlet temperature for industrial application. It remains at the conceptual design stage.

Adams Engine

A small HTR concept is the Adams Atomic Engines' 10 MWe direct simple Brayton cycle plant with low-pressure nitrogen as the reactor coolant and working fluid, and graphite moderation. The reactor core is a fixed, annular bed with about 80,000 fuel elements each 6 cm diameter and containing approximately 9 grams of heavy metal as TRISO particles, with expected average burn-up of 80 GWd/t. The initial units would provide a reactor core outlet temperature of 800°C and a thermal efficiency near 25%. Power output is controlled by limiting coolant flow. A demonstration plant was proposed for completion after 2018, but the design is shelved. The Adams Engine is designed to be competitive with combustion gas turbines.

An antecedent was the ML-1 nitrogen-cooled reactor with closed cycle gas turbine, designed to be air-portable and part of the US Army Nuclear Power Program (ANPP). It was water-moderated, with high-enriched fuel and from 1961 worked for several hundred hours up to two-thirds of its designed 300 kW, but various problems caused the project to be shut down in 1965. The high-pressure gas cycle with nitrogen at 910 kPa was one problem.

PBMR and derivatives

South Africa's pebble bed modular reactor (PBMR) was being developed by the PBMR (Pty) Ltd consortium led by the utility Eskom, latterly with involvement of Mitsubishi Heavy Industries, and drew on German expertise, notably the HTR-Modul design. It aimed for a step change in safety, economics and proliferation resistance. Full-scale production units had been planned to be 400 MWt (165 MWe) but more recent plans were for 200 MWt (80 MWe)[7]. Financial constraints led to delays[8] and in September 2010 the South African government confirmed it would stop funding the project[8]. However, a 2013 application for federal funds from National Project Management Corporation (NPMC) in the USA appeared to revive the earlier direct-cycle PBMR design, emphasising its 'deep burn' attributes in destroying actinides and achieving high burn-up at high temperatures.

The earlier plans for the 400 MWt PBMR following a 2002 review envisaged a direct cycle (Brayton cycle) gas turbine generator and thermal efficiency about 41%, the helium coolant leaving the bottom of the core at about 900°C and driving a turbine. Power would be adjusted by changing the pressure in the system. The helium is passed through a water-cooled pre-cooler and intercooler before being returned to the reactor vessel. The PBMR Demonstration Power Plant (DPP) was expected to start construction at Koeberg in 2009 and achieve criticality in 2013, but after this was delayed it was decided to focus on the 200 MWt design6.

The 200 MWt (80 MWe) later design announced in 2009 was to use a conventional Rankine cycle, enabling the PBMR to deliver super-heated steam via a steam generator as well as generate electricity. This design "is aimed at steam process heat applications operating at 720°C, which provides the basis for penetrating the nuclear heat market as a viable alternative for carbon-burning, high-emission heat sources."[10] An agreement with Mitsubishi Heavy Industries to take forward the R&D on this design was signed in February 2010. MHI had been involved in the project since 2001, having done the basic design and R&D of the helium-driven turbogenerator system and core barrel assembly, the major components of the 400 MWt direct-cycle design.

The PBMR has a vertical steel reactor pressure vessel which contains and supports a metallic core barrel, which in turn supports the cylindrical pebble fuel core. This core is surrounded on the side by an outer graphite reflector and on top and bottom by graphite structures which provide similar upper and lower neutron reflection functions. Vertical borings in the side reflector are provided for the reactivity control elements. Some 360,000 fuel pebbles (silicon carbide-coated 9.6% enriched uranium dioxide particles encased in graphite spheres of 60 mm diameter) cycle through the reactor continuously (about six times each) until they are expended after about three years. This means that a reactor would require 12 total fuel loads in its design lifetime.

A pebble fuel plant at Pelindaba was planned. Meanwhile, the company produced some fuel which was successfully tested in Russia.

The PBMR was proposed for the US Next Generation Nuclear Plant project and submission of an application for design certification reached the pre-application review stage, but is now listed as 'inactive' by the NRC. The company is part of the National Project Management Corporation (NPMC) consortium which applied for the second round of DOE funding in 2013.

PBMR development in South Africa was abandoned in 2010 due to lack of funds. In 2016 Eskom revived consideration of a reactor based on the PBMR, with a view to developing a design that is simpler and more efficient than the original, and also looking at applications for process heat that were not fully explored by the original R&D program.

A new concept is for an advanced high-temperature reactor of 150 MWe to be deployed in the 2030s, with a 50 MWe pilot plant built in the mid-2020s. It would be a combined-cycle plant with gas flow now from bottom to top, and the temperature will be much higher. The pressure vessel will be concrete, and it will have a pebble

bed reactor core. Helium will exit the reactor to a gas turbine at 1200°C, and the exhaust gas from this at 600° C will drive a steam cycle, using a molten salt circuit, with overall 60% thermal efficiency. The gas turbine will produce 40% of the power, the steam cycle 60%.

HTMR Ltd and HTMR Asia Development Ltd are designing the HTMR-100, a 35 MWe (100 MWt) pebble bed HTR for electricity or process heat. The conceptual design, commenced in 2012, formerly known as the Th-100, and inherited from Steenkampskraal Thorium Limited (STL), is expected to be completed in 2018. It is derived from the Jülich and PBMR designs. For electricity, single units have load-following capability, or four can comprise a 140 MWe power plant. There are a range of fuel options involving LEU, thorium and reactor-grade plutonium, with burn-up of 80-90 GWd/t of TRISO fuel pebbles. It has a graphite moderator and helium coolant at 750°C, and a single pass fuel cycle. The reactor vessel is 15 m high, 5.9 m diameter and primary loop pressure is relatively low at 4 MPa. The 8MWe HTMR-25 is also being designed.

GT-MHR

In the 1970s General Atomics developed an HTR with prismatic fuel blocks based on those in the 842 MWt Fort St Vrain reactor, which ran 1976-89 in the USA. Licensing review by the NRC was underway until the projects were cancelled in the late 1970s.

Evolved from this in the 1980s, General Atomics' Gas Turbine – Modular Helium Reactor (GT-MHR), would be built as modules of up to 600 MWt, but typically 350 MWt, 150 MWe. In its electrical application each would directly drive a gas turbine at 47% thermal efficiency. It could also be used for hydrogen production (100,000 t/yr claimed) and other high temperature process heat applications. The annular core, allowing passive decay heat removal, consists of 102 hexagonal fuel element columns of graphite blocks with channels for helium coolant and control rods. Graphite reflector blocks are both inside and around the core. Half the core is replaced every 18 months. Enrichment is about 15.5%, burn-up is up to 220 GWd/t, and coolant outlet temperature is 750°C with a target of 1000°C.

The GT-MHR was being developed by General Atomics in partnership with Russia's OKBM Afrikantov, supported by Fuji (Japan). Areva was formerly involved, but it has developed the basic design itself as Antares. Initially the GT-MHR was to be used to burn pure ex-weapons plutonium at Seversk (Tomsk) in Russia. A burnable poison such as Er-167 is needed for this fuel. The preliminary design stage was completed in 2001, but the programme to construct a prototype in Russia has apparently halted since.

General Atomics said that the GT-MHR neutron spectrum is such, and the TRISO fuel is so stable, that the reactor could be powered fully with separated transuranic waste (neptunium, plutonium, americium and curium) from light water reactor used fuel. The fertile actinides would enable reactivity control and very high burn-up could be achieved with it – over 500 GWd/t – the 'Deep Burn' concept. Over 95% of the Pu-239 and 60% of other actinides would be destroyed in a single pass.

A smaller version of the GT-MHR, the Remote-Site Modular Helium Reactor (RS-MHR) of 10-25 MWe was proposed by General Atomics. The fuel would be 20% enriched and the refuelling interval would be 6-8 years.

Fast neutron reactors

Fast neutron reactors (FNR) are smaller and simpler than light water types, they have better fuel performance and can have a longer refueling interval (up to 20 years), but a new safety case needs to be made for them, at least in the west. They are designed to use the full energy potential of uranium, rather than about one percent of it that conventional power reactors use. They have no moderator, a higher neutron flux and are normally cooled by liquid metal such as sodium, lead, or lead-bismuth, with high conductivity and boiling point. They operate at or near atmospheric pressure and have passive safety features (most have convection circulating the primary coolant). Automatic power regulation is achieved due to the reactivity feedback – loss of coolant flow leads to higher core temperature which slows the reaction. Fast reactors typically use boron carbide control rods.

Fuels are mostly 15-20% enriched and may be uranium nitride – UN, (U,Pu)N, (U,transuranic)N, U-Zr, or (U,Pu) Zr. In the USA no enrichment plant is designed for more than 10% enrichment, but the government has 26 tonnes of HEU unallocated, and this might be blended down for fast reactors.

Most coolants are liquid metal, either sodium, which is flammable and reacts violently with water, or lead/lead-bismuth, which is corrosive but does not react with air or water. It eliminates the need and associated expense of extra components and redundant safety systems required by other technologies for protection against coolant leakages. Both coolants can be used at or near atmospheric pressure, which simplifies engineering and reduces cost. Their high-temperature operation benefits thermodynamic efficiency.

