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Small Nuclear Power Reactors

(Updated March 2023)

- **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 and accumulating over 12,000 reactor years of experience.

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 information page 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.

Small modular reactors (SMRs) are defined as nuclear reactors generally 300 MWe 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. PWR types may have integral steam generators, in which case the reactor pressure vessel needs to be larger, limiting portability from factory to site. Hence many larger PWRs such as the Rolls-Royce UK SMR have external steam generators.

This information page 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 page. Some of the designs described here are not yet actually taking shape, others are operating or under construction. 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.

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.

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[18] 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[c]. 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[d]. 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[17] 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.

In 2020 the IAEA published an update of its SMR book, Advances in Small Modular Reactor Technology Developments, with contributions from developers covering over 70 designs.

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 of high-assay low-enriched uranium (HALEU) 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." In 2019 the DOE contracted with Centrus Energy to deploy a cascade of large centrifuges to produce HALEU fuel for advanced reactors. Urenco USA has announced its readiness to supply HALEU from a dedicated production line at its New Mexico plant.

US support for SMRs ✚

UK support for SMRs ✚

Canadian support for SMRs ✚

Chinese support for SMRs ✚

Other countries ✚

Military developments of small power reactors from 1950s ✚

Temperatures of small reactors ✚

Light water reactors ✚

Heavy water reactors ✚

High-temperature gas-cooled reactors ✚

Fast neutron reactors ✚

Molten salt reactors ✚

Aqueous homogeneous reactors ✚

Heatpipe microreactors ✚

Others ✚

Modular construction using small reactor units ✚

Notes & references ✚

Postscript/Appendix ✚