SNC·LAVALIN

Building what matters

Advanced Fuel CANDU Reactor

Technical Summary

Company Profile

SNC-Lavalin's Nuclear team provides leading nuclear technology products and full-service solutions to nuclear utilities around the globe. Our team of 1,200 engineering, procurement, construction and project management experts offer customized operations, maintenance and plant life management services, including waste management and decommissioning. Our experts in nuclear steam plant and balance of plant engineering carry out life extension projects, and design and deliver state-of-the-art CANDU® reactors, which are capable of operating on many types of fuel including natural uranium, recycled uranium (RU), thorium and mixed oxide (MOX) fuel.

We are the stewards of CANDU technology. The 47 heavy water reactors in operation or under life extension are based on our CANDU design and are an important component of clean air energy programs on four continents. CANDU technology provides safe, reliable, affordable and CO_2-free energy to support the economic viability of businesses and quality of life for consumers in Canada, Romania, Korea, China and Argentina. CANDU reactors have an outstanding performance record, taking four of the top five places on Nuclear Engineering International's 2013 Top Lifetime Performers List.

Continuing a tradition of building nuclear reactors for over 50 years, we make significant contributions to the nuclear energy field. CANDU technology is the basis for Canada's nuclear power program and has been adopted in the nuclear power programs of many countries. The 11 CANDU 6 units, in five countries, have consistently delivered an average lifetime capacity factor of over 87%.

Noteworthy facts about the CANDU reactor fleet

CANDU REACTORS
CONSISTENTLY RANK
AS TOP PERFORMERS
AND HOLD THE WORLD RECORD FOR
LONGEST CONTINUOUS OPERATION

CANDU BRAND
IS RECOGNIZED AS ONE OF
THE TOP 10 MAJOR
ENGINEERING ACHIEVEMENTS
OF THE PAST CENTURY IN CANADA

CANDU REACTORS CAN
BE EASILY ADAPTED FOR
FLEXIBLE FUEL
CYCLE OPTIONS

EXCELLENT
PERFORMANCE
OF THE CANDU 6 FLEET WITH
AN AVERAGE LIFETIME
CAPACITY FACTOR OF OVER
87%

31
CANDU REACTORS
IN THE WORLD
OPERABLE OR
BEING REFURBISHED

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Advanced Fuel CANDU Reactor

The Advanced Fuel CANDU Reactor (AFCR™) is a Generation III advanced fuel-efficient 740 MWe-class Pressurized Heavy Water Reactor developed by Candu Energy, a member of the SNC-Lavalin Group and China National Nuclear Corporation.

Based on over 60 years of proven operational excellence of the CANDU reactor fleet and experience in design, construction, operation and maintenance, the AFCR incorporates the latest advanced features that enhance safety, economics and operation and maintenance ease of the plant.

Safety in Depth

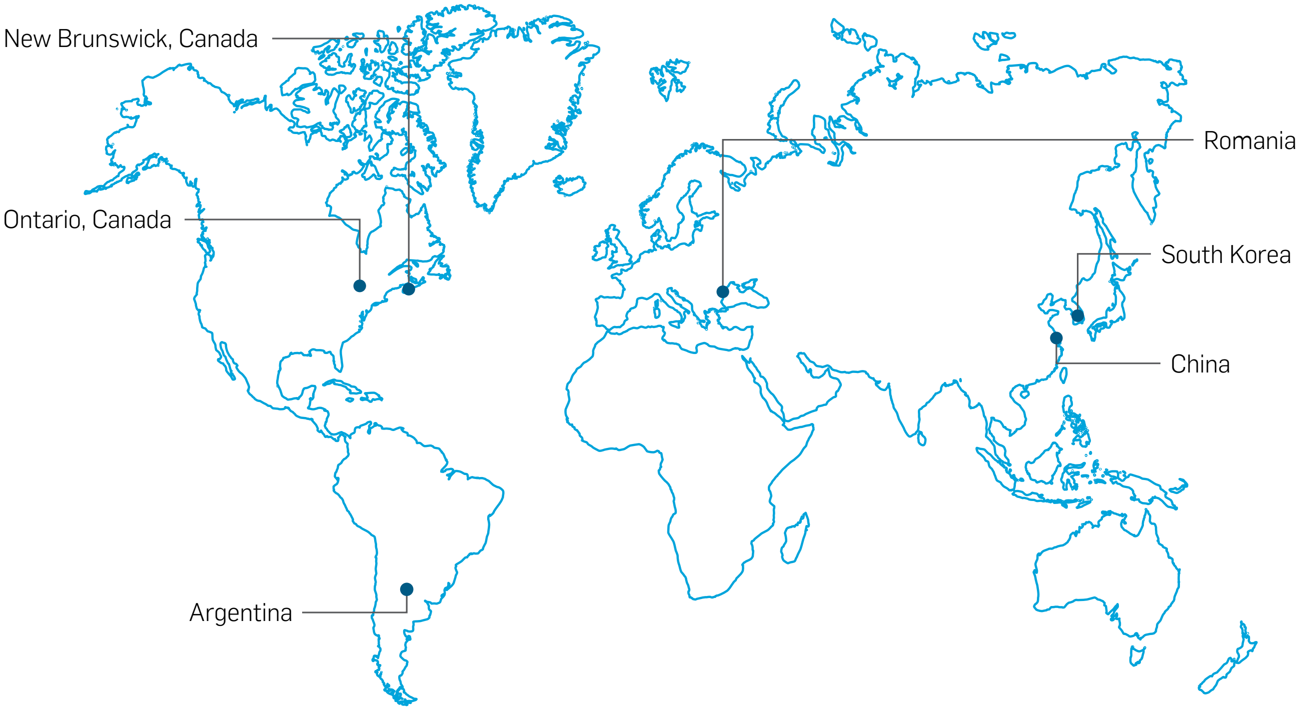
- Active and passive systems
- Enhanced safety margins
- Robust safety system configuration
- Meets post-Fukushima and most recent safety requirements

Proven

- Based on over 60 years of CANDU reactor design and operational expertise worldwide
- Proven technology

Economically Enabling the Fuel Cycle

- Advanced fuel flexibility; ability to efficiently use recycled uranium and thorium-based fuels
- High capacity factors
- Designed for 60 year life



CANDU Reactors Worldwide

CANDU: A Success Story

Canada is a nuclear technology development pioneer with over 60 years of expertise and continuous improvement in the advancement of peaceful uses of nuclear energy. Through its member company, Candu Energy Inc., SNC-Lavalin has the exclusive rights to deliver state-of-the-art CANDU reactors.

