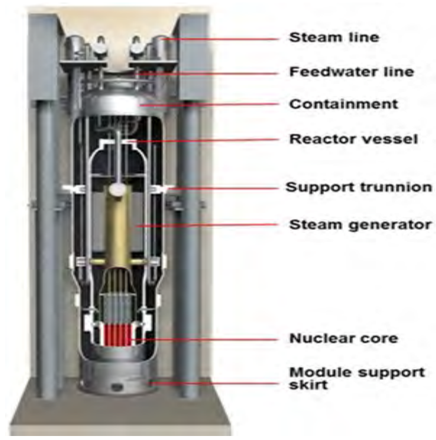
NUCLEAR – SMALL MODULAR REACTOR

DESCRIPTION

A Small Modular Reactors (SMR) is a nuclear power plant that is smaller in size (300 MW or less) than current generation base load plants (1,000 MW or higher). These smaller, compact designs are factory-fabricated reactors that can be transported by truck or rail to a nuclear power site.



The development of clean, affordable nuclear power options is a key element of the Department of Energy's (DOE) *Nuclear Energy Research and Development Roadmap.* To advance that strategy, DOE is seeking to accelerate the commercialization and deployment of SMR technologies.

SMRs offer the advantage of lower initial capital investment, scalability, and siting flexibility at locations unable to accommodate traditional larger reactors. SMRs also have the potential for enhanced safety and security.

The term "modular" in the context of SMRs refers to the ability to fabricate major components of the nuclear steam supply system in a factory environment and ship to the point of use. SMRs are envisioned to require limited on-site preparation and substantially reduce the lengthy construction times that are typical of larger nuclear power plants. SMRs provide simplicity of design, enhanced safety features, the economics and quality afforded by factory production, and more flexibility (financing, siting, sizing, and end-use applications) compared to larger nuclear power plants. Additional modules can be added incrementally as demand for energy increases.

CAPACITY FACTOR

Typical capacity factor for an SMR should be greater than 90%.

TIME TO PERMIT AND CONSTRUCT

The Nuclear Regulatory Commission (NRC) has not yet licensed an SMR design, so there are no firm estimates on how long it will be before this technology is available on the market. But NRC's goal is to reduce permitting time to 3 years, with construction estimated to be another 3 to 4 years. NRC is in pre-application discussions with several SMR proponents and anticipates receiving design certification applications over the next 2 to 3 years. Those currently working with NRC on SMR designs include NuScale Power, Babcock & Wilcox (mPower), Westinghouse and Holtec.

COST

Early construction costs estimates range between $4 million and $6 million/MW.

NOTES

The current NRC regulations for nuclear power were designed for conventional power plants. The unique nature of SMR operations, maintenance and security staffing requirements may require different regulations. Because of the need to resolve these issues, it could be 2018 before any license is issued for SMR technology in the United States.

DOE has created a SMR Licensing Technical Support program to promote the accelerated deployment of SMRs by supporting certification and licensing requirements for U.S.-based SMR projects through cooperative agreements with industry partners. The goal of the program is to support commercial operations of an SMR by 2022. The first agreement has been awarded to the mPower America team of Babcock & Wilcox, Tennessee Valley Authority and Bechtel, which expects to achieve commercial operation of its SMR by 2021.

STATUS OF SMALL AND MEDIUM SIZED REACTOR DESIGNS

A Supplement to the IAEA Advanced Reactors Information System (ARIS)

http://aris.iaea.org

IAEA
International Atomic Energy Agency

September 2012

INTRODUCTION

The ongoing interest in the development and deployment of reactors classified as small or medium sized is reflected in the number of small and medium sized reactors (SMRs) that operate or are under development and the numerous innovative concepts being investigated for electricity generation and for non-electrical applications. According to the classification adopted by the IAEA, small reactors are reactors with an equivalent electric power of less than 300 MW(e) and medium sized reactors are reactors with an equivalent electric power of between 300 and 700 MW(e). Worldwide, 131 SMR units are in operation in 26 Member States, with a capacity of 59 GWe. At present, 14 SMRs are under construction in 6 countries: Argentina, China, India, Pakistan, the Russian Federation and Slovakia. Research is being carried out on approximately 45 innovative SMR concepts for electricity generation and process heat production, desalination, hydrogen generation and other applications. SMRs are under development for all principal reactor lines: light water reactors (LWRs), heavy water reactors (HWRs), gas cooled reactors (GCRs) and liquid metal cooled reactors (LMCRs).

Small and medium sized LWRs are under development in Argentina, Brazil, France, Japan, the Republic of Korea, the Russian Federation and the United States of America. In Argentina, the Central Argentina de Elementos Modulares (CAREM) reactor, a small, integral type pressurized LWR design, with all primary components located inside the reactor vessel and an electrical output of 150–300 MW(e), is under development. Site excavation work for a 27 MW(e) CAREM prototype was completed at the end of August 2012 and construction has begun. In Japan, a 350 MW(e) integrated modular water reactor (IMR) suitable for a hybrid heat transport system with a natural circulation system is in the conceptual design stage. The System Integrated Modular Advanced Reactor (SMART) design from the Republic of Korea, which has a thermal capacity of 330 MW(th), is intended for sea water desalination and received standard design approval in 2012. In the Russian Federation, seven light water SMR designs are under development. The ABV-6M, with an electrical output of 8.6 MW(e), is a nuclear steam generating plant with an integral pressurized LWR with natural circulation of the primary coolant, and is in the detailed design stage. The RITM-200, an integral reactor with forced circulation for universal nuclear icebreakers, is designed to provide 8.6 MW(e). The VK-300 is a 250 MW(e) simplified boiling water reactor (BWR) that operates with natural circulation and employs passive residual heat removal systems (RHRSs). The VBER-300 is a 325 MW(e) pressurized water reactor (PWR) conceptual design that can serve as a power source for floating nuclear power plants. In addition, the Russian Federation is building two units of the KLT-40S series, to be mounted on a barge and used for cogeneration of process heat and electricity. The N.A. Dollezhal Research and Development Institute of Power Engineering (NIKIET) is designing the UNITHERM PWR, based on design experience in marine nuclear installations, and the SHELF PWR, a 6 MW(e) underwater, remotely operated power source.

In the USA, three integral pressurized water SMRs are under development: Babcock & Wilcox's mPower, NuScale and the Westinghouse SMR. The mPower design consists of two 180 MW(e) modules and its design certification application is expected to be submitted to the US Nuclear Regulatory Commission (NRC) in the fourth quarter of 2013. NuScale Power envisages a nuclear power plant made up of twelve 45 MW(e) modules and plans to apply for design certification to the NRC in 2013. The Westinghouse SMR is a conceptual design with an electrical output of 225 MW(e), incorporating passive safety systems and proven components of the AP1000. All three designs have submitted applications to the US Department of Energy for funding to support 'first of a kind' engineering, design certification and licensing [1]. Another effort comes from the IRIS International Consortium, which is designing the International Reactor Innovative and Secure (IRIS), an integral PWR design with an electrical capacity of 335 MW(e). The fixed bed nuclear reactor (FBNR) is a Brazilian conceptual design that does not require on-site refuelling. The Flexblue design under development in France is a small seabed nuclear power plant with an output of 160 MW(e).

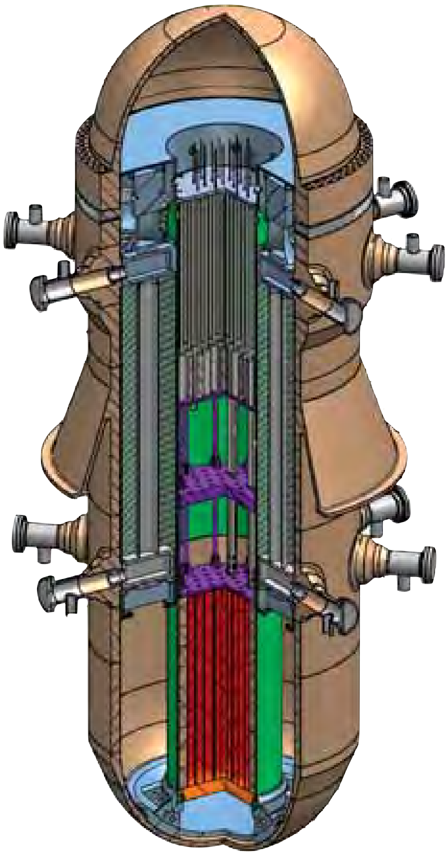
Heavy water SMRs are deployed in Argentina, Canada, China, India, the Republic of Korea, Pakistan and Romania. Canada has developed and deployed the Canada deuterium–uranium (CANDU) reactor series, which offers various power ratings. The Enhanced CANDU 6 (EC6) is an advanced design with a gross electrical capacity of 740 MW(e) that is based on the CANDU 6 design. In India, several HWRs, ranging in size from 220 to 540 to 700 MW(e), are under construction or in operation. The 304 MW(e) advanced heavy water reactor (AHWR300-LEU) design incorporates vertical pressure tubes, low enriched uranium and thorium fuel, and passive safety features; it is currently in the basic design phase.

