AN INTRODUCTION TO SMALL MODULAR REACTORS (SMRs)

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Tony Irwin
Technical Director
SMR Nuclear Technology Pty Ltd

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Background

Nuclear power plants have been generating reliable baseload electricity with low greenhouse gas emissions since the 1950s. Currently there are 433 power reactors operating in 31 countries supplying ~14% of the world's total electricity demand. Modern power reactors typically have an output of >1,000MW electrical which is too large for small countries or small grid systems.

A market is developing for smaller reactors – in particular for Small Modular Reactors (SMRs) which can supply low emissions, high capacity factor, reliable power in remote locations or for small grid systems. They represent a new stage in nuclear reactor design and have the capacity to provide an economically competitive method of electrical power generation.

The designs of SMRs will enable:

- Factory produced modules, ensuring economies of scale and potentially eliminating the major up front capital costs of nuclear reactors;
- Passive safety systems to provide enhanced security;
- Reduced requirements for technical workforces to install and maintain nuclear power plants; and
- A wider range of deployment options, including remote locations and for specific-purpose energy generation, such as desalination plants.

SMR technology is an option for low emissions electricity generation in Australia.

Evolution of nuclear power: bigger was more economical

Historically, nuclear power plants have been built larger and larger. This trend was an attempt to obtain economies of scale in deployment to overcome the high fixed construction costs. As a consequence, modern nuclear power plants incurred substantial financial costs and required large, well connected electricity grids.

The first commercial nuclear power plant connected to the grid was Calder Hall in 1956 located in the northwest coast of England. It had an output of 40 MWe (enough electricity to supply 20,000 households). By the 1970s, nuclear power generators were commonly producing an output of 900 MWeN (net electrical output). In France, the standard unit had an output of 900 MWeN units and increased to 1300 MWeN in the late 1980s and, finally, 1450 MWeN in the 1990s. Currently, a 1650 MWeN Evolutionary Pressurised Water Reactor (EPR) is being built at Flammanville in France, which will supply the electricity demands of more than 800,000 homes.

Nuclear power stations of this magnitude are suited to areas with large local electricity demands or countries where there are large interconnected grid systems enabling large power transfers. In Europe for example there is an extensive grid system enabling transfers between countries to meet demand.

There is a rule of thumb that an individual generating unit should not exceed 15 per cent of the grid capacity. This enables the grid to remain stable on the loss of the largest generating unit.

For many countries, and for isolated remote locations, current unit sizes are too large, and a market is emerging worldwide for SMRs. This new form of nuclear power plant is particularly suitable for remote locations and a market with relatively small electricity demand, like Australia. The capital cost advantage per kW installed capacity of larger reactors may soon be offset by modular factory built construction reducing the capital cost per kW installed capacity of SMRs.

Historically, the main driver for a country adopting nuclear power for electricity generation has been energy security. Many countries (e.g. France, Germany and Japan) turned to nuclear power in the 1970s when the cost of oil quadrupled. Whilst energy security is still a major consideration, climate change is also emerging as a new driver for nuclear power, due to its near zero greenhouse gas emissions.

The future of nuclear power stations: Small Modular Reactors (SMRs)

The International Atomic Energy Agency (IAEA) defines “small” as less than 300 MWe but many SMRs have outputs in the range 25-100 MWe. Depending on the technology, many SMRs designs can incorporate the following features:

- Provide power in remote locations where transport of fossil fuels for conventional electricity generating plant is expensive.
- Provide baseload power for small grids
- Near zero emissions
- Compact - small site area per kW installed capacity, reduced siting costs
- Modules can be easily added as extra capacity is required
- Electricity, steam and co-generation
- Balance of plant equipment is conventional off-the-shelf steam turbine/alternator, pumps and electrical system
- Turbine condenser that can be aircooled in remote locations where water supplies are restricted
- Reliable, high capacity factor, not affected by weather conditions
- Compact factory built transportable module
- Economy and high QA of factory mass production of a simple, standard design
- Main modules are factory built, minimising on-site construction time/ costs and reducing the probability of project delays
- Simple design to operate and maintain (low maintenance costs for passive systems)
- High level of passive or inherent safety
- Reactor modules can be delivered with the fuel already installed, eliminating the need for initial fuel loading on site
- Long periods between refuelling (can be 8-10 years, up to 30 years for some designs)