SNC-Lavalin's Nuclear team provides leading nuclear technology products and full-service solutions to nuclear utilities around the globe. Our highly-skilled employees offer customized operations, maintenance and plant life management services, including waste management and decommissioning for customers worldwide. Our experts in nuclear steam plant (NSP) and balance of plant (BOP) engineering carry out life extension projects, and design and deliver CANDU reactors, which are capable of operating on many types of fuel including natural uranium, recycled uranium (RU), thorium and mixed oxide (MOX).

We develop products to deliver safe, reliable affordable and CO_2-free energy with a vision to the future, while meeting the highest regulatory standards of the global nuclear industry.

Continuing a tradition of building nuclear reactors for over 50 years, we make significant contributions to the nuclear energy field. CANDU technology is the basis for Canada's nuclear power program and has been adopted in the nuclear power programs of several countries.

Proven Delivery Track Record

Candu has achieved an industry-leading track record in delivery of nuclear new build projects with on budget and on schedule successes. Using up to date technologies, proven construction strategies, localization and integrated project management and delivery tools, we have the ability to meet aggressive schedules.

CANDU 6 Project Performance Record Since 1996

In-Service	Plant	Status
1996	Cernavoda Unit 1 – Romania	On Budget* On Schedule
1997	Wolsong Unit 2 – South Korea	On Budget On Schedule
1998	Wolsong Unit 3 – South Korea	On Budget On Schedule
1999	Wolsong Unit 4 – South Korea	On Budget On Schedule
2002	Qinshan, Phase III Unit 1 – China	Under Budget 6 weeks ahead of schedule
2003	Qinshan, Phase III Unit 2 – China	Under Budget 4 months ahead of schedule
2007	Cernavoda Unit 2 – Romania	In service Oct. 5, 2007**

*Per 1991 completion contract

**Work on Cernavoda 2 was suspended in 1989 and resumed in 2003

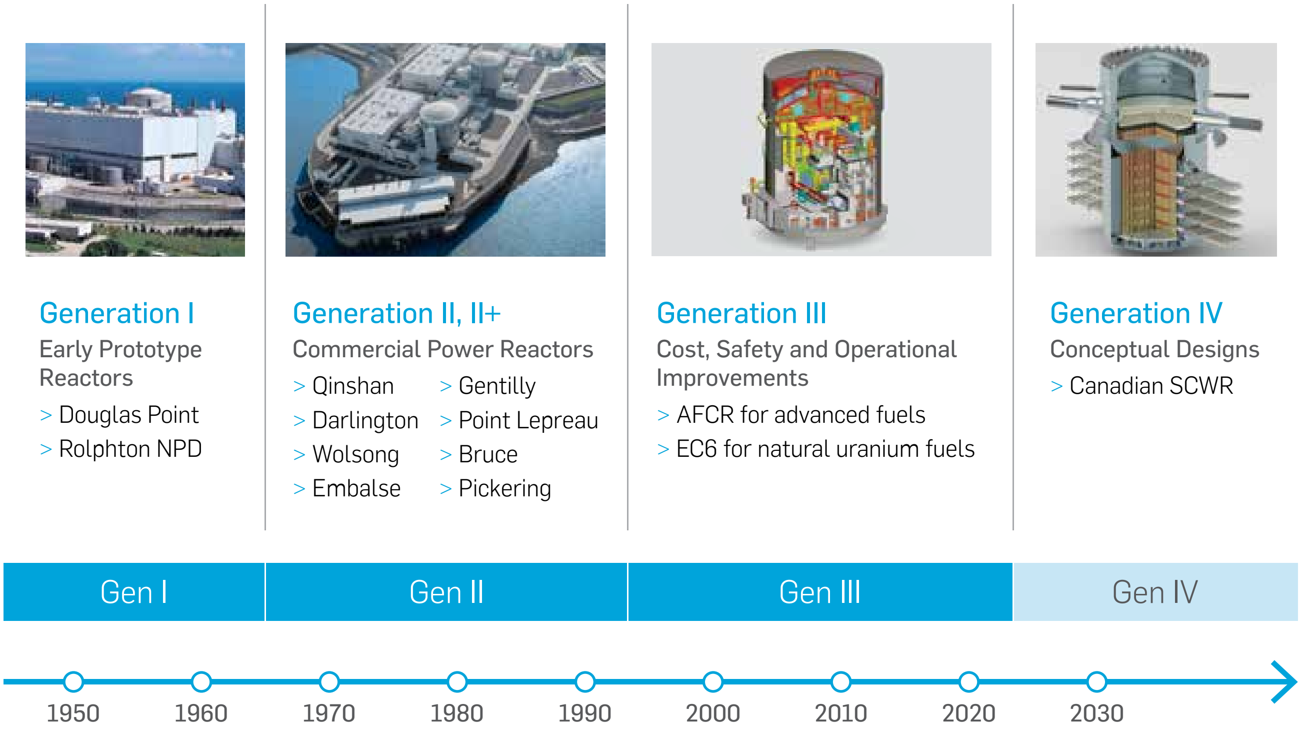
Development of AFCR Technology

Canada has been a leader in nuclear research and development, design and constructing research and commercial nuclear power plants since the 1940s and CANDU reactors first powered the grid in 1962. Since then, we have ensured continuous improvement and innovation to our products.