With regard to GCRs, several designs in the SMR classification are under development in China, South Africa and the USA. China has developed, constructed and operated the HTR-10, an experimental pebble bed helium cooled high temperature reactor (HTR). As a follow-up plant, in April 2011, China began construction of the HTR pebble bed module (HTR-PM) consisting of two 250 MW(th) modules. In South Africa, the pebble bed modular reactor (PBMR) conceptual design is a high temperature gas cooled reactor (HTGR) with an electrical output of 165 MW(e). In the USA, the 150 MW(e) gas turbine modular helium reactor (GT-MHR) is a conceptual design that has the potential to produce hydrogen by high temperature electrolysis or thermochemical water splitting. Finally, the energy multiplier module (EM2) design is an effort to utilize used nuclear fuel without conventional reprocessing.

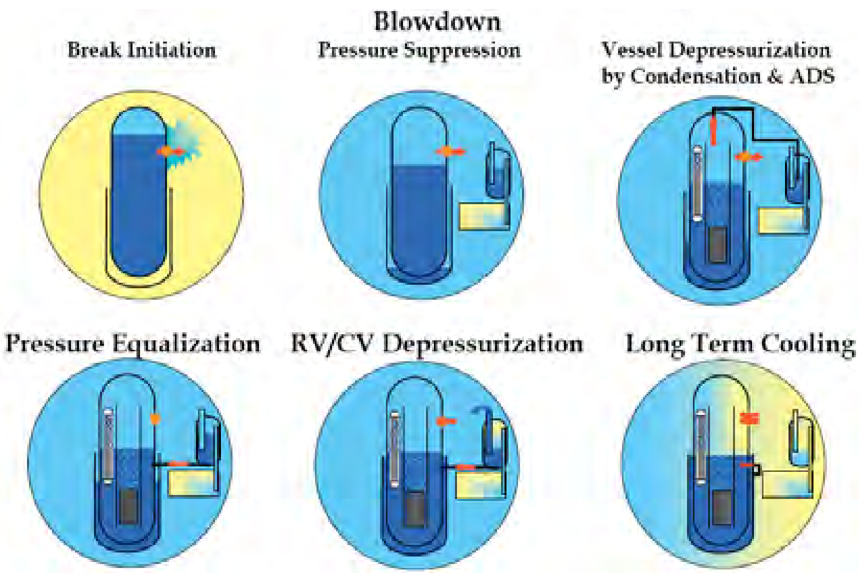
A number of liquid metal cooled SMRs have been designed and operated in China, France, India, Japan, the Russian Federation and the USA. The China Experimental Fast Reactor (CEFR), a sodium cooled 20 MW(e) experimental fast reactor with PuO_2–UO_2 fuel, is currently in operation and was connected to the grid in 2011. India is building the 500 MW(e) Prototype Fast Breeder Reactor (PFBR), which is expected to be commissioned in 2013. Japan has developed the Super-Safe, Small and Simple (4S) reactor, designed to provide 10–50 MW(e), as a very small nuclear reactor design that can be located in a sealed, cylindrical vault underground, with the building above the ground. The Russian Federation's 300 MW(e) design BREST-OD-300 is a lead cooled fast reactor that uses a two circuit heat transport system to deliver heat to a supercritical steam turbine. The Russian Federation has also developed and plans to construct several SVBR-100 units, a small fast reactor with lead–bismuth eutectic alloy as the coolant and a power output of 100 MW(e). Finally, in the USA, the Power Reactor Innovative Small Module (PRISM), a 155 MW(e) liquid metal cooled fast breeder reactor, has been developed and a design control document is currently being drafted to plan the licensing process. The Gen4 Module (G4M) design with an electrical power output of 25 MW(e) is in the conceptual design stage.

This booklet provides a two page description of the given SMR designs. The first page provides a brief technical summary with the main reactor parameters and the second page provides a description of the reactor and its various systems. The predictions of core damage frequencies (CDFs), seismic design and detailed plant and reactor parameters are provided by the design organizations without validation or verification by the IAEA.

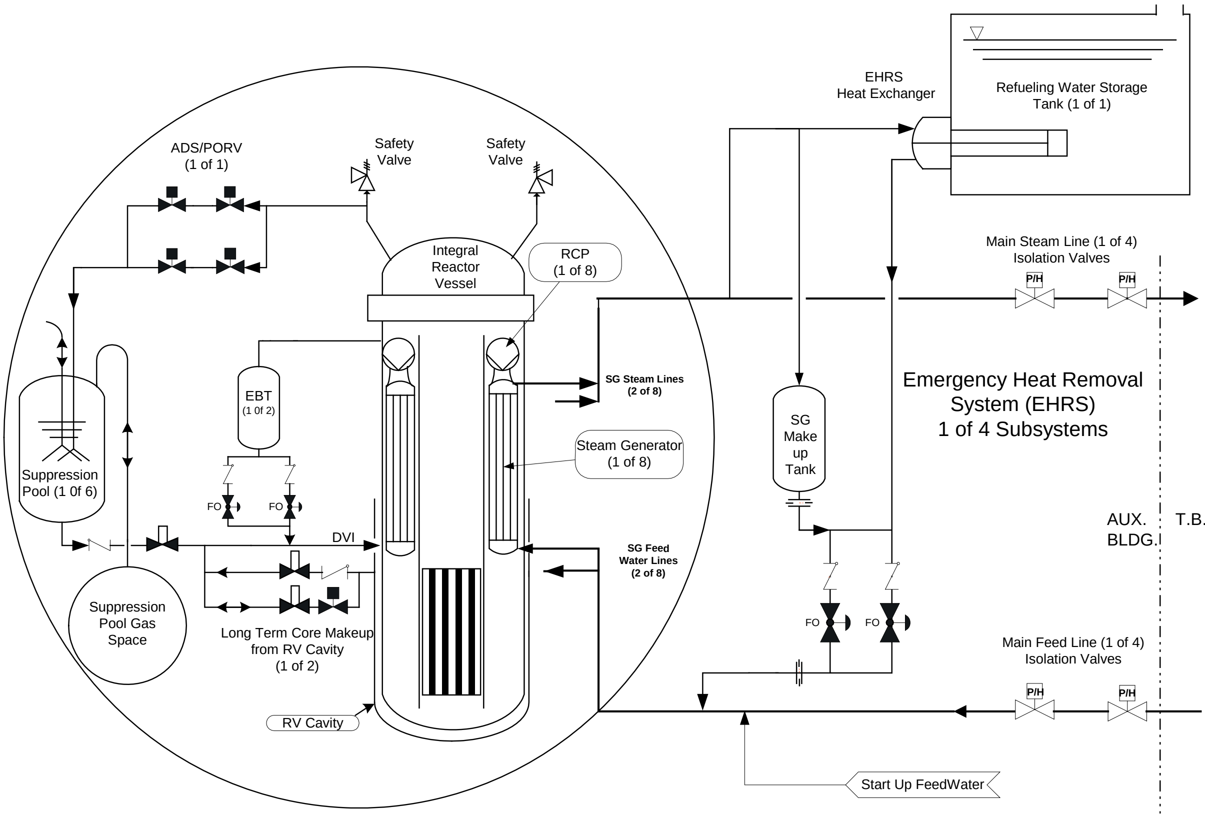
IRIS (IRIS, International Consortium)



Reactor type:	Integral pressurized water reactor
Electrical capacity:	335 MW(e)
Thermal capacity:	1000 MW(th)
Coolant/moderator:	Light water
Primary circulation:	Forced circulation
System pressure:	15.5 MPa
Core outlet temperature:	330°C
Thermodynamic cycle:	Indirect Rankine cycle
Fuel material:	UO_2/MOX
Fuel enrichment:	4.95%
Fuel cycle:	48 months
Reactivity control:	Soluble boron and rod insertion
No. of safety trains:	4
Emergency safety systems:	Passive
Residual heat removal systems:	Passive
Design life:	60 years
Design status:	Basic design
Seismic design:	0.3g
Predicted core damage frequency:	1E-8/reactor year
Planned deployment:	Currently seeking partnership for further development
Distinguishing features:	Integral primary system configuration



SBLOCA safety strategy.