- Sealed core which is returned to the factory for refuelling, reducing the possibility of unauthorised interference with nuclear materials (proliferation resistant)
- Low and stable fuel costs (fossil fuel costs, particularly gas are expected to continue to rise)
- Fuel costs typically only 25 per cent of the production costs
- Smaller initial capital investment compared to a large reactor
- Sixty year life
- Reactor containment can be installed below ground providing protection against external hazards and unauthorised interference

The possible uses for small modular reactor in Australia include powering Australian Defence Force sites, remote mining locations, large industrial sites requiring reliable, competitive cost electricity or process heat supplies, desalination plants, water treatment plants, recycling schemes or irrigation systems and baseload electricity supply for small grid systems.

A major advantage of SMRs is their passive safety. No electrical supplies or pumps are required to cool the reactor, as this is achieved by natural convection and gravity coolant feed. This feature ensures the reactor will remain safe under severe accident conditions. This also reduces the capital and maintenance costs compared to large power reactors and fundamentally changes the economic equation in favour of SMR nuclear power generation.

There is extensive experience of much of the technology employed by SMRs. For many years they have been the power supply for submarines and icebreakers, where totally reliable power with long periods between refuelling is essential. However, their commercial deployment has yet to be proven.

SMRs can be classified into three main types depending on the technology employed:

1. Light water reactors
2. Fast neutron reactors
3. High temperature gas reactors

1. Light Water Reactors

Key features of Small Modular Light Water Reactors:

- Most common power reactor type, proven technology, extensive experience;
- Uses cheap demineralised water as the primary coolant
- Natural or pumped coolant circulation and passive back-up systems for safety
- Coupled to standard turbine/generator as used in fossil fuelled plant

The majority (90%) of nuclear reactors worldwide are known as Light Water Reactors because they use water as the primary coolant.

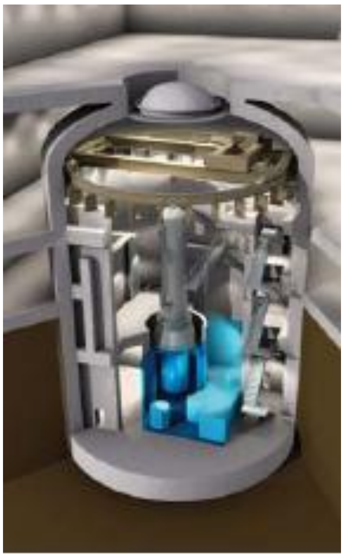
The most common power reactor type worldwide is the Pressurised Water Reactor (PWR), a type of light water reactor, originally based on the US naval reactor used for submarines. In a PWR, the primary coolant water is kept under sufficient pressure to prevent it from boiling, and the heat extracted from the nuclear fuel is transferred to a secondary water circuit in a heat exchanger where steam is produced to drive a turbine.

Fuel assemblies are similar to existing designs for large power reactors so there is no major development required. PWR technology has been licensed for more than 50 years so that the design certification process for a PWR SMR should be quicker than that for a more advanced innovative design.

Examples of Light Water SMRs based on this technology:

Babcock & Wilcox mPower reactor

B&W has over 50 years experience in manufacturing compact PWRs with long core life for the US navy.