The AFCR, Candu's latest and most advanced alternative fuel cycle pressurized heavy water reactor was developed by Candu and China National Nuclear Corporation (CNNC). The AFCR is an evolutionary design based on the proven and highly successful Qinshan reference CANDU 6 reactor design. In addition, the AFCR is a further advancement to the EC6® reactor design with broad based alternative fuel capabilities and modern active/passive safety features.

While retaining the traditional features of our proven CANDU 6 design, the AFCR incorporates the experience and feedback gained over 1100 reactor-years of safe operation and includes innovative features and state-of-the-art technologies that enhance safety, operation and performance including additional active and passive safety features to meet the latest regulatory and post-Fukushima requirements.

NUE consists of a mixture of recycled uranium and depleted uranium and can be used interchangeably with NU in a CANDU reactor.



Evolution of the CANDU Reactor Design Driven by Continuous Improvement and Innovation

The AFCR allows countries to form a synergistic relationship between their Pressurized Water Reactor (PWR) fleet and AFCR units. Recycled uranium from the spent fuel of PWR plants is efficiently reused in AFCRs to improve uranium resource utilization. In addition, the AFCR can use thorium-based fuels which will allow countries with indigenous thorium resources to use them as a near-term energy strategy in the proven CANDU reactor design to minimize dependence on uranium imports.

The AFCR can be exported to markets around the world with resource constraints or local thorium reserves. Technology transfer for localizing fuel manufacture is simple and has been achieved very successfully in a number of countries, including China, for both natural uranium (NU) and natural uranium equivalent (NUE) based fuels.

The latest computer-aided design and drafting (CADD) software tools and innovative integrated systems, linking material management, documentation, safety analysis and project execution databases, are used in the AFCR to ensure that accurate and complete configuration management can be easily maintained by the plant owner.

Technical Description of the AFCR

High Level Design Specifications

Parameter	Description
Plant Type	Pressure tube reactor. D_2O moderated, D_2O cooled.
No. of Units per Plant	Single or twin plant
Capability Factor	> 90%
Number of Fuel Channels	380
Refuelling method	On-power, fuelled in the direction of flow
Containment Structure	1.5 m thick, upright cylinder with flat base and a toroid dome, with steel liner for reduced leakage
Plant Life	60 Year
Design Basis Earthquake	0.25g PGA based on Canadian Standards Association
Exclusion Zone	500 m
Station Blackout (SBO)	> 72 Hrs
Severe Core Damage Frequency	less than 10^{-6}/ reactor year
Large Release Frequency	less than 10^{-7}/ reactor year

Main Characteristics of the AFCR

The Advanced Fuel CANDU® Reactor (AFCR) is a Generation III reactor that uses alternative fuel cycles including recycled uranium and thorium-based fuels and achieves enhanced safety margins. In addition to its advanced fuel cycle capability, the AFCR, like all Generation III CANDU designs incorporates innovative features and current technologies to ensure the safety, operation, and performance of the plant are at modern standards and consistent with recent international trends in design of modern nuclear power plants.

The AFCR design offers:

1. A Generation III reactor design meeting all post-Fukushima requirements
2. A minimum of 60 years of operational life
3. The use of recycled uranium and thorium-based fuels with on-power fuelling
4. High resource utilization
5. High localization possibility
6. Suitability for all electric grids
7. Superior safety performance and good economics
8. An evolutionary design based on the highly successful, proven reference CANDU 6 reactor and the EC6 reactor
9. A design with additional active and new passive safety features
10. Increased safety and operating margins
11. Advanced accident resistance and core damage prevention features
12. Advanced performance and health monitoring
13. Improved plant operability and maintainability with advanced control room design
14. Improved severe accident response
15. Advanced fire protection system
16. Improved containment design features that provide aircraft crash resistance, reduced potential leakages following accidents, and increased testing capability

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The AFCR is a 740 MWe heavy water moderated and cooled pressure tube reactor. Heavy water (D_2O) is a natural form of water used as a moderator to effectively slow neutrons in the reactor, enabling the use of natural uranium (NU) as well as other alternatives as fuel. This feature of high neutron economy is unique to CANDU reactors. The choice of D_2O as the moderator is the key enabler for the use of alternative fuel cycles (recycled uranium and thorium-based fuels) in CANDU reactors.

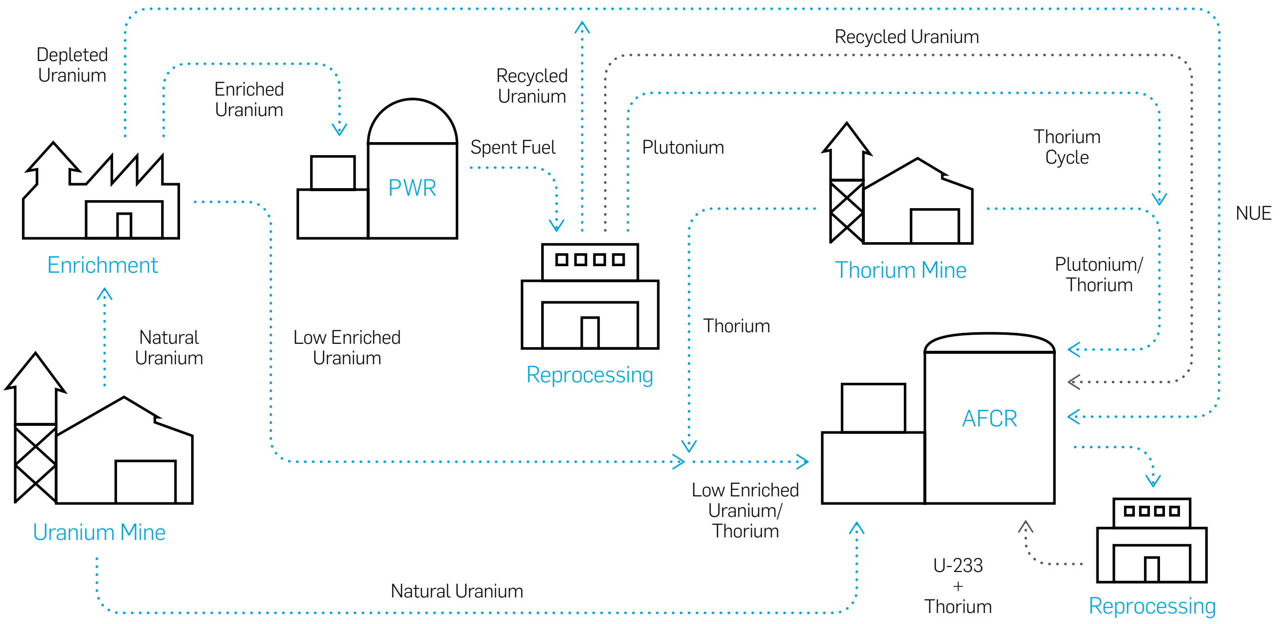
AFCR maintains the traditional CANDU inherent safety design features and includes further safety enhancements to meet the latest safety standards and post-Fukushima requirements.