There are two exceptions to liquid metal cooling: gas and salt.

A gas-cooled fast reactor (GFR) concept – the Energy Multiplier Module (EM^2) – has been announced by General Atomics and is described in the HTR section above. The concept is also being pursued in the Generation IV program, with ALLEGRO being built in France.

Salt cooling is in the molten chloride fast reactor (MCFR) concept being developed by Southern Company Services in the USA with TerraPower, Oak Ridge National Laboratory (ORNL) and EPRI. Also the lead version of the Moltex stable salt reactor is fast. These are described in the Molten salt reactors section below.

Small FNRs are designed to be factory-built and shipped to site on truck, train or barge and then shipped back again or to a regional fuel cycle centre at end of life. They would mostly be installed below ground level and with high surface area to volume ratio they have good passive cooling potential. Disposal is envisaged as entire units, without separate spent fuel storage, or after fuel removed for reprocessing.

See also Fast Neutron Reactors paper.

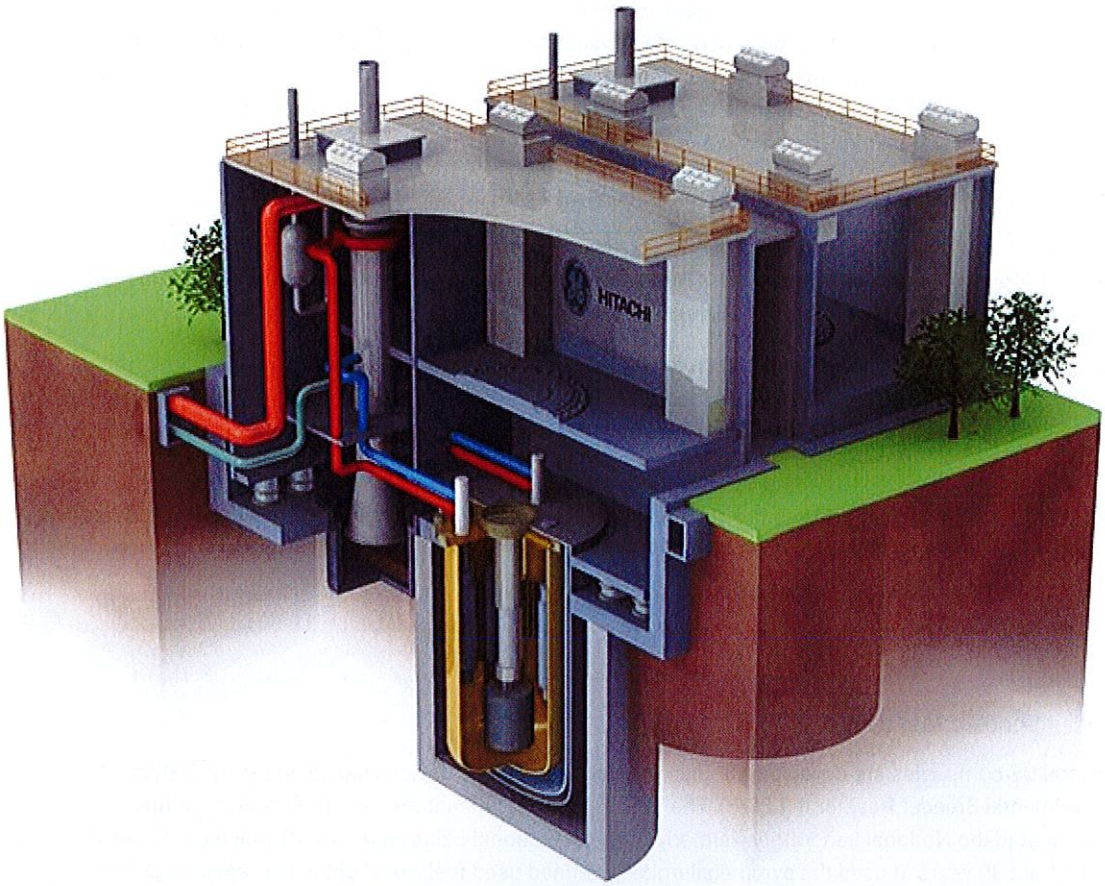
Sodium-cooled fast reactors

Several US companies are developing sodium-cooled fast reactor designs based on the 62.5 MWt Experimental Breeder Reactor II (EBR-II). The EBR-II was a significant fast reactor prototype, a fuel recycle reactor at Idaho National Laboratory (formerly Argonne National Laboratory - West) which produced 19 MWe over about 30 years. It used the pyrometallurgically-refined used fuel from light water reactors as fuel, including a wide range of actinides. After operating from 1963 to 1994 it is now decommissioned. EBR-II was the basis of the US Integral Fast Reactor (IFR) program (originally the Advanced Liquid Metal Reactor program), and that IFR term is again in use. An EBR-III of 200-300 MWe was proposed but not developed (see also information page on Fast Neutron Reactors).

PRISM

GE with the US national laboratories had been developing a modular liquid metal-cooled inherently-safe reactor – PRISM (Power Reactor Innovative Small Module) – under the Advanced Liquid Metal Reactor/Integral Fast Reactor (ALMR/IFR) program funded by the US Department of Energy. The design is based on EBR-II and the original IFR. Another antecedent was GE's fast reactor power plant for USS Seawolf 1957-58. The ALMR/IFR program was cancelled in 1994 and no US fast neutron reactor has so far been larger than 66 MWe and none has supplied electricity commercially. However, the 1994 pre-application safety evaluation report[13] for the original PRISM design concluded that "no obvious impediments to licensing the PRISM design had been identified."

Today's PRISM is a GE Hitachi (GEH) design for compact modular pool-type reactors with passive cooling for decay heat removal. After 30 years of development it represents GEH's Generation IV solution to closing the fuel cycle in the USA. Each PRISM power block consists of two modules of 311 MWe (840 MWt) each, (or, earlier, three modules of 155 MWe, 471 MWt), each with one steam generator, that collectively drive one turbine generator. The pool-type modules below ground level contain the complete primary system with sodium coolant at about 500°C. An intermediate sodium loop takes heat to steam generators.The metal Pu & DU fuel is obtained from used light water reactor fuel. All transuranic elements are removed together in the electrometallurgical reprocessing so that fresh fuel has minor actinides with the plutonium and uranium.



A cutaway of the PRISM design (GE Hitachi)

The reactor is designed to use a heterogeneous metal alloy core with 192 fuel assemblies in two fuel zones. In the version designed for used LWR fuel recycle, all these are fuel, giving peak burnup of 122 GWd/t. In other versions for breeding or weapons plutonium consumption, 42 of them are internal blanket and 42 are radial blanket, with 108 as driver fuel, and peak burnup of 144 GWd/t. For the LWR fuel recycle version, fuel stays in the reactor four years, with one-quarter removed annually, and 72 kg/yr net of fissile plutonium consumed. In the breeder version fuel stays in the reactor about six years, with one-third removed every two years, and net production of 57 kg/yr of fissile plutonium. Breeding ratio depends on purpose and hence configuration, so ranges from 0.72 for used LWR recycle to 1.23 for breeder. Used PRISM fuel is recycled after removal of fission products, though not necessarily into PRISM units.

The commercial-scale plant concept, part of an 'Advanced Recycling Center', would use three power blocks (six reactor modules) to provide 1866 MWe. In 2011 GE Hitachi announced that it was shifting its marketing strategy to pitch the reactor directly to utilities as a way to recycle excess plutonium while producing electricity for the grid. GEH bills it as a simplified design with passive safety features and using modular construction techniques. Its reference construction schedule is 36 months. In October 2016 GEH signed an agreement with Southern Nuclear Development, a subsidiary of Southern Nuclear Operating Company, to collaborate on licensing fast reactors including PRISM. In June 2017 GEH joined a team led by High Bridge Energy Development Co. and including Exelon Generation, High Bridge Associates and URS Nuclear to license PRISM.

GEH is promoting to UK government agencies the potential use of PRISM technology to dispose of the UK's plutonium stockpile, and has launched a web portal in support of its proposal. Two PRISM units would irradiate fuel made from this plutonium (20% Pu, with DU and zirconium) for 45-90 days, bringing it to 'spent fuel standard' of radioactivity, after which is would be stored in air-cooled silos. The whole stockpile could be irradiated thus in five years, with some by-product electricity (but frequent interruptions for fuel changing) and the plant would then proceed to re-use it for about 55 years solely for 600 MWe of electricity generation, with one-third of the fuel being changed every two years. For this UK version, the breeding ratio is 0.8. No reprocessing plant ('Advanced Recycling Center') is envisaged initially, but this could be added later.

In March 2017 GEH and Advanced Reactor Concepts (see below) signed an agreement to collaborate on licensing an SMR design based on the ARC-100, but drawing on the extensive intellectual property and licensing experience of the GEH PRISM program. Initial deployment is envisaged in Canada, and will seek a preliminary regulatory review with the CNSC through its Vendor Design Review process.

