Small Modular Reactors - Status and Prospects for Australia

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There is a developing interest in SMRs (Small Modular Reactors) to provide electricity generation and other services to remote areas, industry and small grid systems. This article reviews recent developments and their possible applications in Australia. – Editors' Note: This article includes information about a commercial product related to the author's business activities. While we would normally separate commercial from non-commercial content in Australian Physics, we believe in this case that there is no conflict of interest. We are interested in exploring topics around energy supply, generation, and sustainability, as well as advances in energy research. This article serves as a starting point, and we welcome additions to the conversation.

In 1956, Calder Hall in the United Kingdom was the world's first commercial nuclear power station. With a unit electrical output of 50 MWe(1), it would be considered today as a small reactor. Following the construction of Calder Hall and small prototype reactors in the USA, economy of scale rapidly drove increases in size. By the 1960s a unit size of 500 MWe was common, and in the 1970s the unit size had increased to over 1,000 MWe. Reactors under construction today include the US Westinghouse AP-1000 (1,200 MWe), Korean APR-1400 (1,400 MWe) and the French AREVA EPR (1,750 MWe) ( ). These reactors are safe and reliable, but their unit electrical output is too large for small grid systems because an unexpected shutdown of a large scale reactor could cause a large drop in the system frequency which could jeopardise power supply for a significant portion of the grid. There is a rule of thumb that the largest single unit should not be more than 15% of the total generation. For example, the largest single electricity generating unit on the Australian east coast National Electricity Market (NEM) is the 750 MWe Kogan Creek power station in Brigalow, Queensland, which constitutes 15% of the approximately 5,000 MW minimum demand in Queensland [1]. The other issue is that the big reactors are very expensive to construct. The estimated cost of the two AP-1000s under construction in the USA is US$15b and the two EPRs in the UK could cost $25b. Securing finance for these projects is difficult.

(1) MWe is the electrical output of the power plant expressed as megawatts of power.

These challenges have led to a developing interest in SMRs, defined by the IAEA as reactors with a power output of less than 300 MWe, but more usually much smaller than this [2]. Small reactors have been employed in scenarios where reliability is essential, such as nuclear powered submarines and icebreakers for 60 years [3]. These reactors are usually Pressurised Water Reactors (PWRs) using light water as moderator and coolant. The primary circuit operates at around 15 MPa and removes the heat from the reactor core, whereby the pressure ensures that the water in the primary circuit, at temperatures up to 340 °C, does not boil. The primary circuit water passes through a steam generator where the heat is transferred to a secondary circuit operating at around 7 MPa supplying steam to a turbine generator to produce electrical power. In a large PWR, the reactor vessel, steam generators, pressuriser and coolant pumps are all separate large components housed in a concrete/steel containment. For example, the containment for the AP-1000 measures 43 m in diameter and 62 m high.

When designing an SMR, simply reducing the size of all the components would result in a high cost per unit output, because a number of small components costs more to manufacture than one large component. This is overcome by an innovative design that wraps the steam generator around the core inside the reactor vessel - thus making it an integrated PWR - and the complete reactor module can be delivered to site on the back of a truck.

Points of advantage

There are several advantages that make small modular reactors attractive:

• Since they are small, it is easier to design a high level of passive or inherent safety, because there is less nuclear material to be cooled in the reactor;

• the reactor vessel can be installed underground providing protection against external hazards (e.g. hurricanes, aircraft crashes) and unauthorised interference;

• constructing the module in a factory reduces on-site construction time (typically a major problem for large reactors), and quality control is better;

• the initial capital cost is lower and modules can be added as demand increases;

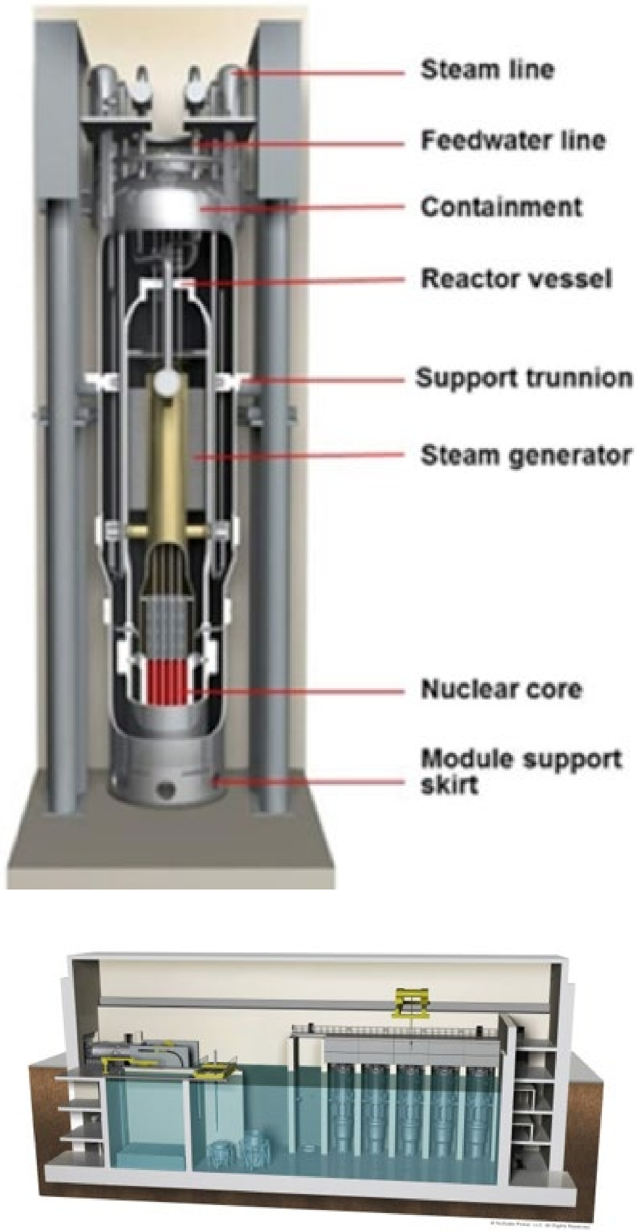
• when one module is shut down for refuelling, the remaining modules are still producing power;