Key safety features include:

- Core features such as a practically zero power coefficient of reactivity, negative fuel temperature coefficient and better distributed channel and bundle power profiles
- Two independent passive shutdown systems, each capable of safely shutting down the reactor with no human intervention
- Two group design to ensure two independent means to achieve the same safety functions
- Refuelling during on-power operation reduces the excess reactivity level needed for reactor control. Reactor characteristics are constant and no additional measures, such as the addition of boron to the reactor coolant (and its radioactive removal), are required
- Natural circulation capability in the reactor cooling system for temperature transients (changes) due to loss of forced flow
- Reactivity control devices cannot be ejected by high pressure because they are located in the low-pressure moderator and do not penetrate the AFCR coolant pressure boundary
- Moderator as a back-up heat sink, unique for CANDU design, maintains core coolability for loss-of-coolant accidents even when combined with unavailability of emergency core cooling
- Elevated water tanks located in the upper level of the reactor building deliver (gravity fed) passive dousing water spray into containment and make-up cooling water to the calandria vessel to remove decay heat. The gravity fed makeup water from the dousing tank to the steam generators for Station Blackout (SBO) events is designed to last for at least 72 hours
- A large concrete reactor vault surrounding the reactor core in the calandria contains a large volume of light water to further slow down or arrest severe core damage progression by providing a second passive core heat sink. Passive water make-up to the calandria vault mitigates severe core damage accidents for 72 hours
- Calandria vault plus shield cooling system or the severe accident recovery and heat removal system (SARHRS) is used to arrest severe core damage progression within the calandria vessel
- Passive capability of the containment itself ensures containment integrity is maintained while an offsite emergency response plan is implemented following onset of severe core damage. A new passive containment heat removal system (PCHRS) maintains the containment integrity for the longer term

All reasonably practicable design measures are taken into account in the AFCR design to prevent accidents and to mitigate their consequences. Our AFCR is designed with both active and passive containment heat sinks to ensure the containment function under severe accident conditions. The AFCR's inherent safety with new passive and active design features aims to practically eliminate plant states that could lead to early or large radioactive releases.

Qinshan CANDU Reactors in Haiyan, China



Alternative Fuel Cycles for AFCR-type Reactors

AFCR Advantages for Advanced Fuel Cycles

Current CANDU reactors, as a result of favourable reactor core physics characteristics and on-power fuelling, use approximately 30% less natural uranium per each kilowatt-hour of electricity as compared to PWR designs. Our unique technology has unequalled flexibility for using alternative fuels, such as recycled uranium and thorium-based fuels. This capability results from a versatile pressure tube design, simple fuel bundle, on-power refuelling, and high neutron economy.

The AFCR uses advanced fuels specifically direct use of recycled uranium (DRU) fuel or low enriched uranium/thorium (LEU/Th) fuel. DRU fuel represents a gradual transition from NU-based fuels that are used in current CANDU 6 reactors. DRU fuel is similar to the already proven natural uranium equivalent (NUE) fuel in that it is composed of RU, from reprocessed pressurized water reactor (PWR) spent fuel but has a slightly higher fissile content (contains about 0.95%wt. ^{235}U) than the NUE fuel.

Our AFCR, although specifically designed for DRU and LEU/Th fuels, retains the ability to easily adapt to various fuel cycle options, such as NU, NUE and Pu/Th.

CANFLEX Fuel Bundle

Fuel

Our AFCR uses the CANFLEX® 43-element fuel bundle design. The increased subdivision of this bundle design improves thermalhydraulic margins and enables the use of RU and Th-based fuels. Each fuel element consists of a column of either sintered (RU or RU/dysprosium in DRU; or LEU or thorium in LEU/Th) fuel pellets inside a sealed zirconium alloy tube. The ends of a circular array of the 43 fuel elements are welded to zirconium alloy support plates to form an integral fuel bundle assembly. Each fuel bundle is approximately 50 cm long and 10 cm in diameter. Its compact size and weight facilitates automated and on-power fuel handling.

All types of CANDU reactor fuel bundles, with fewer components than other reactor types, are easy to manufacture allowing all countries with CANDU reactors to manufacture their own fuel. Excellent uranium utilization and a simple fuel bundle design help minimize the CANDU reactor fuel cycle unit energy cost, in absolute terms, relative to other reactor types. The efficient use of neutrons in CANDU reactors contributes to its fuel cycle flexibility, and consequent reduction in volume of irradiated fuel relative to earlier CANDU reactor designs.