In February 2019 the US DOE launched its Versatile Test Reactor (VTR) programme, set up under the Nuclear Energy Innovation Capabilities Act 2017 and run by Idaho National Laboratory. The programme aims to provide the capability for testing advanced nuclear fuels, materials, instrumentation, and sensors. The VTR, which is intended to be operational at INL by the end of 2025, would be an adapted PRISM reactor to provide accelerated neutron damage rates 20 times greater than current water-cooled test reactors. (The only other fast research reactor operating is the BN-60 in Russia, to be replaced after 2020 by MBIR there.)

See also Electrometallurgical 'pyroprocessing' section in the information page on Processing of Used Nuclear Fuel.

Integral Fast Reactor, ARC-100

Advanced Reactor Concepts LLC (ARC) set up in 2006 is developing a 260 MWt/100 MWe sodium-cooled fast reactor based on the 62.5 MWt Experimental Breeder Reactor II (EBR-II). It will be factory-produced, with components readily assembled onsite, and with 'walk-away' passive safety. Installation would be below ground level.

The ARC-100 system comprises a uranium alloy metal core cartridge submerged in sodium at ambient pressure in a stainless steel tank. The liquid sodium is pumped through the core where it is heated to 510°C, then passed through an integral heat exchanger (within the pool) where it heats sodium in an intermediate loop, which in turn heats working fluid for electricity generation. It would have a refuelling interval of 20 years for cartridge changeover, with 20.7 tonnes of fuel. Initial fuel will be low-enriched uranium (10.1% inner zone, 12.1% middle zone, 17.2% outer zone among 92 fuel assemblies over 1.5 m fuelled height) but it will be able to burn wastes from light water reactors, or plutonium. Reprocessing its used fuel will not separate plutonium. ARC-100 has load-following capability. Thermal efficiency is about 40% and it and could be paired with a supercritical carbon dioxide tertiary circuit to drive a turbine at high efficiency. Operating cost is expected to be $50/MWh.

In March 2017 GEH and ARC signed an agreement to collaborate on licensing an SMR design based on ARC-100, which will leverage extensive intellectual property and licensing experience of the GEH PRISM program. A further agreement in August 2017 licensed PRISM technology to ARC, and provided GEH engineering and design expertise to ARC. Initial deployment is envisaged in Canada, and they will seek a preliminary regulatory review with the CNSC through its Vendor Design Review process, likely to start late in 2017.

In July 2018 ARC and New Brunswick Power announced that they were exploring the potential deployment of the ARC-100 reactor at New Brunswick's Point Lepreau nuclear plant.

CEFR

The China Experimental Fast Reactor of 65 MWt is basically that, rather than a power reactor, though it can incidentally generate 20 MWe. It is an important part of China's reactor development, and details are in the R&D section of the China Fuel Cycle paper. It is sodium-cooled at 530°C and has been operating since 2010.

Rapid-L

A small-scale design developed by Japan's Central Research Institute of Electric Power Industry (CRIEPI) in cooperation with Mitsubishi Research Institute and funded by the Japan Atomic Energy Research Institute (JAERI) is the 5 MWt, 200 kWe Rapid-L, using lithium-6 (a neutron poison) as control medium. It would have 2700 fuel pins of 40-50% enriched uranium nitride with 2600°C melting point integrated into a disposable cartridge or 'integrated fuel assembly'. The reactivity control system is passive, using lithium expansion modules (LEMs) which give burn-up compensation, partial load operation as well as negative reactivity feedback. During normal operation, lithium-6 in the LEM is suspended on an inert gas above the core region. As the reactor temperature rises, the lithium-6 expands, moving the gas/liquid interface down into the core and

hence adding negative reactivity. Other kinds of lithium modules, also integrated into the fuel cartridge, shut down and start up the reactor. Cooling is by molten sodium, and with the LEM control system, reactor power is proportional to primary coolant flow rate. Refuelling would be every 10 years in an inert gas environment. Operation would require no skill, due to the inherent safety design features. The whole plant would be about 6.5 metres high and 2 metres diameter.

The larger RAPID reactor delivers 1 MWe and is U-Pu-Zr fuelled and sodium-cooled.

4S

The Super-Safe, Small & Simple (4S) 'nuclear battery' system is being developed by Toshiba and the Central Research Institute of Electric Power Industry (CRIEPI) in Japan in collaboration with SSTAR work and Westinghouse (owned by Toshiba) in the USA. It uses sodium as coolant (with electromagnetic pumps) and has passive safety features, notably negative temperature coefficient of reactivity. The whole unit would be factory-built, transported to site, installed below ground level, and would drive a steam cycle via a secondary sodium loop. It is capable of three decades of continuous operation without refuelling. Metallic fuel (169 pins 10mm diameter) is uranium-zirconium enriched to less than 20% or U-Pu-Zr alloy with 24% Pu for the 30 MWt (10 MWe) version or 11.5% Pu for the 135 MWt (50 MWe) version. Steady power output over the core lifetime in 30 MWt version is achieved by progressively moving upwards an annular reflector around the slender core (0.68m diameter, 2m high in the small version; 1.2m diameter and 2.5m high in the larger version) at about one millimetre per week. After 14 years a neutron absorber at the centre of the core is removed and the reflector repeats its slow movement up the core for 16 more years. Burn-up will be 34 GWday/t. In the event of power loss the reflector falls to the bottom of the reactor vessel, slowing the reaction, and external air circulation gives decay heat removal. A further safety device is a neutron absorber rod which can drop into the core. After 30 years the fuel would be allowed to cool for a year, then it would be removed and shipped for storage or disposal.

Both versions of 4S are designed to automatically maintain an outlet coolant temperature of 510-550°C – suitable for power generation with high temperature electrolytic hydrogen production. Plant cost is projected at US$ 2500/kW and power cost 5-7 cents/kWh for the small unit – very competitive with diesel in many locations. The design has gained considerable support in Alaska and toward the end of 2004 the town of Galena granted initial approval for Toshiba to build a 10 MWe (30 MWt) 4S reactor in that remote location. A pre-application Nuclear Regulatory Commission (NRC) review was under way to 2008 with a view to application for design certification in October 2010, and combined construction and operating licence (COL) application to follow. Its review is now listed as 'inactive' by NRC. Its design is sufficiently similar to PRISM – GE's modular 150 MWe liquid metal-cooled inherently-safe reactor which went part-way through the NRC approval process (see section above on PRISM) – for it to have good prospects of licensing. Toshiba planned a worldwide marketing program to sell the units for power generation at remote mines, for extraction of tar sands, desalination plants and for making hydrogen. Eventually it expected sales for hydrogen production to outnumber those for power supply.

The L-4S is a Pb-Bi cooled version of the 4S design.

Oklo micro-reactor

Oklo (formerly UPower) is a Californian company founded in 2013 and developing a 2 MWe fast reactor using U-Zr metal fuel based on that in EBR-II, but with lower burn-up. It is designed to operate for 12 years before refuelling. Idaho National Laboratory is working with the company on fuel.

Travelling wave and standing wave reactors

This is not a small reactor, and details are in the information paper on Fast Neutron Reactors and at TerraPower.

Lead- and lead-bismuth cooled fast reactors

BREST-300

Russia has experimented with several lead-cooled reactor designs, and has used lead-bismuth cooling for 40 years in its submarine reactors. (Pb-208 – 54% of naturally-occurring lead – is transparent to neutrons.) A significant Russian design from NIKIET is the BREST fast neutron reactor, of 700 MWt, 300 MWe, or more with lead as the primary coolant, at 540°C, supplying supercritical steam generators. The core sits in a pool of lead at near atmospheric pressure. It is inherently safe and uses a U+Pu nitride fuel. Fuel cycle is 10 months. No weapons-grade plutonium can be produced (since there is no uranium blanket), and used fuel can be recycled indefinitely, with on-site facilities. A pilot unit was planned to be built at Beloyarsk, and 1200 MWe units are planned. It is at preliminary design stage.

SVBR-100

A smaller and newer Russian design as a small modular reactor was to be the lead-bismuth fast reactor (SVBR) of 280 MWt, 100 MWe, being developed by AKME-engineering and involving Gidropress in the design. It is an integral design, with 12 steam generators and two main circulation pumps sitting in the same Pb-Bi pool at 340-490°C as the reactor core. It is designed to be able to use a wide variety of fuels, though the pilot unit would initially use uranium oxide enriched to 16.3%. With U-Pu MOX fuel it would operate in closed cycle. Refuelling interval would be 7-8 years and 60-year operating lifetime was envisaged. The melting point of the Pb-Bi coolant is 123.5°C, so it is readily kept molten during shutdown by decay heat supplemented by external heat sources if required.

The SVBR-100 unit of 280 MWt would be factory-made and transported (railway, road or waterway) as a 4.5m diameter, 8.2m high module. A power station with such modules was expected to supply electricity at lower cost than any other new technology with an equal capacity as well as achieving inherent safety and high proliferation resistance. (Russia built seven Alfa-class submarines, each powered by a compact 155 MWt Pb-Bi cooled reactor, and 80 reactor-years' operational experience was acquired with these.) In October 2015 Rosatom reported: "Experts have confirmed there are no scientific or technical issues that would prevent completion of the project and obtaining a construction licence." Then in November 2016 Rosatom said it expected to work out the main specifications for construction of the SVBR-100 by mid-2017, but in 2018 the project was dropped. Overnight capital cost was earlier estimated as $4000-4500/kW and generating costs 4-5 c/kWh on 90% load factor.