Engineered safety features.

Introduction

IRIS is an LWR with a modular, integral primary system configuration. The concept is being pursued by an international group of organizations. IRIS is designed to satisfy four requirements: enhanced safety, improved economics, proliferation resistance and waste minimization. Its main features are:

- Medium power of up to 335 MW(e) per module;
- Simplified compact design where the primary vessel houses the steam generators, pressurizer and pumps;
- An effective safety approach;
- Optimized maintenance with intervals of at least four years.

Description of the nuclear systems

The IRIS core is an evolutionary design based on conventional UO_2 fuel enriched to 4.95%. This fuel can be fabricated in existing facilities and is licensable to current requirements. Fuel assemblies are constructed in a 17 × 17 lattice. The core contains 89 assemblies, each with an active fuel height of 4.27 m. Refuelling intervals of up to four years are possible. IRIS is designed to accommodate, without modification, a variety of core designs. Future core designs will include higher enriched UO_2 fuel and the capability to use mixed oxide (MOX) fuel. In the MOX case, IRIS is an effective actinide burner.

Description of the safety concept

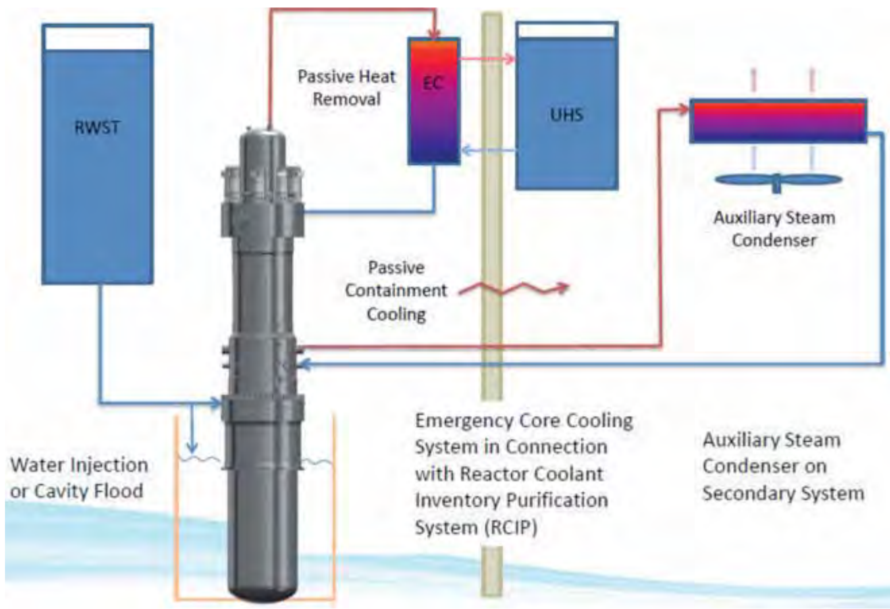
IRIS adopts passive safety systems and the safety by design philosophy including the risk informed approach. Due to IRIS's integral configuration by design (i.e. with no intervention of either active or passive systems), a variety of accidents either are eliminated or their consequences and/or probability of occurring are greatly reduced. In fact, 88% of class IV accidents (the ones with the possibility of radiation release) are either eliminated outright or downgraded. This provides a high level of defence in depth that may allow IRIS to claim no need for an emergency response zone.

Deployment status

The IRIS team has completed the preliminary design of the large scale test facility to prepare for future design certification.

mPower (Babcock & Wilcox, USA)

Reactor type:	Integral pressurized water reactor
Electrical capacity:	180 MW(e)
Thermal capacity:	530 MW(th)
Coolant/moderator:	Light water
Primary circulation:	Forced circulation
System pressure:	14.1 MPa
Core outlet temperature:	320°C
Thermodynamic cycle:	Indirect Rankine cycle
Fuel material:	UO_2
Fuel enrichment:	<5.0%
Fuel cycle:	48 months
Reactivity control:	Rod insertion
No. of safety trains:	N/A
Emergency safety systems:	Passive
Residual heat removal systems:	Passive
Design life:	60 years
Design status:	Basic design
Seismic design:	N/A
Predicted core damage frequency:	N/A
Planned deployment:	2020
Distinguishing features:	Internal once-through steam generator, pressurizer and control rod drive mechanism



Decay heat removal strategy.

Introduction

The Babcock & Wilcox (B&W) mPower™ reactor module is an integral PWR designed by B&W to generate an output of 180 MW(e).

Description of the nuclear systems

The reactor core consists of 69 fuel assemblies (FAs) that have less than 5% enrichment, Gd_2O_3 spiked rods, Ag In–Cd (AIC) and B_4C control rods, and a 3% shutdown margin. There is no soluble boron present in the reactor coolant for reactivity control. The FAs are of a conventional 17 × 17 design with a fixed grid structural cage. They have been shortened to an active length of 241.3 cm and optimized specifically for the mPower reactor.

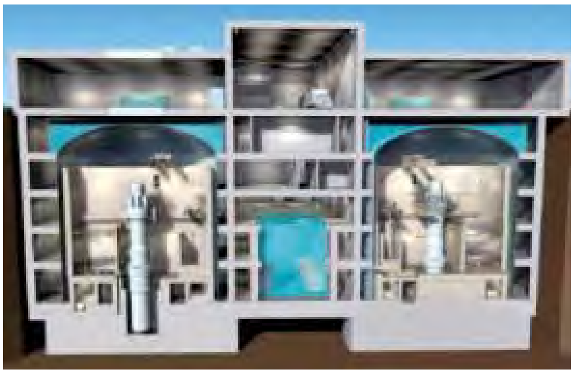
The reactor uses eight internal coolant pumps with external motors driving 3.8 m^3/s of primary coolant through the core. The integrated pressurizer at the top of the reactor is electrically heated and the reactor coolant pressure is nominally 14.1 MPa.

Description of the safety concept

The inherent safety features of the reactor design include a low core linear heat rate which reduces fuel and cladding temperatures during accidents, a large reactor coolant system volume which allows more time for safety system responses in the event of an accident, and small penetrations at high elevations, increasing the amount of coolant available to mitigate a small break loss of coolant accident (LOCA). The emergency core cooling system is connected with the reactor coolant inventory purification system and removes heat from the reactor core after anticipated transients in a passive manner, while also passively reducing containment pressure and temperature. The plant is designed without taking credit for safety related emergency diesel generators, and a design objective is no core uncovering during design basis accidents.

A large pipe break LOCA is not possible because the primary components are located inside the pressure vessel and the maximum diameter of the connected piping is less than 7.6 cm.

The mPower reactor deploys a decay heat removal strategy with a passive heat exchanger connected with the ultimate heat sink, an auxiliary steam condenser on the secondary system, water injection or cavity flooding using the reactor water storage tank, and passive containment cooling.



mPower containment design.

Electrical, and instrumentation and control systems

The mPower reactor is being designed with digital instrumentation and control systems. The system is being designed with a high level of plant automation, including control of startup, shutdown and load following. The digital control system architecture is currently being developed.

Description of the turbine-generator systems

The balance of plant design consists of a conventional power train using a steam cycle and an optional air or water cooled condenser. The condenser determines the final power output of the plant; the water cooled condenser allows for an output power of 180 MW(e), while deploying an air cooled condenser would allow for an output of 155 MW(e).