Direct use of Recycled Uranium Fuel

The DRU fuel is recycled uranium (RU) based fuel, arranged in a 43-element CANFLEX fuel bundle. The nominal enrichment of the RU is 0.95 wt% 235U to achieve a target burnup of 10,000 MWd/tHE. The use of higher fissile content RU fuel compared to NU fuel has greater economic advantages due to higher fuel utilization. RU fuel is in the form of sintered uranium pellets.

Low-Enriched Uranium (LEU) and Thorium (Th) Fuel

The low-enriched uranium (LEU) and thorium (Th) fuel is a heterogeneous combination of the constituent fuels arranged in a 43-element CANFLEX fuel bundle. The fuel is designed to achieve a target burnup of 20,000 MWd/tHE.

43-Element Fuel Bundle Design Characteristics

Fuel	DRU	LEU and Th
Average fuel burnup [MWd/tHE]	10,000	20,000
Bundles per fuel channel	12	12
Reference fuelling scheme	4-bundle shift	2-bundle shift

Economic Value Using Advanced Fuel Cycles

The use of DRU and LEU/Th fuels in the AFCR core increases the CANDU advantage even further with fuel requirements as low as 50-60% of PWR baseline designs. In addition, CANDU reactor fuel bundles are small and, therefore easier to modify relative to more complex fuel assemblies of other nuclear reactor technologies. This allows advantages for current or future fuel development and verification testing programs compared to other reactor types.

Adopting alternative fuel cycles such as NUE, DRU, and LEU/Th significantly improves the uranium utilization rates while meeting nuclear power generation requirements. In fact, an AFCR twin-unit plant using DRU fuel would save approximately 10,000 tonnes of natural uranium over its 60-year design life.

The AFCR has the advantage of not requiring reactor shutdown for batch fuelling, and conversely, uses easy-to-handle fuel bundles, which are inserted/removed in the reactor core on-demand, with the aid of on-power fuelling capability. The small sized fuel bundles and on-power fuelling allow the establishment of optimal core configurations with minimal effort and without relying on the use of liquid neutron absorbers to suppress excess reactivity, as is the case with PWR designs. Absorbers can have adverse fuel cost and system chemistry impacts.

The cumulative effect of these CANDU reactor technology specific features results in the following capabilities of the AFCR:

a) Re-using PWR used fuel stream in the immediate term in the form of DRU fuel, in a cost effective manner

b) Introducing new fertile material into the fuel stream with the first new build reactors (LEU/Th)

c) Approaching “closed” fuel cycles, requiring sequentially less new fuel material with each next generation CANDU reactor unit —a major market and technology change potential

The AFCR features offer a cost effective solution, is available in the short term and is suitable for meeting intermediate and long-term aspirations for sustainable fuel supply, without requiring major investments or technological risks.

Safety is at Our Core

The AFCR incorporates the proven principles and characteristics of the reference CANDU 6 design and the extensive knowledge base of CANDU reactor technology gained over decades of successful operation. It has been enhanced to reflect and comply with the latest regulatory requirements, including Canadian and Chinese safety requirements as well as International Atomic Energy Agency (IAEA) codes and standards.

AFCR Safety Design Philosophy

> Evolutionary design based on proven design and experience feedback
> Meet Generation III reactor safety goals
> Strengthen defense in depth
> Increase safety margins
> Apply two group safety design philosophy
> Incorporate post-Fukushima requirements
> Extend plant design to cope with BDBAs through inherent safety design with robust complementary design features
> Ensure rugged plant design against malevolent acts and external events
> Minimize environmental impact
> Advanced active and passive safety features for practical elimination of large releases

AFCR Safety Design Philosophy

The AFCR is designed based on the “defence-in-depth” safety philosophy applied to all CANDU plants with enhancements to further improve overall safety. These enhancements include core design incorporating a practically zero power coefficient of reactivity, improved performance of safety systems, inherent safety design for resistance of accidents, a combination of active and passive safety features for prevention of core damage and mitigation of consequences of accidents, and a robust containment design to minimize the risk to the public and the environment.

Our AFCR is an advanced CANDU reactor plant to meet Generation III reactor standards, including:

> Ample thermal and safety margins for safe operation
> More rugged design and higher availability with a plant life of 60 years
> Resistance of accident through inherent safety design features
> Physical and functional separation of safety systems
> Simplified, more reliable systems
> A combination of passive and active safety designs for accident prevention and mitigation
> Further reduced probability of severe core damage
> Very low large release frequency to minimize the risk to the public
> Higher burn-up to use alternative fuel more efficiently and reduce the amount of waste
> Robustness of the plant against malevolent acts and external events

AFCR Safety Goals

Safety goals are established to effectively implement fundamental nuclear safety objectives and to ensure that nuclear power plant operation poses no significant additional risk to public health, safety, security, and the environment in comparison with other risks to which the public is normally exposed. Establishment of safety goals for the AFCR is based on the Generation III requirements. It achieves the following quantitative design target safety goals with ample margins:

- The occurrence frequency of events that may lead to severe core damage is less than 10^{-6} events per operating reactor year
- The frequency of events that may result in a large radioactive release is less than 10^{-7} events per operating reactor year

The design approach for the AFCR ensures safety during construction, commissioning and operation. All reasonably practicable design measures, including those for design extension conditions, are taken into account in the AFCR design to prevent accidents and to mitigate their consequences. Our AFCR ensures with a high level of confidence that, for all postulated accidents considered in the design including those of very low probability, radiological consequences would be below prescribed limits. The AFCR design features ensure that the likelihood of accidents with serious radiological consequences is extremely low. The intent is to practically eliminate accident sequences with a large or early release.