In December 2009, AKME-engineering, a 50-50 joint venture, was set up by Rosatom and the En+ Group (a subsidiary of Basic Element Group) as an open joint stock company to develop and build a pilot SVBR unit[14]. En+ is an associate of JSC EuroSibEnergo and a 53.8% owner of Rusal, which had been in discussion with Rosatom regarding a Far East nuclear power plant and Phase II of the Balakovo nuclear plant. It was to contribute most of the capital, and Rosatom is now looking for another investor. In 2011 the EuroSibEnergo 50% share passed to its subsidiary JSC Irkutskenergo. The main project participants are OKB Gidropress at Podolsk, VNIPIET OAO at St Petersburg, and the RF State Research Centre Institute of Physics & Power Engineering (IPPE or FEI) at Obninsk.

The plan was to complete the design development and put online a 100 MWe pilot facility by 2019, with total investment of RUR36 billion ($550 million). The site was to be the Research Institute of Atomic Reactors (RIAR or NIIAR) at Dimitrovgrad – Russia's largest nuclear research centre – though earlier plans were to put it at IPPE/FEI at Obninsk. The SVBR-100 would have been the first reactor cooled by heavy metal to to generate electricity. It is described by Gidropress as a multi-function reactor for power, heat or desalination.

An SVBR-10 was also envisaged, with the same design principles, a 20-year refuelling interval and generating capacity of 12 MWe, and it too is a multi-purpose unit.

(Link to SVBR brochure)

Gen4 (Hyperion) Power Module

The Gen4 Module is a 70 MWt/25 MWe lead-bismuth cooled reactor concept using 19.75% enriched uranium nitride fuel, from Gen4 Energy. The reactor was originally conceived as a potassium-cooled self-regulating 'nuclear battery' fuelled by uranium hydride[11]. However, in 2009, Hyperion Power changed the design to uranium nitride fuel and lead-bismuth cooling to expedite design certification[12]. This now classes it as a fast

neutron reactor, without moderation. The company claims that the ceramic nitride fuel has superior thermal and neutronic properties compared with uranium oxide. Enrichment is 19.75% and operating temperature about 500°C. The unit would be installed below ground level.

The reactor vessel housing the core and primary heat transfer circuit is about 1.5 metres wide and 2.5 metres high. It is easily portable, sealed and has no moving parts. A secondary cooling circuit transfers heat to an external steam generator. The reactor module is designed to operate for electricity or process heat (or cogeneration) continuously for up to 10 years without refuelling. Another reactor module could then take its place in the overall plant. The old module, with fuel burned down to about 15% enrichment, would be put in dry storage at site to cool for up to two years before being returned to the factory.

In March 2010, Hyperion (as the company then was) notified the US Nuclear Regulatory Commission that it planned to submit a design certification application in 2012. The company said then that it has many expressions of interest for ordering units. In September 2010, the company signed an agreement with Savannah River Nuclear Solutions to possibly build a demonstration unit at the Department of Energy site there. Hyperion planned to build a prototype by 2015, possibly with uranium oxide fuel if the nitride were not then available. In March 2012 the US DOE signed an agreement with Hyperion regarding constructing a demonstration unit at its Savannah River site in South Carolina.

In 2014 two papers on nuclear marine propulsion were published arising from a major international industry project led by Lloyd's Register. They describe a preliminary concept design study for a 155,000 dwt Suezmax tanker that is based on a conventional hull form with a 70 MW Gen4 Energy power module for propulsion.

In March 2012 Hyperion Power Generation changed its name to Gen4 Energy, and the name of its reactor to Gen4 Module (G4M). It pitched its design for remote sites having smaller power requirements.

Westinghouse LFR

The Westinghouse Lead-cooled Fast Reactor (LFR) programme originated from an investigation performed in 2015 aimed at identifying the technology that would best support addressing the challenges of nuclear power, for global deployment. It is at the conceptual design stage for up to 450 MWe as a modular pool-type unit, simple, scalable and with passive safety. It will have flexible output to complement intermittent renewable feed to the grid. Its high temperature – eventually 650°C – capabilities will allow industrial heat applications. Westinghouse expects it to be very competitive, having low capital and construction costs with enhanced safety. Further operational and safety enhancements are also achieved by adoption of a fuel/cladding combination with high temperature capability based on those under development by Westinghouse in the accident tolerant fuel programme.

In February 2017 the company signed an agreement with the Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA) and Ansaldo Nucleare to develop the design. The development also involves several UK companies and initial licensing is envisaged with the UK Office for Nuclear Regulation (ONR). A prototype LFR will be about 300 MWe, running at 500°C.

Beyond base-load electricity generation, the high-temperature operation of the LFR will allow for effective load-following capability enabled by an innovative thermal energy storage system, as well as delivery of process heat for industrial applications and water desalination.

Encapsulated Nuclear Heat-Source

The Encapsulated Nuclear Heat-Source (ENHS) is a liquid metal-cooled reactor concept of 50 MWe being developed by the University of California, Berkeley. The core is at the bottom of a metal-filled module sitting in a large pool of secondary molten metal coolant which also accommodates the eight separate and unconnected steam generators. There is convection circulation of primary coolant within the module and of secondary coolant outside it. Outside the secondary pool the plant is air-cooled. Control rods would need to be adjusted every year or so and load-following would be automatic. The whole reactor sits in a 17 metre deep silo. Fuel is a uranium-zirconium alloy with 13% enrichment (or U-Pu-Zr with 11% Pu) with a 15-20 year life. After this the module is removed, stored on site until the primary lead (or Pb-Bi) coolant solidifies, and it would

then be shipped as a self-contained and shielded item. A new fuelled module would be supplied complete with primary coolant. The ENHS is designed for developing countries and is highly proliferation-resistant but is not yet close to commercialisation.

STAR-LM, STAR-H2, SSTAR

The Secure Transportable Autonomous Reactor (STAR) project at Argonne National Laboratory was developing small, multi-purpose systems that operate nearly autonomously for the very long term. The STAR-LM is a factory-fabricated fast neutron modular reactor design cooled by lead-bismuth eutectic, with passive safety features. Its 300-400 MWt size means it can be shipped by rail. It uses uranium-transuranic nitride fuel in a 2.5 m diameter cartridge which is replaced every 15 years. Decay heat removal is by external air circulation. The STAR-LM was conceived for power generation with a capacity of about 175 MWe.

The STAR-H2 is an adaptation of the same reactor for hydrogen production, with reactor heat at up to 800°C being conveyed by a helium circuit to drive a separate thermochemical hydrogen production plant, while lower grade heat is harnessed for desalination (multi-stage flash process). Its development is further off.

A smaller STAR variant is the Small Sealed Transportable Autonomous Reactor (SSTAR) which was being developed by Lawrence Livermore, Argonne and Los Alamos National Laboratories in collaboration with others including Toshiba. It has lead or Pb-Bi cooling, 564°C core outlet temperature and has integral steam generator inside the sealed unit, which would be installed below ground level. Conceived in sizes 10-100 MWe, main development was focused on a 45 MWt/20 MWe version as part of the US Generation IV effort. After a 20- or 30-year life without refuelling, the whole reactor unit is then returned for recycling the fuel. The reactor vessel is 12 metres high and 3.2 m diameter and the core one metre high and 1.2 m diameter (20 MWe version). SSTAR would eventually be coupled to a Brayton cycle turbine using supercritical carbon dioxide with natural circulation to four heat exchangers. A prototype was envisaged for 2015, but development has apparently ceased.

LSPR

A lead-bismuth-eutectic (LBE) cooled fast reactor of 150 MWt/53 MWe, the LSPR (LBE-Cooled Long-Life Safe Simple Small Portable Proliferation-Resistant Reactor), is under development in Japan. Fuelled units would be supplied from a factory and operate for 30 years, then be returned. The concept is intended for developing countries.

SEALER

LeadCold Reactors (Blykalla Reaktorer) was founded in 2013 as a spin-off company from the Royal Institute of Technology (KTH) in Stockholm. It has a subsidiary in Canada. Its SEALER-3 (Swedish Advanced Lead Reactor) is a lead-cooled fast reactor designed with the smallest possible core that can achieve criticality in a fast spectrum using 20% enriched uranium oxide fuel. The basic reactor is 8 MWt, with a peak electric power of 3 MWe, leading to a core life of 30 full power years (at 90% availability with no refulelling) with coolant below 450°C to minimise corrosion. The company has developed novel aluminium-steel alloys that are highly corrosion-resistant in contact with liquid lead. The reactor vessel is designed to be small enough to permit transportation by aircraft.

As the regulatory framework for licensing of small reactors in Canada is better established than in most other countries, Nunavut and the Northwest Territories are likely to become the first markets for SEALER units. The Canadian Nuclear Safety Commission (CNSC) commenced phase 1 of a 15-month pre-licensing vendor design review in January 2017, but the review is now on hold at the vendor's request. In 2016 an Essel Group Middle East subsidiary agreed to invest in the Swedish-Canadian project, and in January 2017 a $200 million investment agreement was signed to license and construct "the world's first privately funded lead-cooled nuclear power plant." The funding will enable LeadCold to complete the pre-licensing review with the CNSC, complete a detailed engineering design of the reactor, carry out the R&D necessary for licensing the design in Canada, and construct a full-scale 3 MWe demonstration unit by about 2025. In April 2018 the company began collaboration on safety analysis with Netherlands-based NRG, which operates the Petten high-flux research reactor.