125 MWe Integral PWR

- Reactor pressure vessel containing core and steam generators
- Complete module 4.5m in diameter and 23m high
- Factory built, rail shippable
- 36 months construction
- Secure underground containment
- Simple passive safety
- Air cooled condenser for remote locations

Source: Babcock&Wilcox Nuclear Energy Systems, Inc

Initial B&W mPower integral modular reactor design

B&W mPower reactor vessel with integral steam generator

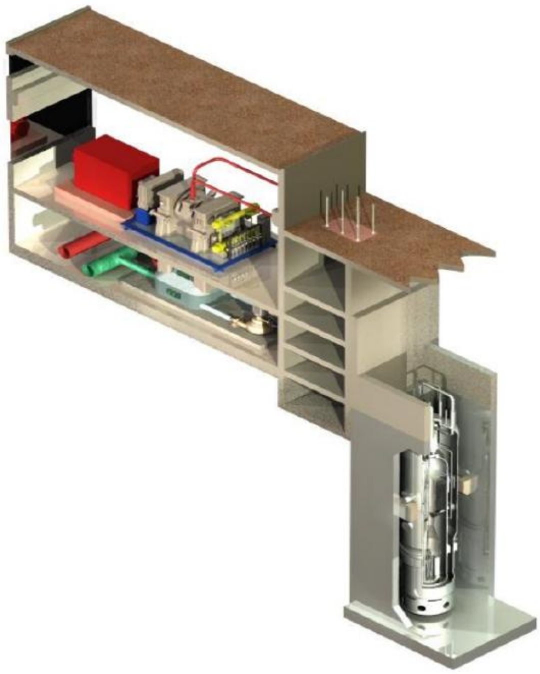
- Reactor pressure vessel 3.6m in diameter and 22m high
- Standard PWR fuel assemblies
- 4+ year operating cycle
- passive decay heat removal
- 60 year life

Source: Babcock & Wilcox Nuclear Energy Systems, Inc

B&W constructed a test facility at the Centre for Advanced Engineering and Research (CAER) in Virginia to evaluate the design and performance. This facility reached full reactor operating temperature and pressure conditions in 2012. Design Certification application expected early 2013.

Nuscale Power

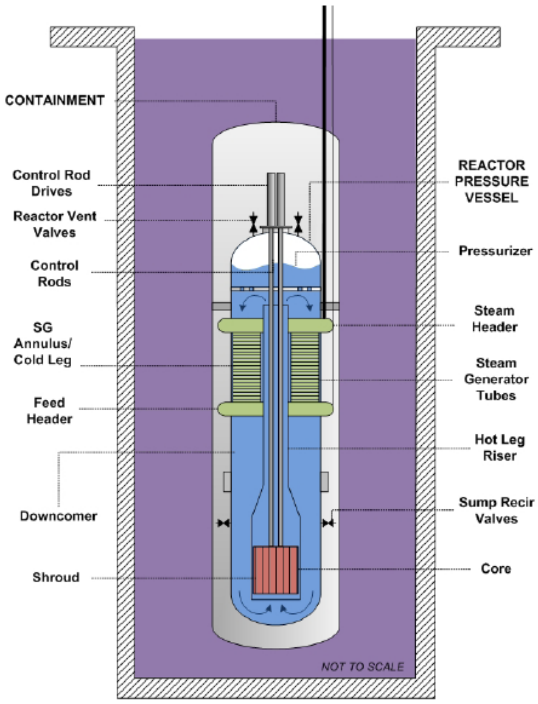
The technology for this small PWR originated in the US Department of Energy and was further developed by Oregon State University. It is now being commercially developed by NuScale Power Company.



NuScale Power Module

- 150 MWTh PWR
- 45 MWe electrical output
- Modules can be combined for required electrical output
- 24 month refuelling cycle

Source: www.nuscalepower.com



Reactor module

- Containment 4.4m diameter, 19.8m high, weight 450Te
- Reactor pressure vessel 2.7m diameter, 13.7m high
- Two independent integral steam generator bundles, helical tubes
- Primary coolant natural circulation 12.7 MPa
- 1.8m long PWR fuel assemblies

Source: www.nuscalepower.com

Other light water SMRs include:

Westinghouse SMR – 800 MWTh/225 MWe PWR with passive safety features. Integral steam generator. Reactor vessel 3.5m in diameter and 25m high, installed below ground level. Application for US design certification is expected soon.