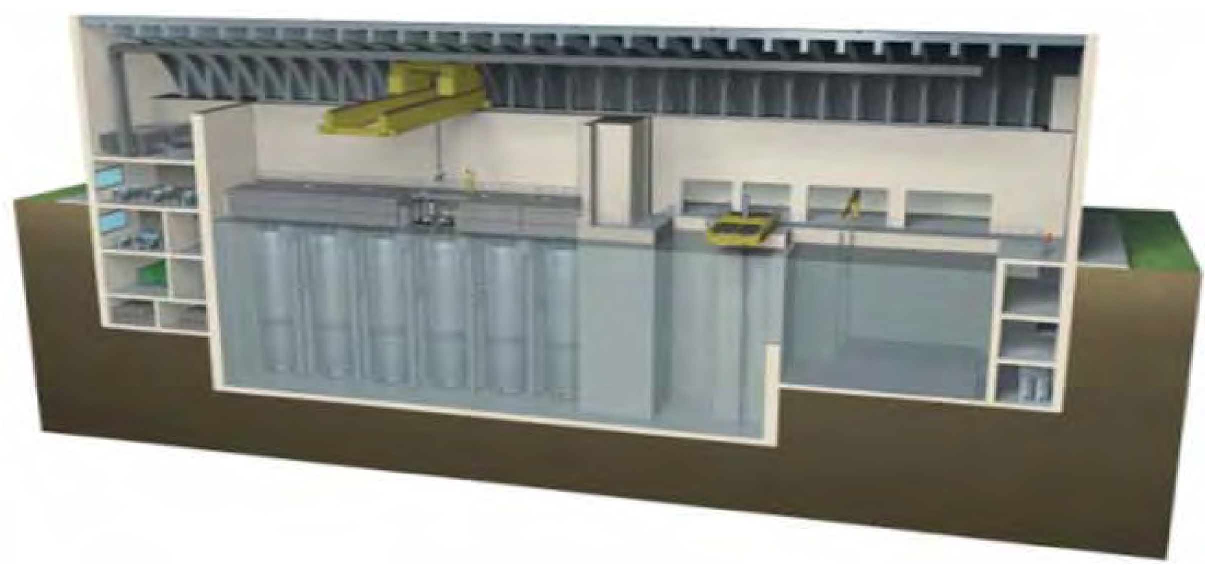
Deployment status and planned schedule

B&W and Bechtel Power Corporation entered into a formal alliance called Generation mPower to design, license and deploy mPower modular plants. A letter of intent has been signed with the Tennessee Valley Authority for joint development and pursuit of a construction permit and operating licence for up to six B&W mPower reactors [11].

B&W submitted an application to the US Department of Energy for the SMR development support programme in March 2012 and is awaiting the results, expected by the end of 2012 [1].

NuScale (NuScale Power Inc., USA)

Reactor type:	Integral pressurized water reactor
Electrical capacity:	45 MW(e)
Thermal capacity:	160 MW(t)
Coolant/moderator:	Light water
Primary circulation:	Natural circulation
System pressure:	8.72 MPa
Core outlet temperature:	329°C
Thermodynamic cycle:	Indirect Rankine
Fuel material:	UO_2
Fuel enrichment:	<4.95%
Fuel cycle:	24 months
Reactivity control:	Rod insertion
No. of safety trains:	Two trains
Emergency safety systems:	Passive
Residual heat removal systems:	Passive
Design life:	60 years
Design status:	Basic design
Seismic design:	0.5g
Predicted core damage frequency:	1E-8/reactor year
Planned deployment:	2020
Distinguishing features:	Synergy through plant simplicity; reliance on existing light water technology and availability of an integral test facility



NuScale plant layout.

Introduction

In 2007, NuScale Power Inc. was formed to commercialize the concept of a plant that can consist of 1–12 independent modules, each capable of producing a net electric power of 45 MW(e). Each module includes a pressurized LWR operated under natural circulation primary flow conditions. Each reactor is housed within its own high pressure containment vessel, which is submerged underwater in a stainless steel lined concrete pool.

Description of the nuclear systems

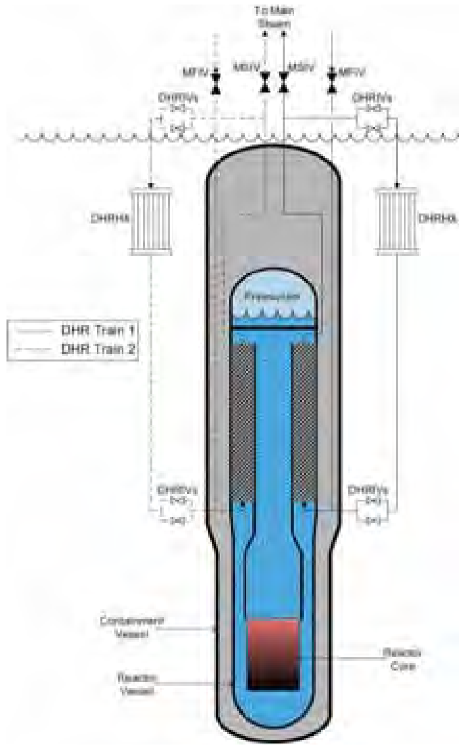
The designer claims that the NuScale reactor core contains 5% of the amount of fuel in large reactors. UO_2 fuel is used at an enrichment of less than 4.95% in a 17 × 17 fuel assembly with an active height of 2.0 m. The reactor has a fuel cycle lasting 24 months.

Description of the safety concept

The NuScale plant includes a comprehensive set of engineered safety features designed to provide stable, long term nuclear core cooling, as well as severe accident mitigation. They include a high pressure containment vessel, two passive decay heat removal and containment heat removal systems, a shutdown accumulator and severe accident mitigation.

The NuScale reactor module operates solely on natural convection and resides in a high strength stainless steel containment vessel. The decay heat removal system shown in the following figure consists of two independent trains operating under two-phase natural circulation in a closed loop. The designers claim that the pool surrounding the reactor module provides three days of cooling supply for decay heat removal. The stainless steel containment also provides a decay heat removal capability by first venting reactor vessel steam, steam condensing on the containment, the condensate collecting in the lower containment region, and reactor recirculation valves opening to provide recirculation through the core. This is said to provide 30 days or more of cooling followed by indefinite air cooling.

The multi-module NuScale plant spent fuel pool is designed with the capability of storing and cooling all of the fuel offloaded from 12 modules, as well as an additional 10 years' worth of used nuclear fuel.



Decay heat removal system.

Electrical, and instrumentation and control systems

The current NuScale design proposes using digital controls for the main control room and one operator controlling four reactor modules. Comprehensive human factor engineering and human–system interface studies are underway to determine the optimum number of reactors that can be effectively and safely controlled by a single operator.

Description of the turbine-generator systems

There are individual turbines for each of the reactor modules that are skid mounted and standard models currently available.

Deployment status and planned schedule

The NuScale Integral System test facility is being used to evaluate design improvements, and to conduct integral system tests for NRC certification.

NuScale Power Inc. submitted an application to the US Department of Energy for the SMR development support programme in March 2012 and is awaiting the results, expected by the end of 2012 [1].

Westinghouse SMR (Westinghouse, USA)

Reactor type:	Integral pressurized water reactor
Electrical capacity:	225 MW(e)
Thermal capacity:	800 MW(th)
Coolant/moderator:	Light water
Primary circulation:	Forced circulation
System pressure:	15.5 MPa
Core outlet temperature:	310°C
Thermodynamic cycle:	Indirect Rankine cycle
Fuel material:	UO_2
Fuel enrichment:	<5.0%
Fuel cycle:	24 months
Reactivity control:	Soluble boron and rod insertion
No. of safety trains:	N/A
Emergency safety systems:	Passive
Residual heat removal systems:	Passive
Design life:	N/A
Design status:	Basic design
Seismic design:	N/A
Predicted core damage frequency:	N/A
Planned deployment:	N/A
Distinguishing features:	Incorporates passive safety systems and proven components of the AP1000

Internal control rod drive mechanism testing.

Introduction

Westinghouse officially introduced the Westinghouse SMR design in February 2011, and is currently preparing for a role in the US Department of Energy's demonstration programme. The Westinghouse SMR is a 200 MW(e) class integral PWR with all primary components located inside the reactor vessel.

Description of the nuclear systems

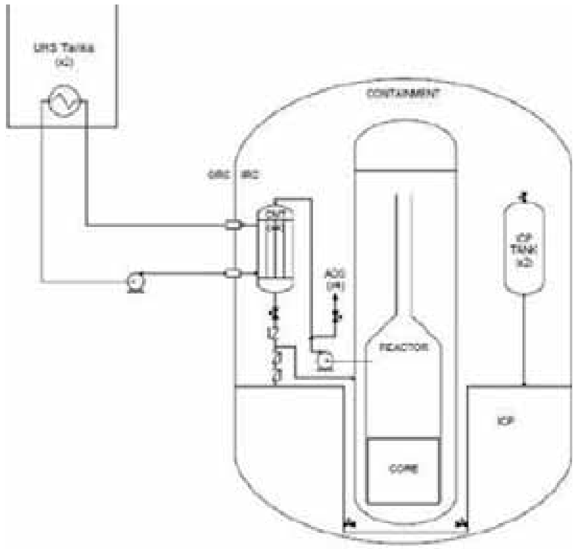
The reactor core is a partial height version of the 17 × 17 fuel assembly design used in the AP1000 reactor. The active core height is 2.4 m with 89 fuel assemblies and 37 internal control rod drive mechanisms (CRDMs). The fuel is 5% enriched and the core is designed to be refuelled every 24 months.