Defence-in-Depth

Consistent with the overall safety concept of defence-in-depth, the AFCR aims to prevent, as far as practicable, challenges to the integrity of physical barriers; failure of a barrier when challenged, and failure of a barrier as a consequence of the failure of another barrier. This approach is structured in five levels consistent with regulatory documents CNSC REGDOC-2.5.2, IAEA SSR2/1, and NNSA HAF102-2004 as presented below:

- **Level 1** – Prevention of deviations from normal operation and failures of structures, systems and components (SSCs) by conservative design and high-quality construction
- **Level 2** – Detection and control of deviations from normal operation in order to prevent anticipated operational occurrences (AOOs) from escalating to accident conditions and to return the plant to a state of normal operation by using inherent and engineered design features to minimize or exclude uncontrolled transients to the extent possible
- **Level 3** – Minimize the consequences of accidents by providing inherent safety features, fail-safe design, additional equipment, and mitigating procedures
- **Level 4** – Control of severe plant conditions in which the design basis may be exceeded, including the prevention of accident progression and mitigation of the consequences of severe accidents, by providing equipment and procedures to manage accidents and mitigate their consequences as far as practicable
- **Level 5** – Mitigation of radiological consequences of potential releases of radioactive substances by adequately equipped emergency support centre and on-site and off-site emergency response

Levels of defence are implemented such that the reliability of each protection level is preserved commensurate with the expected frequency and consequence of challenges. Should one level fail, it is compensated or corrected by the subsequent level.

Measures of the first three levels of defence are considered within the design basis to ensure integrity of fission product barriers and to limit potential radiation hazards to members of the public. Measures of the fourth level of defence are considered beyond design basis to keep the likelihood and radioactive releases of severe plant conditions as low as practicable. The fifth level of defence deals with off-site emergency response.

During normal operation, the built in level of defence ensures the plant operates safely and reliably by incorporating substantial design margins, adopting high-quality standards and by advanced reliable control systems to accommodate plant transients and arrest the progression of the transients once they start. Following a design basis accident (DBA), the safety systems and equipment automatically start to shut down the reactor and maintain it in a safe shutdown condition indefinitely.

Safety systems, which perform the safety functions, follow the design principles of separation, diversity and reliability. High degrees of redundancy within systems are provided to ensure the safety functions can be carried out assuming a single failure with the systems. Protection against external events and internal hazards (e.g., seismic events, tornadoes, floods, fire, and malevolent acts) is also provided, ensuring independence of systems or components performing safety and highly reliable and effective mitigation of postulated events, including severe accidents.

The AFCR has inherent design robustness against severe core damage, including preventing severe core damage at high pressure and precluding high pressure melt and direct containment heating. In general, the progression of a severe core damage accident in a CANDU reactor would be slow because the fuel is surrounded by a large quantity of light and heavy water, which acts as a heat sink to remove the decay heat. Furthermore, the creep mechanical deformation mechanism leading to disassembly of the core is a slow process.

The AFCR design incorporates four major physical barriers to the release of radioactive materials from the reactor core to the environment:

- The fuel matrix. The bulk of the fission products generated are contained within the fuel grains or on the grain boundaries, and are not readily available to be released even if the fuel sheath fails
- The fuel sheath. There are large margins to fuel sheath failure under normal operating conditions
- The Heat Transport System (HTS). Even if fission products are released from the fuel, they are contained within the HTS. The HTS can withstand pressures and temperatures resulting from accident conditions. Adequate margins to fuel sheath failure are maintained, taking credit for the protective actions of the engineered safety features
- Containment. In the event of an accident that released fission products into the reactor building, automatic containment isolation will occur; ensuring subsequent release of radioactivity to the environment is controlled

CANDU Isotope Production Advantage

CANDU reactors can also produce isotope products. Cobalt-60 is produced using the adjusters in CANDU reactors. The favourable conditions of high neutron flux mean high production rates of Co-60 are realized quickly. Cobalt-60 is used in the industrial and health care fields for sterilization and sanitization applications.

Designed Based on Post-Fukushima Requirements

To make nuclear safety in the post-Fukushima era more robust and effective, the lessons learned from the Fukushima nuclear accident, including applicable recommendations from the Canadian Nuclear Safety Commission (CNSC) Fukushima Task Force Report have been implemented into the AFCR. We have also incorporated:

> NNSA post-Fukushima requirements
> CNSC regulatory requirements relating to the Fukushima accident
> IAEA, US Nuclear Regulatory Commission (NRC) and World Association of Nuclear Operators (WANO) recommendations relating to lessons learned from the Fukushima accident

The AFCR incorporates key features to prevent and mitigate severe accidents including passive and active provisions that provide water make-up to the steam generators, to the calandria vessel, to the calandria vault and passively and actively remove heat from the containment for the long term. A PCHRS is provided as a long term containment heat sink. The PCHRS removes heat from the containment by natural circulation with no operator intervention for 72 hours. Sufficient provisions are provided to protect the containment function during severe accidents for the AFCR.

Provisions to prevent accident progression and mitigate the accident consequences are taken into account in the AFCR together with consideration of CANDU reactor safety features. The AFCR maintains the CANDU reactor's built-in severe accident prevention and mitigation features, including the moderator as emergency heat sink to maintain core coolability, and presence of a large water source around the calandria to cool potential debris. Each safety function is performed by at least two independent means in the AFCR. Active and passive safety provisions are provided to ensure the fundamental safety functions (reactivity control, fuel cooling and containment of radioactive material) are achieved for all plant states. For any design basis or severe-accident, the reactor can be shut down by two independent shutdown systems, in addition to the control system. Safety enhancements for severe accident prevention and mitigation measures include independent passive and active make-up to the calandria vessel and calandria vault to maintain coolability in the calandria and reactor vault.

To ensure calandria vessel cooling from the outside via the water in the calandria vault and in-vessel retention (IVR), both active and passive measures are provided for the calandria vault make-up. The passive water make-up to the calandria vault is provided by gravity from a dedicated water tank at a high elevation inside the containment. Also the condensate from the PCHRS internal condensers is collected to feed the calandria vault. The water make-up to the calandria vault by pump action is provided by the SARHRS.