South Korea SMART (System Integrated Modular Advanced Reactor) – 330 MWTh/100 MWe PWR with integral steam generators designed by the Korea Atomic Energy Research Institute (KAERI). Three year refuelling cycle and 60 year life. Standard Design Approval granted July 2012.

Argentina CAREM – 100 MWTh, 27 MWe PWR with integral steam generators designed by INVAP (the designer of ANSTO's 20 MWTh OPAL research reactor). Primary cooling by natural circulation.

France AREVA NP-300 – for power, heat or desalination based on the French nuclear submarine design, with passive safety systems. 50 – 250 MWe.

Russia Akademik Lomonosov – two KLT-40S reactors normally used to power icebreakers are being installed on a 20,000 Te barge to provide floating nuclear power for remote areas.

2. Fast Neutron Reactors

Key features of Small Modular Fast Neutron Reactors

- Very compact design due to high conductivity liquid metal coolant
- Higher efficiency than light water reactors due to higher operating temperature
- Very long operating time between refuelling (up to 30 years)
- Inherent safety features

Unlike the thermal neutron PWR, where the water slows down (moderates) the neutrons produced in the fission process, a fast reactor has no moderator and is smaller, simpler and has better fuel performance.

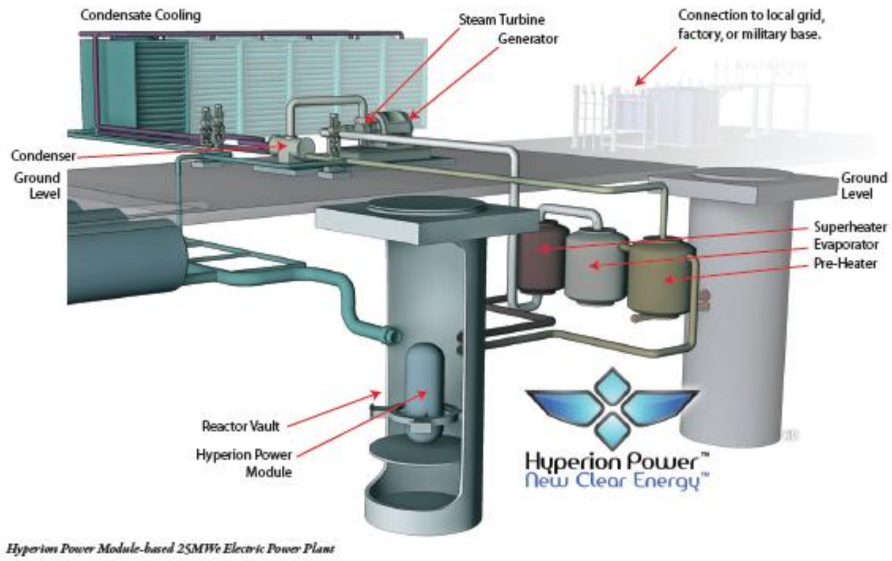
There is extensive experience of fast reactor technology dating back to the 1950s but new materials now available will enable the full potential of these systems to be realised. Fast reactors only require refuelling at very long intervals - up to 30 years. They operate at or near atmospheric pressure (this minimises plant stresses) and are inherently safe with a negative temperature coefficient which means, if the temperature rises, the nuclear reaction is slowed and the power reduces.

They are normally cooled by liquid metals with high conductivity and a high boiling point such as sodium, lead or lead-bismuth. Fast neutron SMRs have outlet temperatures of 500^{o}C, and hence improved thermal efficiency (compared to thermal reactors). This outlet temperature is also suitable for hydrogen production. They typically use natural convection primary cooling systems and have passive back-up cooling systems which mean that they do not rely on external power sources for safety.