The CRDM utilizes latch assemblies, interfaces with fuel, and controls that are based on existing designs. It also uses a three coil magnetic jack based on the AP1000, and a test programme has been initiated for the CRDM.

The reactor coolant pumps are three phase, horizontally mounted axial flow pumps, each providing 0.8 m^3/s at 30.5 m of head. There are eight pumps, and they have a seal-less configuration that eliminates the need for pump seal injection. Each motor is rated at about 260 kW. The steam generators are recirculating, once-through straight tubes, which achieves a compact physical envelope inside the reactor vessel. The hot leg of the reactor drives the coolant up through the middle of the tube bundle, and the flow comes back down the tube bundle, from which the feedwater is circulated and sent to the external steam drum followed by the turbine.

The reactor vessel internals are based on the AP1000 design but modified to smaller dimensions. The pressurizer is integrated into the vessel head, thus minimizing the vessel size to 3.5 m in diameter and 24.7 m in height.

The safety features of the AP1000 are extended to the SMR design, and Westinghouse claims that no operator intervention is required for seven days following an incident. The containment vessel utilizes fully modular construction due to its small size of 9.8 m in diameter and 27 m in height.



Decay heat removal strategy.

Description of the safety concept

The Westinghouse SMR utilizes four heat exchangers connected to two ultimate heat sinks for decay heat removal.

Electrical, and instrumentation and control systems

The instrumentation and control system for the Westinghouse SMR is the OVATION-based digital control system.

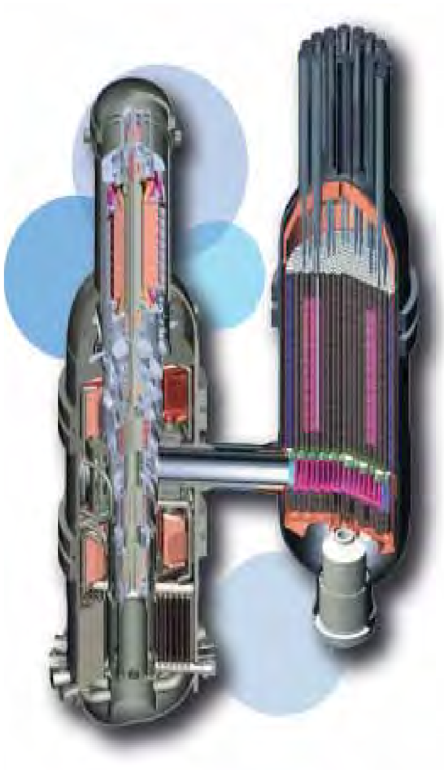
Description of the turbine-generator systems

The main components and facilities of the reactor plant are located below grade, including the containment, the spent fuel pool, the radioactive waste storage areas and the defence in depth facilities.

Deployment status

Westinghouse submitted an application to the US Department of Energy for the SMR development support programme in March 2012 and is awaiting the results, expected by the end of 2012 [1].

GT-MHR (General Atomics, USA)



Reactor type:	High temperature gas cooled reactor
Electrical capacity:	150 MW(e)
Thermal capacity:	350 MW(th)
Coolant/moderator:	Helium/graphite
Primary circulation:	Forced circulation
System pressure:	6.39 MPa
Core outlet temperature:	750°C
Thermodynamic cycle:	Brayton cycle
Fuel material:	UCO
Fuel enrichment:	15.5%
Fuel cycle:	18 months
Reactivity control:	Rod insertion
No. of safety trains:	N/A
Emergency safety systems:	N/A
Residual heat removal systems:	N/A
Design life:	60 years
Design status:	Conceptual design
Seismic design:	N/A
Predicted core damage frequency:	N/A
Planned deployment:	N/A
Distinguishing features:	Efficient production of hydrogen by high temperature electrolysis or thermochemical water splitting

Introduction

The gas turbine modular helium reactor (GT-MHR) couples an HTGR with a Brayton power conversion cycle to produce electricity at high efficiency. As it is capable of producing high coolant outlet temperatures, the modular helium reactor system can also efficiently produce hydrogen by high temperature electrolysis or thermochemical water splitting.

Description of the nuclear systems

The standard fuel cycle for the commercial GT-MHR utilizes low enriched uranium (LEU) in a once-through mode without reprocessing. General Atomics claims that the GT-MHR produces less heavy metal radioactive waste per unit energy produced because of the plant's high thermal efficiency, high fuel burnup and lower fertile fuel inventory. Similarly, the GT-MHR produces less total plutonium and ^{239}Pu (materials of proliferation concern) per unit of energy produced.

Description of the safety concept

The GT-MHR safety design objective is to provide the capability to reject core decay heat relying only on passive (natural) means of heat transfer without the use of any active safety systems. The GT-MHR safety concept is centred on retention of the radionuclides in the fuel under all normal and postulated accident conditions to the degree that doses at the site boundary will be within the US Environmental Protection Agency's radionuclide protective action guidelines, without reliance on AC powered systems or operator action.

The GT-MHR fuel form presents formidable challenges to diversion of materials for weapon production, as either fresh or as spent fuel.

Description of the turbine-generator systems

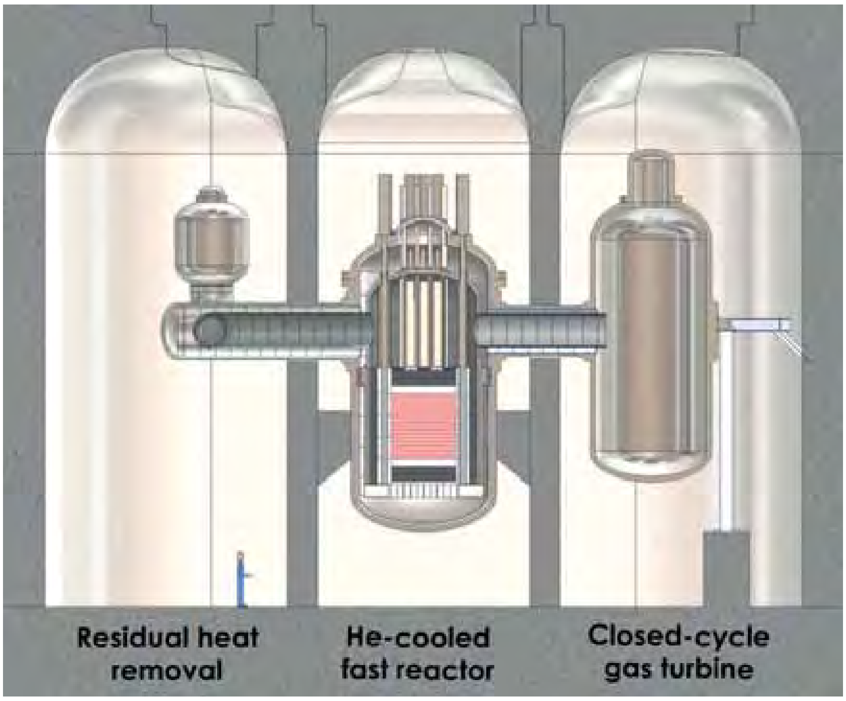
The GT-MHR direct Brayton cycle power conversion system contains a gas turbine, an electric generator and gas compressors. The use of the direct Brayton cycle results in a net plant efficiency of approximately 48%.

The GT-MHR gas turbine power conversion system has been made possible by utilizing large, active magnetic bearings, compact, highly effective gas to gas heat exchangers and high strength, high temperature steel alloy vessels.