SEALER-5 is a 5 MWe reactor design. Replacing the standard uranium oxide fuel with uranium nitride (UN), the same core can host 40% more fissile material. This allows the core to operate at 40% higher thermal power for the same duration as SEALER-3, *i.e.* 30 years.

SEALER-10 is the waste management system. After 30 years of operation, the early SEALER units will be transported back to a centralised recycling facility. The plutonium and minor actinides present in the spent fuel will then be separated and converted into nitride fuel for reycle in a 10 MWe SEALER reactor. One such reactor will be sufficient to manage the used fuel of ten smaller SEALER units.

Chinese Hedianbao

A small research institute at Hefei, Anhui province in China is doing some conceptual work on a "portable nuclear battery pack" designed to fit inside a standard shipping container. The lead-cooled fast reactor would be able to generate 10 megawatts thermal, and is based on a Russian submarine reactor design.

Korean fast reactor designs

In South Korea, the Korea Atomic Energy Research Institute (KAERI) has been working on sodium-cooled fast reactor designs, but a second stream of fast reactor development there is via the Nuclear Transmutation Energy Research Centre of Korea (NuTrECK) at Seoul University (SNU). It is working on a lead-bismuth cooled design of 35 MW which would operate on pyro-processed fuel. It is designed to be leased for 20 years and operated without refuelling, then returned to the supplier. It would then be refuelled at the pyro-processing plant and have a design life of 60 years. It would operate at atmospheric pressure, eliminating major concern regarding loss of coolant accidents.

Molten salt reactors

These use molten fluoride salts as primary coolant, at low pressure. Lithium-beryllium fluoride and lithium fluoride salts remain liquid without pressurization up to 1400°C, in marked contrast to a PWR which operates at about 315°C under 150 atmospheres pressure. In most designs (not the AHTR, TMSR or Moltex) the fuel is dissolved in the primary coolant.

During the 1960s, the USA developed the molten salt breeder reactor concept as the primary back-up option for the fast breeder reactor (cooled by liquid metal) and a small prototype 8 MWt Molten Salt Reactor Experiment (MSRE) operated at Oak Ridge over four years to 1969 (the MSR programme ran 1957-1976). U-235 tetrafluoride enriched to 33% was in molten lithium, beryllium and zirconium fluorides at 860°C which flowed through a graphite moderator. A second campaign used U-233 fuel, but the program did not progress to building a MSR breeder utilising thorium. There is now renewed interest in the concept in Japan, Russia, China, France and the USA, and one of the six Generation IV designs selected for further development is the molten salt reactor (MSR).

In the normal MSR, the fuel is a molten mixture of lithium and beryllium fluoride (FLiBe) salts with dissolved enriched uranium – U-235 or U-233 fluorides (UF_4). The core consists of unclad graphite moderator arranged to allow the flow of salt at some 700°C and at low pressure. Much higher temperatures are possible but not yet tested. Heat is transferred to a secondary salt circuit and thence to steam[9]. The basic design is not a fast neutron reactor, but with some moderation by the graphite, may be epithermal (intermediate neutron speed) and breeding ratio is less than 1.

Thorium can be dissolved with the uranium in a single fluid MSR, known as a homogeneous design. Two-fluid, or heterogeneous MSRs would have fertile salt containing thorium in a second loop separate from the fuel salt containing fissile uranium and could operate as a breeder reactor (MSBR). In each case secondary coolant salt circuits are used.

The fission products dissolve in the fuel salt and may be removed continuously in an on-line reprocessing loop and replaced with fissile uranium or, potentially, Th-232 or U-238. Actinides remain in the reactor until they fission or are converted to higher actinides which do so.

The liquid fuel has a negative temperature coefficient of reactivity and a strong negative void coefficient of reactivity, giving passive safety. If the fuel temperature increases, the reactivity decreases. The MSR thus has a significant load-following capability where reduced heat abstraction through the boiler tubes leads to increased coolant temperature, or greater heat removal reduces coolant temperature and increases reactivity. Primary reactivity control is using the secondary coolant salt pump or circulation which changes the temperature of the fuel salt in the core, thus altering reactivity due to its strong negative reactivity coefficient. The MSR works at near atmospheric pressure, eliminating the risk of explosive release of volatile radioactive materials.

Other attractive features of the MSR fuel cycle include: the high-level waste comprising fission products only, hence shorter-lived radioactivity (actinides are less-readily formed from U-233 than in fuel with atomic mass greater than 235); small inventory of weapons-fissile material (Pu-242 being the dominant Pu isotope); high temperature operation giving greater thermal efficiency; high burn-up of fuel and hence low fuel use (the French self-breeding variant claims 50kg of thorium and 50kg U-238 per billion kWh); and safety due to passive cooling up to any size. Several have freeze plugs so that the primary salt can be drained by gravity into dump tanks configured to prevent criticality. Control rods are actually shut-down rods.

Lithium used in the primary salt must be fairly pure Li-7, since Li-6 produces tritium when fissioned by neutrons. Li-7 has a very small neutron cross section. This means that natural lithium must be enriched, and is costly. Pure Li-7 is not generally used in secondary coolant salts. But even with enriched Li-7, some tritium is produced and must be retained and recovered.

The MSR concept is being pursued in the Generation IV programme with two variants: one a fast neutron reactor with fissile material dissolved in the circulation fuel salt, and with solid particle fuel in graphite and the salt functioning only as coolant.

MSRs would normally operate at much higher temperatures than LWRs – up to at least 700°C, and hence have potential for process heat. Molten fluoride salts (possibly simply cryolite – Na-Al fluoride) are a preferred interface fluid in a secondary circuit between the nuclear heat source and any chemical plant. The aluminium smelting industry provides substantial experience in managing them safely.

One MSR developer, Moltex, has put forward a molten salt heat storage concept (GridReserve) to enable the reactor to supplement intermittent renewables. When electricity demand is low, the heat from a 1000 MWe Stable Salt Reactor (SSR, see below) can be transferred to a nitrate salt held in storage tanks for up to eight hours, and later used to drive a turbine when demand rises. This heat storage technology is already used with concentrated solar power (CSP) but isn't suitable for conventional nuclear reactors, which produce heat at around 300°C; however, the SSR outlet temperature of about 600°C is high enough to be used with this system.

See also Molten Salt Reactors information paper for more detail of the designs described below.

Liquid Fluoride Thorium Reactor (LFTR)

The Liquid Fluoride Thorium Reactor (LFTR) is a heterogeneous MSR design which breeds its U-233 fuel from a fertile blanket of of lithium-beryllium fluoride (FLiBe) salts with thorium fluoride. Some of the neutrons released during fission of the U-233 salt in the reactor core are absorbed by the thorium in the blanket salt. The resulting U-233 is separated from the blanket salt and in FLiBe becomes the liquid core fuel. LFTRs can rapidly change their power output, and hence be used for load-following.

Flibe LFTR

Flibe Energy in the USA is studying a 40 MW two-fluid graphite-moderated thermal reactor concept based on the 1960s-'70s US molten-salt reactor programme. It uses lithium fluoride/beryllium fluoride (FLiBe) salt as its primary coolant in both circuits. Fuel is uranium-233 bred from thorium in FLiBe blanket salt. Fuel salt circulates through graphite logs. Secondary loop coolant salt is sodium-beryllium fluoride (BeF_2-NaF). A 2 MWt pilot plant is envisaged, and eventually 600 MWt/250 MWe commercial plants.

Thorium Molten Salt Reactor (TMSR)

China is building a 5 MWe thorium-breeding molten-salt reactor (Th-MSR or TMSR), essentially an LFTR, with 2020 target for operation at the Shanghai Institute of Nuclear Applied Physics (SINAP). It has low-enriched TRISO fuel as pebble bed, and FLiBe coolant. China claims to have the world's largest national effort on these and hopes to obtain full intellectual property rights on the technology. The US Department of Energy is collaborating with the China Academy of Sciences on the programme, which had a start-up budget of $350 million. The target date for TMSR deployment is 2032. See also US AHTR section below and information paper on China's Nuclear Fuel Cycle.

Fuji MSR

The Fuji MSR is a graphite-moderated design to operate as a near-breeder with ThF_4-UF_4 fuel salt and FLiBe coolant at 700°C. It can consume plutonium and actinides, and be from 100 to 1000 MWe. It is being being developed internationally by a Japanese, Russian and US consortium: the International Thorium Molten Salt Forum (ITMSF) based in Japan. Several variants have been designed, including a 10 MWe mini Fuji. Thorium Tech Solutions (TTS) plans to commercialise the Fuji concept, and is working on it with the Halden test reactor in Norway.