Examples of fast reactor SMRs:

Gen4 Module

Originally designed by Los Alamos National Laboratory, USA, now being commercially developed by Gen4 Energy Inc (was Hyperion Power).
Power 70 MWTh, electrical output 25 MWe
Can also be configured for steam or co-generation
Containment vessel 1.5m wide and 2.5m high
Weight < 50 Te
Coolant lead-bismuth
Sealed core, operates for 10 years without refuelling, return to factory
Sited underground



Source: www.hyperionpowergeneration.com

Toshiba 4S (Super-Safe, Small & Simple)

Developed by Toshiba and the Central Research Institute of Electric Power Industry (CRIEPI) in Japan in collaboration with Westinghouse USA. 10 MWe or 50 MWe versions, sodium cooled, electromagnetic pumps, 550°C outlet temperature and passive safety features. Operates for 30 years without refuelling. The above ground turbine building occupies an area of 22m by 16m by 11m.

The first 4S SMR could be installed to provide electricity to the remote community of Galena in Alaska. The project started in 2004, and application for design certification is planned for 2012. Projected engineering, procurement and construction (EPC) cost is US$2,500/kW installed capacity, power cost is US$50-70/MWh.

SSTAR (Small Sealed Transportable Autonomous Reactor)

Developed by Lawrence Livermore, Argonne and Los Alamos National Laboratories in the USA. Factory fabricated, cooled by lead-bismuth with integral steam generator, 564°C outlet temperature. Sealed unit 3.2m diameter and 12m high installed below ground level. 30 year life without refuelling. Main development is of a 45 MWTh/20 MWe version.

3. Very High Temperature Gas Reactor (VHTR)

Key features of Small Modular Very High Temperature Gas Reactors

- Capable of operating at very high temperatures for hydrogen production or high efficiency (50%) electricity generation
- Proven fuel technology
- Inherent safety features due to fuel type and gas coolant

This technology also dates back to the 1960s and reactors were built and operated in the UK, Germany and the USA. The fuel is in the form of TRISO (tristructural isotropic) particles, <1mm diameter, combined with graphite and silicon carbide into pebbles or prisms and is stable to over 1600^{o}C. The preferred coolant gas is helium, with outlet temperatures up to 1,000^{o}C, enabling the reactor to be coupled to a Brayton cycle gas turbine/alternator with up to 50 per cent unit efficiency possible.

The VHTR is one of the six reactor types selected by the *Generation IV International Forum* in 2002 for future nuclear energy systems that would excel in safety, sustainability, cost-effectiveness and avoidance of misuse of nuclear materials (proliferation resistance). The VHTR is a US priority for the next generation reactors and fuel irradiation experiments and qualification of high temperature materials are in progress.

Examples of VHTRs:

HTTR (High Temperature Test Reactor)

Built by the Japan Atomic Energy Research Institute (JAERI), this 30 MWTh unit started operating in 1998. Based on the HTTR, JAERI is developing larger modules.

HTR-10 (China)

10 MWTh high temperature gas cooled experimental reactor at the Institute of Nuclear and New Energy Technology (INET), Tsinghua University, north of Beijing. Started operating in 2000 at 700^{o}C, potential to 900^{o}C. Construction of larger versions approved in principle.

PBMR (South Africa)

The Pebble Bed Modular Reactor (PBMR) was developed by ESKOM in South Africa based on the 1980s German designs. The project reached an advanced state before the South African government removed funding in 2010.

Major issues for deployment of SMRs in Australia

- Change of law to allow licensing and construction of a nuclear power reactor for electricity generation in Australia
- Changes in ARPANSA (the Australian Radiation Protection and Nuclear Safety Authority) or the establishment of a new nuclear regulator for licensing of nuclear power reactors
- Availability of a low-level radioactive waste facility in Australia
- Availability of SMRs with design certification and proven operating record
- Commitment of an electricity generation company, mining company or other organisation to an SMR program, and
- Identification of suitable sites.

Conclusions

Any reactor design would still have to be licensed by an Australian nuclear regulator, following the required change in Australian law to allow a power reactor to be built in Australia. However, if this occurred, new nuclear technologies coming on stream offer genuine options for Australia.

Small Modular Reactors are an option for electricity generation, process heat, and co-generation particularly for remote sites in Australia where transport of fossil fuel for conventional generating plant is expensive.

Light water SMRs could be US-certified by 2015.

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