Deployment status

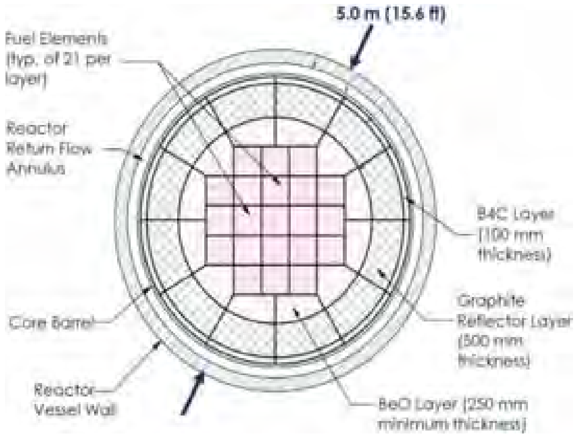
Pre-application licensing interactions with the NRC began in 2001, including submission of a licensing plan. From a technology development standpoint, the path forward for deployment of the GT-MHR technology is necessarily a demonstration project, such as the next generation nuclear plant project [2].

EM^2 (General Atomics, USA)



Reactor type:	High temperature gas cooled fast reactor
Electrical capacity:	240 MW(e)
Thermal capacity:	500 MW(th)
Coolant:	Helium
Primary circulation:	Forced circulation
System pressure:	N/A
Core outlet temperature:	850°C
Thermodynamic cycle:	Direct Brayton cycle
Fuel material:	Used nuclear fuel
Fuel enrichment:	1% ^{235}U, 1% Pu, MA
Fuel cycle:	30 years
Reactivity control:	N/A
No. of safety trains:	N/A
Emergency safety systems:	N/A
Residual heat removal systems:	Passive
Design life:	30 years
Design status:	Conceptual design
Seismic design:	N/A
Predicted core damage frequency:	N/A
Planned deployment:	N/A
Distinguishing features:	Helium cooled fast reactor; reduces spent fuel inventories

EM² reactor and gas turbine.



Core layout.

Introduction

The EM² is designed as a modification of an earlier high temperature helium cooled reactor. It is an effort to utilize used nuclear fuel without conventional reprocessing.

Description of the nuclear systems

The reactor is designed to produce 500 MW(th) and 240 MW(e) based on a closed cycle gas turbine. The EM² is a fast reactor design intended to burn used nuclear fuel and has a 30 year core without the need for refuelling or reshuffling. The spent fuel cladding is first removed and the fuel pulverized and processed using the atomics international reduction oxidation (AIROX) dry process to remove fission products. The fuel burned in the reactor is recycled upon discharge.

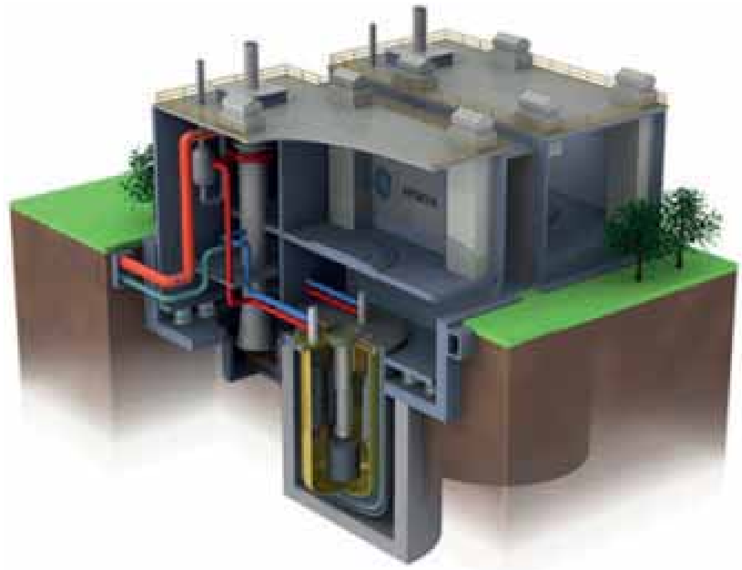
The core contains SiC–SiC clad porous UC plates arranged in a SiC–SiC assembly frame making a fuel assembly (FA). There are 21 FAs creating each layer and 17 layers stacked on top of each other, surrounded by a BeO layer, then a graphite reflector layer, and finally a B_4C layer, all sitting in the core barrel [15].

In a first generation plant, the fuel consists of about 22.2 t of LEU starter and about 20.4 t of used nuclear fuel. The used nuclear fuel is roughly 1% ^{235}U, 1% Pu and mixed actinides (MA), and 3% fission products; the rest is ^{238}U. The design organization claims that there is no need for uranium enrichment after the first generation reactor, as the discharge from the preceding generation is used for the succeeding generation. Out of each discharge, about 38.5 t is used in the succeeding generation while about 4 t of fission products are removed.

Description of the turbine-generator systems

Using a gas turbine cycle, the designers claim to achieve 48% efficiency with a core outlet temperature of 850°C. The entire containment is designed to be below grade and sealed for the 30 year core period [16].

PRISM (GE-Hitachi, USA)



Reactor type:	Liquid metal cooled fast breeder reactor
Electrical capacity:	311 MW(e)
Thermal capacity:	840 MW(th)
Coolant:	Sodium
Primary circulation:	Forced circulation
System pressure:	Low pressure operation
Core outlet temperature:	485°C
Thermodynamic cycle:	Indirect Rankine cycle
Fuel material:	U–Pu–Zr
Fuel enrichment:	26% Pu,10% Zr
Fuel cycle:	18 months
Reactivity control:	Rod insertion
No. of safety trains:	N/A
Emergency safety systems:	Passive
Residual heat removal systems:	Passive reactor vessel auxiliary cooling system
Design life:	N/A
Design status:	Detailed design
Seismic design:	N/A
Predicted core damage frequency:	1E-6/reactor year
Planned deployment:	N/A
Distinguishing features:	Underground containment on seismic isolators with a passive air cooling ultimate heat sink; part of the advanced recycling centre for spent nuclear fuel

Introduction

The PRISM design uses a modular, pool type, liquid sodium cooled reactor. The reactor fuel elements are a uranium–plutonium–zirconium metal alloy. The reactor uses passive shutdown and decay heat removal features.

Description of the nuclear systems

The PRISM reactor core was designed to meet several objectives:

- To limit peak fuel burnup;
- To limit the burnup reactivity swing;
- To provide an 18 month refuelling interval;
- To provide a 54 month lifetime for the fuel;
- To provide a 90 month lifetime for the blankets.

The reactor is designed to use a heterogeneous metal alloy core. The core consists of 42 fuel assemblies, 24 internal blanket assemblies, 33 radial blanket assemblies, 42 reflector assemblies, 48 radial shield assemblies, and 6 control and shutdown assemblies.

The primary heat transport system is contained entirely within the reactor vessel. The flow path goes from the hot pool above the core through the intermediate heat exchangers (IHXs), where it is cooled; the sodium exits the IHX at its base and enters the cold pool. The cold pool sodium is then drawn through the fixed shield assemblies into the pump inlet manifold. The four electromagnetic pumps take suction from the cold pool sodium through a manifold and discharge into the high pressure core inlet plenum through the piping connecting each manifold to the plenum. The sodium is then heated as it flows upwards through the core and back into the hot pool.