• SMRs can be multipurpose producing process heat in addition to electricity.

An example of a small modular reactor in an advanced stage of development is the 60 MWe USA NuScale SMR [4]. This reactor has a natural circulation primary circuit with integral steam generators and pressuriser. The factory produced NuScale Power Module (NPM) consists of the reactor vessel inside a steel containment vessel and is directly connected to its own conventional steam turbine-generator. Each NPM is installed below ground in a 6 m wide bay in a seismically designed, steel lined concrete pool filled with demineralised water. The pool enables the reactors to be passively cooled indefinitely without the need for external electrical or water supplies, thus improving safety.

For the safety of a nuclear reactor, the Core Damage Frequency (CDF) is a useful figure of merit. It is defined as "The probability per year of the loss of a facility's structural integrity or melting of a significant fraction of the nuclear fuel accompanied by loss of effectiveness of the nuclear fuel cladding barrier" [5]. For existing reactors this is typically 10-4 - 10-6/yr, whereas for SMRs the CDF is a few orders of magnitude lower (e.g., 5 x 10-9/yr).

A power plant based on NPMs could house up to 12 modules in the water pool, giving it a gross output of 720 MWe. This would be sufficient to supply over half a million homes with electricity. Interestingly, the plant would occupy only a small footprint (18 ha) and the turbine condensers could be air cooled, so the site does not need to be close to water reservoirs such as the coast or large lakes. This opens opportunities for a distributed system of power sources, thus bringing power generators closer to where they are needed, for example industrial facilities. Also, SMR-based power plants can be designed to load-follow, thus enabling them to be used in a power system where renewable energy sources play a significant role.



NuScale Power Module (US NRC) [top panel] and reactor building [bottom panel]. (Images courtesy of NuScale Power)

The NuScale SMR is currently going through the licensing process with the US Nuclear Regulatory Commission, and in 2018 it agreed that:

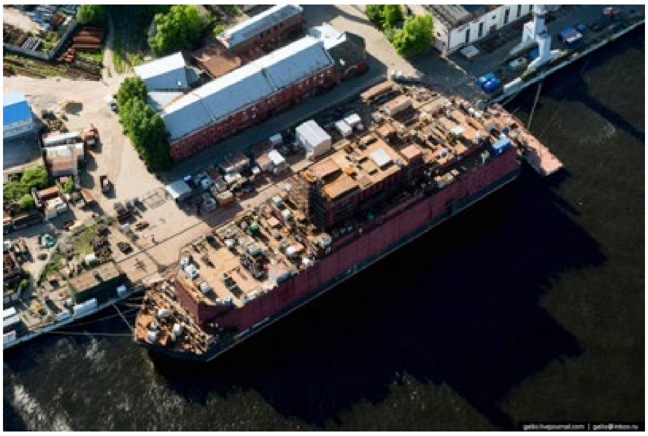
• The SMR does not need any emergency (class 1E) [6] electrical supplies because reactor cooling is achieved without any electrical supplies. This is the first power reactor to achieve this.

• The emergency planning zone (EPZ), normally 10 miles around a nuclear power plant in the USA, can be scaled back for SMRs to reflect their reduced CDF and hence reduced risks. For the NuScale SMR this would be the site boundary.

Utah Associated Municipal Power Systems, a community owned organisation supplying electricity to the US mid-west will be the first NuScale customer. An area has been agreed within the US Department of Energy Idaho National Laboratory site, and the first module is expected to be operating in 2026.

SMRs under construction

Russia has used nuclear powered icebreakers for many years, and in 2007, a project was started to install two KLT-40S 35 MWe icebreaker reactors on a non-powered barge to provide floating power for remote areas in Russia. Construction was completed in 2018 at the Baltic shipyard, St Petersburg.