Our AFCR has an optional emergency containment filtered venting system (ECFVS) based on proven technology and similar to ECFVSs that have been installed in the other CANDU units. The ECFVS constitutes an additional layer of defence to prevent catastrophic failure of containment and is part of severe accident management guidelines (SAMG).

AFCR Fundamental Safety Function Features

Nuclear safety requires that radioactive products from the nuclear fission process are contained both within the systems for the protection of the workers and outside the structures for the protection of the public. The AFCR achieves this requirement at all times through the following fundamental safety functions:

1. Control of reactivity: Controlling the reactor power and, when necessary, shutting down the reactor
2. Removal of heat from the fuel: Removing heat from the reactor core, including decay heat following shutdown, to prevent fuel overheating and removing heat from the irradiated fuel in the spent fuel bay
3. Confinement of radioactive material and control of operational discharges, as well as limiting accidental releases
4. Containing radioactive products that are normally produced and existing in the fuel as well as in the process systems; and providing controlled, filtered and monitored releases of radioactive materials during normal operation, AOOs and accident conditions

The AFCR also provides sufficient means for monitoring safety critical parameters to guide operator actions at all times to ensure that the fundamental safety functions are being carried out. Fundamental safety functions are fulfilled for all plant states.

These nuclear safety functions are carried out to a very high degree of reliability in the AFCR by applying the following principles:

- The use of high-quality components and installations
- The use of inherent safety features to the extent practical
- The use of two Group safety design philosophy
- Implementing multiple defense-in-depth barriers for prevention of radioactive release
- Providing engineered safety features to prevent and mitigate the consequences of design basis accidents (DBAs)
- Providing complementary features to prevent and mitigate the consequences of beyond design basis accidents (BDBAs), including severe accidents

Reactivity Control

The AFCR has three methods for reactivity control: reactor power control and two independent safety shutdown systems. Reactor power control is carried out by the AFCR's reactor regulating system (RRS). The RRS controls the reactor power within stipulated limits in various operational states. The system operates independently of the two shutdown systems. The RRS includes liquid zone control units to adjust the flux level in the reactor and control absorber and adjuster units that absorb neutrons and optimize reactor power output and fuel burnup. This system allows for a setback function to reduce power at a controlled rate and also a stepback function to enable fast power reduction in the core.

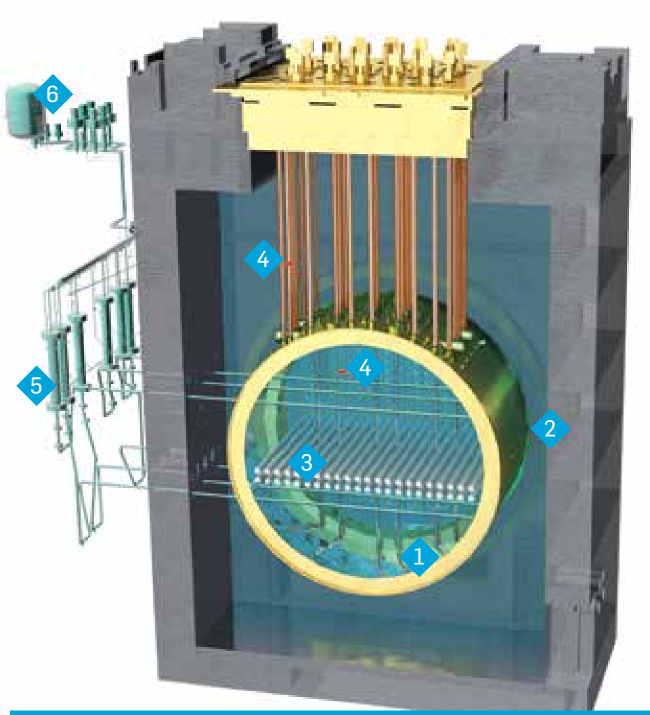
Shutdown system 1 (SDS1) consists of 32 cadmium vertical shutoff rods which fall into the core by gravity with initial spring assist. All shutoff rods are introduced into the core via guide tubes permanently positioned in the low pressure and low-temperature moderator environment. There are no mechanisms for rapidly ejecting any shutoff rods due to their placement in the low pressure moderator (a distinctive safety feature of the pressure-tube reactor design). The design of the shutoff rods is based on the proven CANDU 6 reactor design and includes enhancements for our AFCR.

Shutdown system 2 (SDS2) consists of six high-pressure gadolinium (neutron absorber) tanks for injection into the moderator through six horizontally oriented nozzles. The negative reactivity is introduced by highpressure injection of the gadolinium solution into the moderator in the calandria quickly rendering the reactor core subcritical, effectively stopping the fission chain reaction. The gadolinium nitrate solution is dispersed uniformly throughout the reactor, thus maximizing the shutdown effectiveness.

SDS1 and SDS2 are fully redundant, independent, diverse, separated shutdown systems, providing fast shutdown means in addition to the RRS. SDS1 and SDS2 are physically, logically, and functionally separated, and do not share devices with each other or with the control system. Each shutdown system has two diverse trip parameters, where practical, which are effective for each accident.

Reactivity control in the AFCR is a triple layer of defence that ensures reactor shutdown at all times (no loss of shutdown event).

Reactivity Control



1 Moderator

2 Reactor

3 Calandria Tubes (Not all are shown in illustration)

Shutdown System 1

4 Shutoff Units

Shutdown System 2

5 Gadolinium Tanks

6 Helium Tank

Fuel Cooling

Sufficient fuel cooling in the AFCR is provided for all plant states from normal operations through to design extension conditions. These plant states and the various conditions are described individually below.

Normal Operations

Heat Transport System (HTS) pumps circulate D_2O coolant to transfer heat from the fuel to the feedwater on the secondary side of the steam generators.

Shutdown State

Shutdown Cooling System removes decay heat from the core under full HTS pressure and temperature.