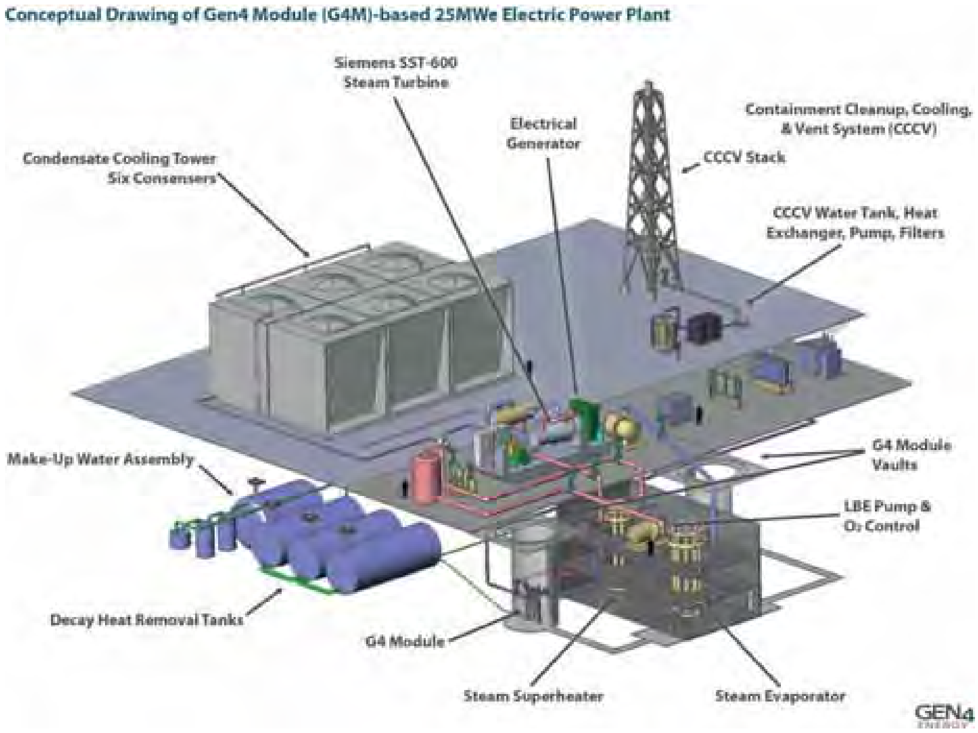
Description of the safety concept

The designers state that the inherent shutdown characteristics of the reactor core are a diverse and independent means of shutdown in addition to the control rod scram. The passive features are composed of several reactivity feedback properties including: the Doppler effect, sodium density and void, axial fuel expansion, radial expansion, bowing, control rod drive line expansion and reactor vessel expansion. The negative feedbacks maintain the reactor at a safe, stable state at an elevated temperature, but the reactor may still be critical if none of the reactor control rods have been inserted. The ultimate shutdown system has been added to bring the reactor to a subcritical state.

Description of the turbine-generator systems

A PRISM power block consists of three reactor modules, each with one steam generator (SG), that collectively supply one turbine-generator set. Steam from the three SGs is combined and supplied at near saturation conditions to the high pressure inlet of the turbine-generator. The exhaust steam enters the two low pressure turbine sections after it passes through moisture separators and reheaters. The steam is exhausted and, after passing through a series of condensers and coolers, enters the feedwater and condensate system [23, 24].

G4M (Gen4 Energy Inc., USA)



Reactor type:	Liquid metal cooled reactor
Electrical capacity:	25 MW(e)
Thermal capacity:	70 MW(th)
Coolant:	Lead–bismuth
Primary circulation:	Forced circulation
System pressure:	N/A
Core outlet temperature:	500°C
Thermodynamic cycle:	Indirect Rankine cycle
Fuel material:	Uranium nitride
Fuel enrichment:	19.75%
Fuel cycle:	10 years
Reactivity control:	Rod insertion and B_4C ball insertion
No. of safety trains:	2
Emergency safety systems:	N/A
Residual heat removal systems:	Passive
Design life:	5–15 (nominal 10) years
Design status:	Conceptual design
Seismic design:	N/A
Predicted core damage frequency:	N/A
Planned deployment:	N/A
Distinguishing features:	Transportable factory fuelled design

Introduction

Founded in 2007 as Hyperion Power Generation Inc., Gen4 Energy was formed to develop the Gen4 Module (G4M), first conceived at the Los Alamos National Laboratory (LANL) in New Mexico. Through the commercialization programme at LANL's Technology Transfer Division, Hyperion Power Generation was awarded the exclusive licence to utilize the intellectual property and develop the module [25].

Description of the nuclear systems

The reactor has been designed to deliver 70 MW of power over a ten year lifetime without refuelling. The materials in the core are uranium nitride fuel, HT-9 as the structural material, lead–bismuth eutectic (LBE) as the coolant, quartz as the radial reflector, and B_4C rods and pellets for in-core reactivity control. The reactor is approximately 1.5 m in diameter and 2.5 m in height, in which there are 24 subassemblies containing the fuel pins. The pin assembly is filled with liquid LBE to provide a high conductivity thermal bond between the fuel and cladding. The gap in the fuel pins has been sized to preclude fuel clad mechanical interference throughout the core's lifetime. A plenum is located at one end, which serves as both a fission gas plenum and a repository for the LBE inside the pin as the fuel swells with burnup.

The core coolant is LBE, with a mixed mean exit temperature of 500°C. This temperature limits the cladding temperature, so that maximum cladding creep over the 10 year lifetime of the reactor is less than 1%.

Description of the safety concept

There are two independent, safety grade reactivity control systems in the core: a control rod system comprising 18 B_4C control rods and a reserve shutdown system consisting of a central cavity into which B_4C spheres may be inserted into the core. Both the control rods and the spheres are inserted into dry wells in the core, which are hexagonally shaped thimbles. These thimbles penetrate the reactor vessel and are sealed from the primary coolant. Both systems can independently take the core to long term cold shutdown.

The safety concept of the G4M is driven by a set of design criteria that the designers believe are sufficient to ensure protection of the facility and its surroundings. These criteria are a sealed core, operational simplicity, minimal to no in-core movement, mechanical components and separation of power production and conversion operations.

During operational shutdowns, decay heat is removed from the G4M by two methods. The first method transfers heat from the core by natural circulation of coolants in the primary and secondary loops to the steam generators. The second removes heat by passive vaporization of water from the surface of the secondary containment vessel.

Deployment status

Gen4 Energy announced in April 2012 that they would not be pursuing the US Department of Energy's small modular reactor licensing support programme because they concluded that "use of well-known Light Water Reactor (LWR) technology of 45 to 300 MW intended for deployment in the USA had a much higher probability of success given the [Funding Opportunity Announcement's] stated maximum of two awards" [26].

SUMMARY OF SMR DESIGN STATUS

Reactor design	Reactor type	Designer, country	Capacity (MW(e))/ configuration	Design status
CNP-300	Pressurized water reactor	CNNC, China	325	In operation
PHWR-220	Pressurized heavy water reactor	NPCIL, India	236	In operation
CEFR	Liquid metal cooled fast reactor	CNEIC, China	20	In operation
KLT-40S	Pressurized water reactor	OKBM Afrikantov, Russian Federation	35 × 2 modules barge mounted	Under construction
HTR-PM	High temperature gas cooled pebble bed reactor	Tsinghua University, China	211	Under construction
PFBR-500	Liquid metal cooled fast breeder reactor	IGCAR, India	500	Under construction
CAREM	Integral pressurized water reactor	CNEA, Argentina	27	Site excavation completed
EC6	Pressurized heavy water reactor	AECL, Canada	740	Detailed design; CANDU 6 reference plants are in operation
SMART	Integral pressurized water reactor	KAERI, Republic of Korea	100	Detailed design
ABV-6M	Pressurized light water reactor	OKBM Afrikantov, Russian Federation	8.6 × 2 modules, barge mounted land based	Detailed design
RITM-200	Integral pressurized water reactor	OKBM Afrikantov, Russian Federation	50	Detailed design
VBER-300	Pressurized water reactor	OKBM Afrikantov, Russian Federation	325	Detailed design
WWER-300	Pressurized water reactor	OKBM Gidropress, Russian Federation	300	Detailed design
IRIS	Integral pressurized water reactor	IRIS, International Consortium	335	Detailed design
mPower	Integral pressurized water reactor	B&W, USA	180 × 2 modules	Pre-application interactions with the US NRC in July 2009; design certification application expected to be submitted in the fourth quarter of 2013

Reactor design	Reactor type	Designer, country	Capacity (MW(e))/ configuration	Design status
NuScale	Integral pressurized water reactor	NuScale Power Inc., USA	45 × 12 modules	NuScale plans to apply for design certification with the US NRC in 2013
SVBR-100	Liquid metal cooled fast reactor	AKME Engineering, Russian Federation	101	Detailed design
PRISM	Liquid metal cooled fast breeder reactor	GE-Hitachi, USA	155	Detailed design
4S	Liquid metal cooled reactor	Toshiba, Japan	10	Detailed design
IMR	Integrated modular water reactor	Mitsubishi Heavy Industries, Japan	350	Conceptual design
VK-300	Boiling water reactor	RDIPE, Russian Federation	250	Conceptual design
UNITHERM	Pressurized water reactor	RDIPE, Russian Federation	2.5	Conceptual design
Westinghouse SMR	Integral pressurized water reactor	Westinghouse, USA	225	Basic design
Flexblue	Subsea pressurized water reactor	DCNS, France	160 seabed anchored	Conceptual design
PBMR	High temperature gas cooled pebble bed reactor	PBMR Pty, South Africa	165	Conceptual design
GT-MHR	High temperature gas cooled reactor	General Atomics, USA	150	Conceptual design
EM^2	High temperature gas cooled fast reactor	General Atomics, USA	240	Conceptual design
BREST-OD-300	Liquid metal cooled fast reactor	RDIPE, Russian Federation	300	Conceptual design
G4M	Liquid metal cooled fast reactor	Gen4 Energy, USA	25 × N modules, single module or multimodule	Conceptual design
AHWR300-LEU	Pressure tube type heavy water moderated reactor	BARC, India	304	Basic design
FBNR	Integral pressurized water reactor	FURGS, Brazil	72	Concept description
SHELF	Pressurized water reactor	NIKIET, Russian Federation	6	Concept description

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B&W mPower™

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Who: Babcock & Wilcox (B&W) mPower, Inc.