AHTR/FHR

Research on molten salt coolant has been revived at Oak Ridge National Laboratory ORNL) in the USA with the Advanced High-Temperature Reactor (AHTR).[16] This is a larger reactor using a coated-particle graphite-matrix TRISO fuel like that in the GT-MHR (see above section on the GT-MHR) and with molten fluoride (FLiBe) salt as primary coolant. While similar to the gas-cooled HTR it operates at low pressure (less than 1 atmosphere) and higher temperature, and gives better heat transfer than helium. The FLiBe salt is used solely as primary coolant, and achieves temperatures of 750-1000°C or more while at low pressure. This could be used in thermochemical hydrogen manufacture.

A 5 MW thorium-fuelled prototype is under construction at Shanghai Institute of Nuclear Applied Physics (SINAP, under the China Academy of Sciences) originally with 2015 target for operation, now 2020. This is also known as the fluoride salt-cooled high-temperature reactor (FHR). A 100 MWt demonstration pebble-bed plant with open fuel cycle is planned by about 2025. SINAP sees this design having potential for higher temperatures than MSRs with fuel salt.

A small version of the AHTR/FHR is the SmAHTR, with 125 MWt thermal size matched to early process heat markets, or producing 50+ MWe. Operating temperature is 700°C with FLiBe primary coolant and three integral heat exchangers. It is truck transportable, being 9m long and 3.5m diameter. Fuel is 19.75% enriched uranium in TRISO particles in graphite blocks or fuel plates. Refuelling interval is 2.5 to 4 years depending on fuel configuration. Secondary coolant is FLiNaK to Brayton cycle, and for passive decay heat removal, separate auxiliary loops go to air-cooled radiators. Later versions are intended to reach 850° to 1000°C, using materials yet to be developed.

In the USA a consortium including UC Berkeley, ORNL and Westinghouse is designing a 100 MWe pebble-bed FHR, with annular core. It is designed for modular construction, and from 100 MWe base-load it is able to deliver 240 MWe with gas co-firing for peak loads. Fuel pebbles are 30 mm diameter, much less than gas-cooled HTRs. The PB-FHR has negative void reactivity and passive decay heat removal.

Reactor sizes of 1500 MWe/3600 MWt are envisaged, with capital costs estimated at less than $1000/kW.

Integral MSR

Canada-based Terrestrial Energy set up in 2013 has designed the Integral MSR (IMSR). This simplified MSR integrates the primary reactor components, including primary heat exchangers to secondary clean salt circuit, in a sealed and replaceable core vessel that has a projected life of seven years. The IMSR will operate at 600-700°C, which can support many industrial process heat applications. The moderator is a hexagonal arrangement of graphite elements. The fuel-salt is a eutectic of low-enriched uranium fuel (UF_4) and a fluoride carrier salt at atmospheric pressure. Secondary loop coolant salt is ZrF_4-KF. Emergency cooling and residual

heat removal are passive. Each plant would have space for two reactors, allowing seven-year changeover, with the used unit removed for offsite reprocessing when it has cooled and fission products have decayed. Terrestrial Energy hopes to commission its first commercial reactor by the 2020s.

The IMSR is scalable and three sizes were initially presented: 80 MWt, 300 MWt, and 600 MWt, ranging from 30 to 300 MWe, but from 2016 the company is focused on 400 MWt/192 MWe. The total levelized cost of electricity from the largest is projected to be competitive with natural gas. The smallest is designed for off-grid, remote power applications, and as prototype. Industrial heat at 600°C is also envisaged in 2016 plans.

Compared with other MSR designs, the company deliberately avoids using thorium-based fuels or any form of breeding, due to "their additional technical and regulatory complexities."

In November 2017 Terrestrial Energy completed phase 1 of the Canadian Nuclear Safety Commission's (CNSC's) pre-licensing vendor review of the IMSR-400. The company plans to submit either an application seeking design certification or a construction permit application for the IMSR-400 no later than October 2019 to the NRC. It hopes to commission its first commercial reactor in the 2020s.

In February 2019 the project progressed to stage 2 of site evaluation by Canadian Nuclear Laboratories – a separate process to licensing – in relation to possibly siting a commercial plant at Chalk River by 2026.

In January 2015 the company announced a collaborative agreement with US Oak Ridge National Laboratory (ORNL) to advance the design over about two years, and in May a similar agreement with the Dalton Nuclear Institute in the UK. In March 2017 the company entered into a contract with the University of New Brunswick for validation and verification work for the IMSR. The company has applied for a US loan guarantee of up to $1200 million to support financing of a project to licence, construct and commission the first US IMSR, a 190 MWe commercial facility.

Terrestrial Energy reviewed four potential US sites for the reactor, including one at the Idaho National Laboratory (INL), and an agreement was signed with Energy Northwest in March 2018 for the first IMSR to be built here. The other three sites are located east of the Mississippi.

Transatomic Power TAP

Transatomic Power Corp is a US company partly funded by Founders Fund and aiming to develop a single-fluid MSR using very low-enriched uranium fuel (1.8%) or the entire actinide component of used LWR fuel. The TAP reactor has an efficient zirconium hydride moderator and a LiF-based fuel salt bearing the UF_4 and actinides, hence a very compact core. The secondary coolant is FLiNaK salt to a steam generator. The neutron flux is greater than with graphite moderator, and therefore contributes strongly to actinide burning. Fission products are mostly removed batch-wise and fresh fuel added. Decay heat removal can be by convection.

After a 20 MWt demonstration reactor, the envisaged first commercial plant would be 1250 MWt/550 MWe running at 44% thermal efficiency with 650°C in the primary loop, using a steam cycle. The company had to withdraw some exaggerated claims concerning actinide burn-up made in *MIT Technology Review* in 2016. In September 2018 the company announced that it would cease operations and make its intellectual property freely available online.

ThorCon

Martingale in the USA is designing the ThorCon MSR, which is a 250 MWe scaled-up Oak Ridge MSRE. It is a single-fluid thorium converter reactor in the thermal spectrum, graphite moderated. It uses a combination of U-233 from thorium and low-enriched U-235 (19.7% enriched) from mined uranium. Fuel salt is sodium-beryllium fluoride (BeF_2-NaF) with dissolved uranium and thorium tetrafluorides (Li-7 fluoride is avoided for cost reasons). Secondary loop coolant salt is also sodium-beryllium fluoride. It operates at 700°C. There is no online processing – this takes place in a centralized plant at the end of the core life – with off-gassing of some fission products meanwhile.

Several 550 MWt, 250 MWe modules would comprise a power station. Each module contains two replaceable reactors in sealed 'cans'. Each can contains a reactor 'pot', a primary heat exchanger and a primary loop pump. Each can is 11.6m high, 7.3m diameter and weighs 360 tonnes. The cans sit in silos below grade (30 m down). Below each is a 32-cylinder fuel salt drain tank, under a freeze valve.

At any one time, just one of the cans of each module is producing power. The other can is in cool-down mode. Every four years the can that has been cooling is removed and replaced with a new can. The fuel salt is transferred to the new can, and the can that has been operating goes into cool-down mode. In October 2015 Martingale signed an agreement with three Indonesian companies to commission a ThorCon plant there in 2021.

Moltex SSR

Moltex Energy's Stable Salt Reactor (SSR) is a conceptual UK MSR reactor design that relies on convection from static vertical fuel tubes in the core to convey heat to the reactor coolant. Because the nuclear material is contained in fuel assemblies, standard industrial pumps can be used for the low radioactivity coolant salt. Core temperature is 500-600°C, at atmospheric pressure. Decay heat is removed by natural air convection.

Fuel tubes three-quarters filled with the molten fuel salt are grouped into fuel assemblies which are similar to those used in standard reactors, and use similar structural materials. The fuel salt is about 60% NaCl, 20% $PuCl_2$, 20% UCl_3, with almost any level of actinide & lanthanide trichlorides mixed in depending on the spent oxide fuel used in reprocessing – about 16% fissile overall. The individual fuel tubes are vented so that noble fission product gases escape into the coolant salt, which is a ZrF_4-KF-NaF mixture, the radionuclide accumulation of which is managed. Iodine and caesium stay dissolved in the fuel salt. Other fission product gases condense on the upper fuel tube walls and fall back into the fuel mixture before they can escape into the coolant. The fuel assemblies can be moved laterally without removing them. Refuelling is thus continuous online, and after the fuel is sufficiently burned up the depleted assemblies are stored at one side of the pool for a month to cool, then lifted out so that the salt freezes. Reprocessing is straightforward, and any level of lanthanides can be handled.

SSR factory-produced modules are 150 MWe containing fuel, pumps, primary heat exchanger, control blades and instrumentation. Several, up to gigawatt-scale, can share a reactor tank, half-filled with the coolant salt which transfers heat away from the fuel assemblies to the peripheral steam generators, essentially by convection, at atmospheric pressure. Two versions were promoted in late 2018: SSR-W and, about two years behind developmentally, the SSR-U.

The SSR-W is simplest and cheapest, due to compact core and no moderator. The primary fissile fuel in this original fast reactor version is plutonium-239 chloride with minor actinides and lanthanides, recovered from LWR fuel or from an SSR-U reactor. Coolant salt is ZrF_4-NaF-KF stabilised with ZrF_2, and maximum temperature of 650°C. A 300 MWe demonstration plant was envisaged, the SSR-W300 wasteburner. However, a limited market for this version is anticipated. An agreement has been signed with New Brunswick Power for initial deployment at Point Lepreau in Canada, and a Canadian Nuclear Safety Commission pre-licensing vendor design review has commenced.