Barge (140m long x 30m wide, 21,000 tonnes displacement) with 2 x 35 MWe SMRs under construction in St Petersburg. (Image courtesy of Rosatom)

In April 2018, the barge was towed from St Petersburg, through the Baltic and North seas to Murmansk in Northern Russia where the reactors are being loaded with fuel. First deployment in 2019 will be at Pevek, the most northern city in Russia, where power is needed particularly for mining companies in this remote region.

(2) MWTh is the thermal output of the reactor in MW of heat.

Floating SMRs are also developed in China to supply off-shore oil rigs. Further, in China, a Very High Temperature Gas Reactor demonstration plant is nearing completion. Here, two helium cooled 250 MWTh (2) modules will supply one 211 MWe steam turbine. Operating at reactor temperatures in excess of 750oC, this type of reactor could be used to supply process heat for many industrial processes, including hydrogen production.

In Argentina, the 32 MWe CAREM modular reactor is currently under construction by CNEA/INVAP. This reactor is scheduled to be operating in late 2021. Indeed, Australia has its own relationship with these companies as they designed and built the OPAL research reactor at the Australian Nuclear Science and Technology Organisation (ANSTO).

Nuclear Power in Australia?

Small modular reactors have solicited a positive response from the Nuclear Fuel Cycle Royal Commission (South Australia, 2016), which found in its final report: "*The smaller capacity of SMRs makes them attractive to integration in smaller electricity markets such as the NEM in South Australia*"; and:"*The lifecycle emissions for nuclear power plants are in the range of solar PV and wind*" [7]. The Commission also recommended that the existing legal prohibitions on construction of a nuclear power plant in Australia be removed. At present, there are legislative provisions prohibiting nuclear power included in the Environmental Protection and Biodiversity Conservation Act (EPBC 1999 S.140A) and the Australian Radiation Protection and Nuclear Safety Act (ARPANS 1998 S.10). These provisions were introduced mainly in a response to the 1986 Chernobyl accident, whilst before that time there was an appreciation of the part that nuclear power can play in the reduction of greenhouse gas emissions. It is also interesting to note that low-carbon energy grids have so far usually only been possible using nuclear power, with the exception of countries that use extensive hydro resources [8]. This reference is a useful resource for looking at current emissions and energy transfers between countries worldwide, and between states in Australia.

In terms of considering nuclear power for Australia, much of the framework and infrastructure required for a nuclear power program already exists. Australia is a signatory to all the nuclear conventions including the Non-Proliferation Treaty, and Australia has long been active in nuclear science, technology and research through

ANSTO. In 2017, Australia accepted an invitation to join the *Generation IV* International Forum, which is co-ordinating the research effort for advanced reactors. This invitation was due to ANSTO's world-leading capabilities in advanced nuclear materials. Australia also has a strong nuclear safeguards organisation, the Australian Safeguards and Non-Proliferation Office (ASNO) and an independent nuclear regulator, the Australian Radiation Protection And Nuclear Safety Agency (ARPANSA).

There would be scope for SMRs in Australia as they would provide diversity and reliable electricity generation and could load-follow to work in tandem with renewable energy sources. Small modular reactors would make a vital contribution to the reduction of greenhouse gas emissions from fossil-fuel based electricity generation and provide a pathway to reductions in other sectors, particularly transport and process heat for industry. SMRs could be placed close to the consumer, such as large industrial sites. They could also bring on board new industries, and, conversely, Australian innovation could drive new developments for domestic and international markets. Further, we could play a key role in helping other countries in the region with addressing energy security challenges and reducing carbon emissions.

Education

Finally, education is an important part of preparing for a nuclear power program, and there are a number of activities and initiatives to have a conversation on the topic. For example, the University of New South Wales has been offering a Master of Engineering Science (Nuclear Engineering) course from 2013, and the University of Sydney includes a guest lecture on nuclear fundamentals in their Energy and the Environment course. Also, the Australian National University Master of Nuclear Science course was established in 2007 which covers a broader range of nuclear topics for Australian government officials and foreign students. There are also new nuclear facilities being built across south east Asia and the aim is to train students, both from Asia and Australia, to work in these facilities. Further, members of Engineers Australia are active in raising public awareness of nuclear issues via Rotary and Probus talks and public lectures, thus engaging at a broader level.

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About the author

Tony Irwin (FIEAUST MIET FAIE CPEng) is a Chartered Engineer, Technical Director of SMR Nuclear Technology Pty Ltd and Chair of Engineers Australia Sydney Division Nuclear Engineering Panel. Tony worked for British Energy in the UK for more than thirty years commissioning and operating 8 nuclear power reactors. In 1999, he moved to Australia and joined the Australian Nuclear Science and Technology Organisation (ANSTO) where he managed fuel strategies and provided advice on nuclear issues to the Federal Government. He was subsequently appointed as the first Reactor Manager of ANSTO's new OPAL research reactor. Tony is now a Consultant. He is an Honorary Associate Professor and principal lecturer for the ANU Master of Nuclear Science Course Reactor and Fuel Cycle modules.