What: Pre-application design certification interaction to discuss small modular reactor issues related to B&W's mPower™ design.

When: Began pre-application interactions in July 2009. Design certification application expected 3rd quarter of calendar year 2014.

Project Overview

The staff of the U.S. Nuclear Regulatory Commission (NRC) is currently engaged in pre-application activities on the mPower™ small modular reactor design. The mPower™ is an integral pressurized-water reactor (iPWR), designed by the B&W mPower, Inc. It is a light water reactor with the reactor and steam generator located in a single reactor vessel located in an underground containment. The mPower™ reactor has a rated thermal output of 530 MWt and electrical output of 180 MWe.

For additional detail, see the following related pages:

- Pre-Application Review
- Pre-Application Documents
- Requests for Additional Information
- Topical and Technical Reports
- Meeting Information
- Design-Specific Review Standard

Page Last Reviewed/Updated Friday, April 12, 2013

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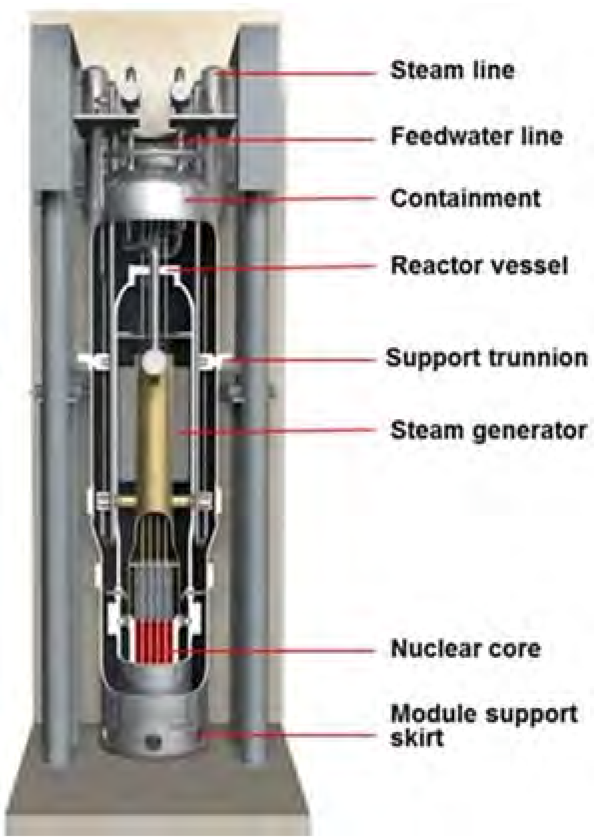
NuScale



Who: NuScale Power, LLC

What: Pre-application design certification interaction to discuss small modular reactor issues related to the NuScale design.

When: Began pre-application interactions in July 2008. Design certification application expected 3rd quarter of calendar year 2015.

Website: http://www.nuscalepower.com/ EXIT

Project Overview

The staff of the U.S. Nuclear Regulatory Commission (NRC) is currently engaged in pre-application activities on the NuScale small modular reactor (SMR) design. NuScale is an integral pressurized-water reactor (iPWR), designed by NuScale Power, LLC. The design is based on MASLWR (Multi-Application Small Light Water Reactor) developed at Oregon State University in the early 2000s. NuScale is a natural circulation light water reactor with the reactor core and helical coil steam generator located in a common reactor vessel in a cylindrical steel containment. The reactor vessel/containment module is submerged in water in the reactor building safety related pool. The reactor building is located below grade. The reactor building is designed to hold 12 SMRs. Each NuScale SMR has a rated thermal output of 160 MWt and electrical output of 45 MWe, yielding a total capacity of 540 MWe for 12 SMRs.

For additional detail, see the following related pages:

- Pre-Application Review
- Pre-Application Documents
- Requests for Additional Information

- Meeting Information
- NuScale Plant Overview/Reactor Overview Video

Page Last Reviewed/Updated Wednesday, July 03, 2013

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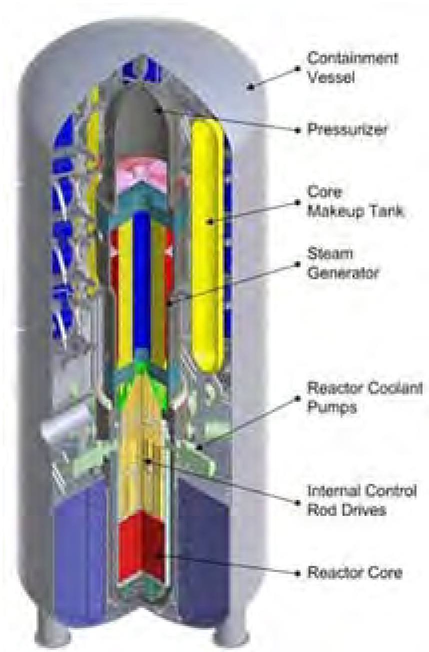
Westinghouse Small Modular Reactor (SMR)



Who: Westinghouse Electric Company

What: Pre-application interactions to discuss small modular reactor issues related to Westinghouse SMR.

When: Design certification application expected 2nd quarter of calendar year 2014.

Website: http://www.westinghousenuclear.com/smr/index.htm

Project Overview

The staff of the U.S. Nuclear Regulatory Commission (NRC) is currently engaged in pre-application activities on the Westinghouse SMR design. The Westinghouse SMR is an integral pressurized-water reactor (iPWR), designed by Westinghouse Electric Company with passive cooling. It is a light water reactor with the reactor and steam generator located in a single reactor vessel. The reactor building is located below grade. The Westinghouse SMR has a rated thermal output of 800 MWt and electrical output of 225 MWe.

For additional detail, see the following related pages:

- Pre-Application Review
- Pre-Application Documents
- Meeting Information

Page Last Reviewed/Updated Thursday, April 25, 2013

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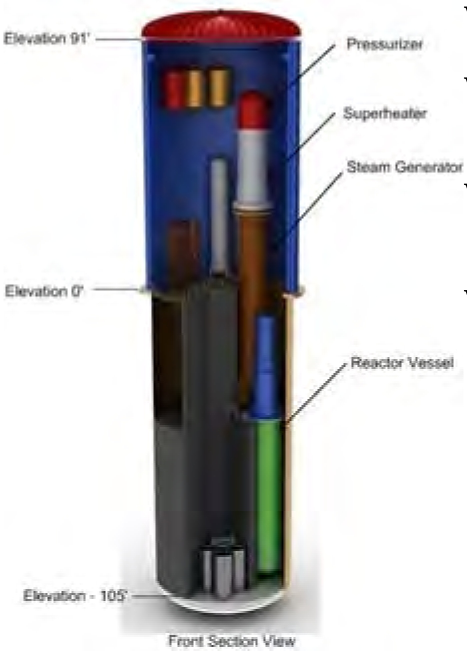
Holtec SMR-160



Who: Holtec SMR, LLC

What: Pre-application interactions to discuss small modular reactor issues related to Holtec SMR-160.

When: Design certification application expected 4th quarter of calendar year 2016.

Website: http://www.smrllc.com/index.html

Project Overview

The staff of the U.S. Nuclear Regulatory Commission (NRC) is currently engaged in pre-application activities on the Holtec SMR-160 design. The Holtec SMR-160 is a pressurized water reactor (PWR), designed by Holtec SMR, LLC with passive cooling. It is a light water reactor with the reactor, steam generator, and spent fuel pool located in containment. The reactor core is located below grade. The Holtec SMR-160 has a rated electrical output of 160 MWe.

For additional detail, see the following related pages:

- Pre-Application Review
- Pre-Application Documents
- Meeting Information

Page Last Reviewed/Updated Monday, May 20, 2013