The company then announced the physically larger and more expensive SSR-U 'global workhorse version' of its design, with a thermal neutron spectrum running on LEU fluorides (up to 7% enriched) with graphite built into the fuel assemblies, which increases the size of the core. It runs at a higher temperature than the fast version – minimum 600°C – with ZrF_4-NaF coolant salt stabilised with ZrF_2. It is designed to be compatible with thorium breeding to U-233. It is seen as having a much larger potential market, and initial deployment in the UK in the 2030s is anticipated, with potential for replacing CCGT and coal plants.

In the thorium breeder version of SSR-U, thorium would be in the coolant salt and the U-233 produced is progressively dissolved in bismuth at the bottom of the salt pool. This contains U-238 to denature it and ensure there is never a proliferation risk. Once the desired level of U-233 is achieved (under 20%), the bismuth with uranium is taken out batch-wise, and the mixed-isotope uranium is chlorinated to become fuel. If the fuel is used in a fast reactor, plutonium and actinides can be added.

Moltex has also put forward its GridReserve molten nitrate salt heat storage concept to enable the reactor to supplement intermittent renewables.

Molten Chloride Fast Reactor

Southern Company Services in the USA is developing the Molten Chloride Fast Reactor (MCFR) with TerraPower, Oak Ridge National Laboratory (ORNL) – which hosts the work – the Electric Power Research Institute (EPRI) and Vanderbilt University. No details are available except that fuel is in the salt, and there is

nothing in the core except the fuel salt. As a fast reactor it can burn U-238, actinides and thorium as well as used light water reactor fuel, requiring no enrichment apart from initial fuel load (these details from TerraPower, not Southern). It is reported to be large. The only other reactors using chloride salts are the Elysium MCSFR and Moltex SSR.

In January 2016 the US DOE awarded a Gateway for Accelerated Innovation in Nuclear (GAIN) grant to the project, worth up to $40 million. In August 2016 Southern Nuclear Operating Company signed an agreement to work with X-energy to collaborate on development and commercialization of their respective small reactor designs. With TerraPower and ORNL, X-energy is designing the Xe-100 pebble-bed HTR of 48 MWe.

Elysium MCSFR

Elysium Industries in the USA and Canada has the Molten Chloride Salt Fast Reactor (MCSFR) design with fuel in the chloride salt. It operates below grade at near atmospheric pressure and uses no water near the fuel salt. It is designed to load-follow. A range of sizes from 110 to 2700 MWt are under consideration. Used fuel from light water reactors or depleted uranium with some plutonium can fuel it. Selected fission products are removed online. Passive safety includes a freeze plug. It has negative temperature and void coefficients.

MOSART

Russia's Molten Salt Actinide Recycler and Transmuter (MOSART) is a larger fast reactor fuelled only by transuranic (TRU) fluorides from uranium and MOX LWR used fuel. The 2400 MWt design has a homogeneous core of Li-Na-Be or Li-Be fluorides without graphite moderator.

See also information paper on Molten Salt Reactors.

Seaborg Waste Burner – SWaB

Seaborg Technologies in Denmark (founded 2015) has a thermal-epithermal single fluid reactor design for 50 MWt pilot unit with a view to 250 MWt commercial modular units fuelled by spent LWR fuel and thorium. Fuel salt is Li-7 fluoride with thorium, plutonium and minor actinides as fluorides. This is pumped through the graphite column core and heat exchanger. Fission products are extracted on-line. Secondary coolant salt is FLiNaK, at 700°C. Spent LWR fuel would have the uranium extracted for recycle, leaving Pu and minor actinides to become part of the MSR fuel, with thorium. The company claims very fast power ramp time.

In March 2017 the public funding agency Innovation Fund Denmark made a grant to Seaborg to "build up central elements in its long-term strategy and position itself for additional investments required to progress towards commercial maturity." This is the first Danish investment into nuclear fission research since the country introduced a ban on nuclear power in 1985.

Aqueous homogeneous reactors

Aqueous homogeneous reactors (AHRs) have the fuel mixed with the moderator as a liquid. Typically, low-enriched uranium nitrate is in aqueous solution. About 30 AHRs have been built as research reactors and have the advantage of being self-regulating and having the fission products continuously removed from the circulating fuel. A 1 MWt AHR operated in the Netherlands 1974-77 using Th-HEU MOX fuel. Further detail is in the Research Reactors paper.

A theoretical exercise published in 2006 showed that the smallest possible thermal fission reactor would be a spherical aqueous homogenous one powered by a solution of Am-242m$(NO_3)_3$ in water. Its mass would be 4.95 kg, with 0.7 kg of Am-242m nuclear fuel, and diameter 19 cm. Power output would be a few kilowatts. Possible applications are space program and portable high-intensity neutron source. The small size would make it easily shielded.

Heatpipe reactors

Westinghouse eVinci

Distinct from other small reactor designs, the eVinci is a heatpipe reactor, using a fluid in numerous sealed horizontal steel heatpipes to conduct heat from the hot fuel (where the fluid vapourises) to the external condenser (where the fluid releases latent heat of vapourisation) with heat exchanger. No pumps are needed to effect continuous isothermal vapour/liquid internal flow at low pressure. The principle is well established on a small scale, but here a liquid metal is used as the fluid and reactor sizes up to several megawatts are envisaged. Experimental work on heatpipe reactors for space has been with much smaller units (about 100 kWe), using sodium as the fluid. They have been developed since 1994 as a robust and low technical risk system for space exploration with an emphasis on high reliability and safety.

The eVinci reactors would be fully factory built and fuelled. As well as power generation, process heat to 600°C would be available. Units would have five- to ten-year operational lifetime, with walk-away safety due to inherent feedback diminishing the nuclear reaction with excess heat, also effecting load-following.

Others

LEADIR-PS100

This is a new design from Northern Nuclear Industries in Canada, combining a number of features in unique combination. The 100 MWt, 36 MWe reactor has a graphite moderator, TRISO fuel in pebbles, lead (Pb-208) as primary coolant, all as integral pool-type arrangement at near atmospheric pressure. It delivers steam at 370°C, and is also envisaged as an industrial heat plant. The coolant circulates by natural convection. The fuel pebbles are in four cells, each with graphite reflectors, and capacity can be increased by adding cells. Shutdown rods are similar to those in CANDU reactors. Passive decay heat removal is by air convection. The company presents it as a Gen IV design

Modular construction using small reactor units

Westinghouse and IRIS partners have outlined the economic case for modular construction of their IRIS design (about 330 MWe), and the argument applies similarly to other similar or smaller units. They pointed out that IRIS with its size and simple design is ideally suited for modular construction in the sense of progressively building a large power plant with multiple small operating units. The economy of scale is replaced here with the economy of serial production of many small and simple components and prefabricated sections. They expected that construction of the first IRIS unit would be completed in three years, with subsequent reduction to only two years.

Site layouts have been developed with multiple single units or multiple twin units. In each case, units will be constructed so that there is physical separation sufficient to allow construction of the next unit while the previous one is operating and generating revenue. In spite of this separation, the plant footprint can be very compact so that a site with, for instance, three IRIS single modules providing 1000 MWe capacity would be similar or smaller in size than one with a comparable total power single unit.

Many small reactors are designed with a view to serial construction and collective operation as modules of a large plant. In this sense they are 'small modular reactors' – SMRs – but not all small reactors are of this kind (e.g. the Toshiba 4S), though the term SMR tends to be used loosely for all small designs.

Eventually plants comprising a number of SMRs are expected to have a capital cost and production cost comparable with larger plants. But any small unit such as this will potentially have a funding profile and flexibility otherwise impossible with larger plants. As one module is finished and starts producing electricity, it will generate positive cash flow for the next module to be built. Westinghouse estimated that 1000 MWe delivered by three IRIS units built at three year intervals financed at 10% for ten years require a maximum negative cash flow less than $700 million (compared with about three times that for a single 1000 MWe unit). For developed countries, small modular units offer the opportunity of building as necessary; for developing countries it may be the only option, because their electric grids cannot take 1000+ MWe single units.

Notes & references

Notes

a. In USA, UK, France, Russia, China, and India, mostly using high-enriched fuel. Reactors built as neutron sources are not designed to produce heat or steam, and are less relevant here. [Back]

b. A very general rule is that no single unit should be larger than 15% of grid capacity [Back]

c. Traditional reactor safety systems are 'active' in the sense that they involve electrical or mechanical operation on command. Some engineered systems operate passively, *e.g.* pressure relief valves. Both require parallel redundant systems. Inherent or full passive safety depends only on physical phenomena such as convection, gravity or resistance to high temperatures, not on functioning of engineered components. Because small reactors have a higher surface area to volume (and core heat) ratio compared with large units, a lot of the engineering for safety (including heat removal in large reactors) is not needed in the small ones. [Back]

d. In 2010, the American Nuclear Society convened a special committee to look at licensing issues with SMRs in the USA, where dozens of land-based small reactors were built since the 1950s through to the 1980s, proving the safety and security of light water-cooled, gas-cooled, and metal-cooled SMR technologies. The committee had considerable involvement from SMR proponents, along with the Nuclear Regulatory Commission, Department of Energy laboratories and universities – a total of nearly 50 individuals. The committee's interim report[1] includes the following two tables, which highlight some of the differences between the established US reactor fleet and SMRs.

Comparison of current-generation plant safety systems to potential SMR design

Current-generation safety-related systems	SMR safety systems
High-pressure injection system. Low-pressure injection system.	No active safety injection system required. Core cooling is maintained using passive systems.
Emergency sump and associated net positive suction head (NPSH) requirements for safety-related pumps.	No safety-related pumps for accident mitigation; therefore, no need for sumps and protection of their suction supply.
Emergency diesel generators.	Passive design does not require emergency alternating-current (AC) power to maintain core cooling. Core heat removed by heat transfer through vessel.
Active containment heat systems.	None required because of passive heat rejection out of containment.
Containment spray system.	Spray systems are not required to reduce steam pressure or to remove radioiodine from containment.
Emergency core cooling system (ECCS) initiation, instrumentation and control (I&C) systems. Complex systems require significant amount of online testing that contributes to plant unreliability and challenges of safety systems with inadvertent initiations.	Simpler and/or passive safety systems require less testing and are not as prone to inadvertent initiation.
Emergency feedwater system, condensate storage tanks, and associated emergency cooling water supplies.	Ability to remove core heat without an emergency feedwater system is a significant safety enhancement.

Comparison of current-generation plant support systems to potential SMR design

Current LWR support systems	SMR support systems
Reactor coolant pump seals. Leakage of seals has been a safety concern. Seal maintenance and replacement are costly and time-consuming.	Integral designs eliminate the need for seals.
Ultimate heat sink and associated interfacing systems. River and seawater systems are active systems, subject to loss of function from such causes as extreme weather conditions and bio-fouling.	SMR designs are passive and reject heat by conduction and convection. Heat rejection to an external water heat sink is not required.
Closed cooling water systems are required to support safety- related systems for heat removal of core and equipment heat.	No closed cooling water systems are required for safety-related systems.
Heating, ventilating, and air-conditioning (HVAC). Required to function to support proper operation of safety -related systems.	The plant design minimizes or eliminates the need for safety-related room cooling eliminating both the HVAC system and associated closed water cooling systems.

Some of the early (1950s-1980) small power reactors were developed so as to provide an autonomous power source (ie not requiring continual fuel delivery) in remote areas. The USA produced eight such experimental reactors 0.3 to 3 MWe, deployed in Alaska, Greenland and Antarctica. The USSR produced about 20, of many kinds, and one (Gamma) still operates at the Kurchatov Institute. Another is the Belarus Pamir, mentioned in the HTR section above. [Back]

e. The first two-unit VBER-300 plant was planned to be built in Aktau city, western Kazakhstan, with completion of the first unit originally envisaged in 2016, and 2017 for the second. The Kazakhstan-Russian Nuclear Stations joint stock company (JSC) was established by Kazatomprom and Atomstroyexport (on a 50:50 basis) in October 2006 for the design, construction and international marketing of the VBER-300. See page on the VBER-300 on the Kazatomprom website (www.kazatomprom.kz) [Back]

f. The 200 MWt (50 MWe net) Melekess VK-50 prototype BWR in Dimitrovgrad, Ulyanovsk commenced operation in 1965. [Back]

g. Central Argentina de Elementos Modulares (CAREM). See the Invap website (www.invap.com.ar). [Back]

h. The page on the NHR-5 on the website of Tsingua University's Institute of Nuclear Energy Technology (now the Institute of Nuclear and New Energy Technology, www.inet.tsinghua.edu.cn) describes the NHR-5 as "a vessel type light water reactor with advanced features, including integral arrangement, natural circulation, hydraulic control rod driving and passive safety systems. Many experiments have been conducted on the NHR-5, such as heat-electricity cogeneration, air-conditioning and seawater desalination." [Back]

i. See the page on Modular Nuclear Reactors on the Babcock & Wilcox website (www.babcock.com). [Back]

j. The 69 fuel assemblies are identical to normal PWR ones, but at about 1.7 m long, a bit less than half the length. [Back]

k. Between 1966 and 1988, the **AVR** (Arbeitsgemeinschaft VersuchsReaktor) experimental pebble bed reactor at Jülich, Germany, operated for over 750 weeks at 15 MWe, most of the time with thorium-based fuel (mixed with high-enriched uranium). The fuel consisted of about 100,000 billiard ball-sized fuel elements. Maximum burn-ups of 150 GWd/t were achieved. It was used to demonstrate the inherent safety of the design due to negative temperature coefficient: reactor power fell rapidly when helium coolant flow was cut off.

The 300 MWe **THTR** (Thorium HochTemperatur Reaktor) in Germany was developed from the AVR and operated between 1983 and 1989 with 674,000 pebbles, over half containing Th/HEU fuel (the rest graphite moderator and some neutron absorbers). These were continuously recycled and on average the fuel passed six times through the core. Fuel fabrication was on an industrial scale. The reactor was shut down for sociopolitical reasons, not because of technical difficulties, and the basic concept with inherent safety features of HTRs was again proven. It drove a steam turbine.

The 200 MWt (72 MWe) **HTR-modul** was then designed by Siemens/Interatom as a modular unit to be constructed in pairs, with a core height three times its diameter, allowing passive cooling for removal of decay heat, eliminating the need for emergency core cooling systems. It was licensed in 1989, but was not constructed. This design was part of the technology bought by Eskom in 1996 and is a direct antecedent of the pebble bed modular reactor (PBMR).

During 1970s and 1980s Nukem manufactured more than 250,000 fuel elements for the AVR and more than one million for the THTR. In 2007, Nukem reported that it had recovered the expertise for this and was making it available as industry support.

In addition to these pebble bed designs, the 20 MWt Dragon reactor ran in UK 1964-75, the 115 MWt Peach Bottom reactor in USA ran 1966-74, and 8432 MWt Fort St Vrain ran 1976-89 - all with prismatic fuel, and the last two supplying power commercially. In the USA the Modular High-Temperature Gas-cooled reactor (MHTGR) design was developed by General Atomics in the 1980s, with inherent safety features, but the DOE project ended in 1993. [Back]

l. The 80 MWt ALLEGRO demonstration GFR is planned by Euratom to incorporate all the architecture and the main materials and components foreseen for the full-sized GFR but without the direct (Brayton) cycle power conversion system. It is being developed in a French-led project, and operation about 2025 is envisaged. [Back]

m. The Hyperion Power Module was originally designed by Los Alamos National Laboratory as a 70 MWt 'nuclear battery' that uses uranium hydride (UH3) fuel, which also functions as a moderator. UH3 stores vast quantities of hydrogen, but this stored hydrogen dissociates as the temperature rises above the operating temperature of 550°C. The release of hydrogen gas lowers the density of the UH3, which in turn decreases reactivity. This process is reversed as the core temperature drops, leading to the reabsorption of hydrogen. The consequent increase in moderator density results in an increase in core reactivity[11]. All this is without much temperature change since the main energy gain or loss is involved in phase change. [Back]

n. In October 2010, GEH announced it was exploring the possibility with Savannah River Nuclear Solutions of building a prototype PRISM reactor at the Department of Energy's Savannah River Site.

o. As MSRs will normally operate at much higher temperatures than LWRs, they have potential for process heat. Another option is to have a secondary helium coolant in order to generate power via the Brayton cycle. [Back]

p. Most Air Cooled Condenser (ACC) technology has a limitation in that the tubes carrying the steam must be made of carbon steel which severely limits the service life of the ACC. Holtec has developed an ACC with stainless steel tubes bonded to aluminum fins and thus with much longer service life. [Back]

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Postscript/Appendix

Some of the developments described in this paper are fascinating and exciting. Nevertheless it is salutary to keep in mind the words of the main US pioneer in nuclear reactor development. Admiral Hyman Rickover in 1953 – about the time his first test reactor in the USA started up – commented on the differences between an "academic reactor" and a "practical reactor". See: http://en.wikiquote.org/wiki/Hyman_G._Rickover for the full quote:

An academic reactor or reactor plant almost always has the following basic characteristics: (1) It is simple. (2) It is small. (3) It is cheap. (4) It is light. (5) It can be built very quickly. (6) It is very flexible in purpose. (7) Very little development will be required. It will use mostly 'off-the-shelf' components. (8) The reactor is in the study phase. It is not being built now.

On the other hand a practical reactor can be distinguished by the following characteristics: (1) It is being built now. (2) It is behind schedule. (3) It is requiring an immense amount of development on apparently trivial items. (4) It is very expensive. (5) It takes a long time to build because of the engineering development problems. (6) It is large. (7) It is heavy. (8) It is complicated.

The tools of the academic-reactor designer are a piece of paper and a pencil with an eraser. If a mistake is made, it can always be erased and changed. If the practical-reactor designer errs, he wears the mistake around his neck; it cannot be erased. Everyone can see it.