Forced Circulation Lost in Heat Transport System

The AFCR ensures that fuel is effectively cooled by the primary HTS thermosyphoning. Decay heat is continuously removed from the core as long as a source of feedwater is available to the steam generators.

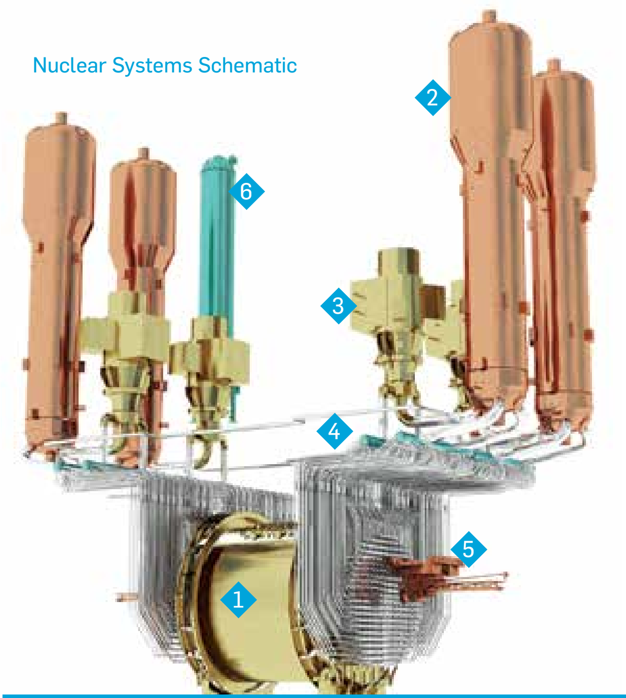
Loss of Feedwater Supply to the Steam Generators

The emergency water supply (EWS) system provides passive make-up water supply to the steam generators.

Non-Loss of Coolant Accident (LOCA) Events

Gravity make-up to the steam generators is provided by the EWS system to effectively remove decay heat from the core for at least 72 hours.

Nuclear Systems Schematic



1 Calandria
2 Steam Generator (4)
3 Heat Transport Pump (4)
4 Header (8)
5 Fuelling Machine (2)
6 Pressurizer

Station Blackout

Reactor core cooling via the steam generators is maintained for at least 72 hours with no operator intervention required. For long-term cooling, make-up water to the steam generators is provided by the EWS system pump. Each independent EWS reservoir contains enough water to remove decay heat for at least nine days for each unit.

Loss of Coolant Accident (LOCA) Events

The emergency core cooling system (ECCS) effectively cools the fuel and maintains fuel channel integrity. The ECCS provides water injection to the HTS in three phases:

- High-pressure emergency core injection (ECI) from accumulators;
- Medium-pressure ECI from the dousing tank; and
- Low-pressure ECC recovers, recirculates and cools the water from the reactor building basement

LOCA Combined with loss of ECC event

The moderator provides an emergency heat sink to maintain core coolability by effectively removing decay heat from core. The decay heat is sufficiently removed by moderator boil off, even when moderator cooling is unavailable. The moderator is an effective heat sink that stops accidents at the fuel channel boundary.

The AFCR provides large quantities of moderator water (260 m^3) plus passive and active water make-up to the calandria vessel to prevent severe core damage accidents:

- Passive water make up from the dousing tank to the calandria vessel by gravity
- Active moderator make-up by a dedicated severe accident prevention and mitigation system to cool the core for the long term

Calandria vault water provides for in-vessel retention (IVR) of core debris. The shield water system has sufficient thermal capacity to slow down the progression of a severe accident. Accident progression in a CANDU reactor would be slow due to the significant quantity of heat sinks surrounding the core. The water in the calandria vault ensures calandria vessel cooling to maintain core debris IVR.

The AFCR has both passive and active provisions to ensure water inventory in the calandria vault is maintained for calandria vessel cooling. This includes two passive systems for make-up water to calandria vault ensuring calandria vessel cooling for at least 72 hours:

- Independent water is provided for passive make-up to calandria vault only
- Condensate from the PCHRS is collected and returned to the calandria vault

Active make-up water is also provided to the calandria vault by the SARHRS using the water from either the EWS reservoir or the basement for long term cooling. The calandria vault water heat sink stops accidents at the calandria vessel boundary.

CANDU Spent Fuel Bay

Spent Fuel Cooling

The AFCR's spent fuel bay (SFB) ensures spent fuel cooling is maintained for 15 days without being dependent on operator action. Spent fuel is sufficiently cooled as long as it is covered by the water in the bay. The SFB has a redundant spent fuel bay make-up and cooling system, status monitoring and leakage detection. In addition, the SFB has mitigation measures for emergency spent fuel cooling including provisions for pool water make up and pool cooling. It is located at grade level and therefore potential for leakage during various accidents is significantly reduced relative to other reactor designs.

AFCR's Major Passive Heat Sinks

Four major passive heat sinks in the AFCR ensure decay heat removal from the reactor core and from containment:

- Gravity fed dousing water to fill fuel channels, SGs and calandria vessel
  - AFCR dousing water inventory is increased from CANDU 6 design to 2350 m^3
- Moderator volume is 260 m^3
- Shielding cooling water volume is 520 m^3
- Independent water source from the dousing water combined with condensate from passive containment heat removal system (PCHRS) fills calandria vault by gravity
  - Additional independent 600 m^3 of water is added to the dousing tank dedicated for calandria vault make-up only
  - Condensate from PCHRS is collected for calandria vault make-up

Containment

The AFCR has a robust containment to address DBAs and BDBAs. AFCR containment design pressure at 200 kPa(g) covers all DBAs, including a LOCA and a main steam line break (MSLB). The maximum containment pressure for DBAs is about 140 kPa(g). AFCR containment can withstand accident pressure of 400 kPa(g) with margin. The AFCR contains a steel liner to reduce leakage rate and minimize potential radioactive releases.

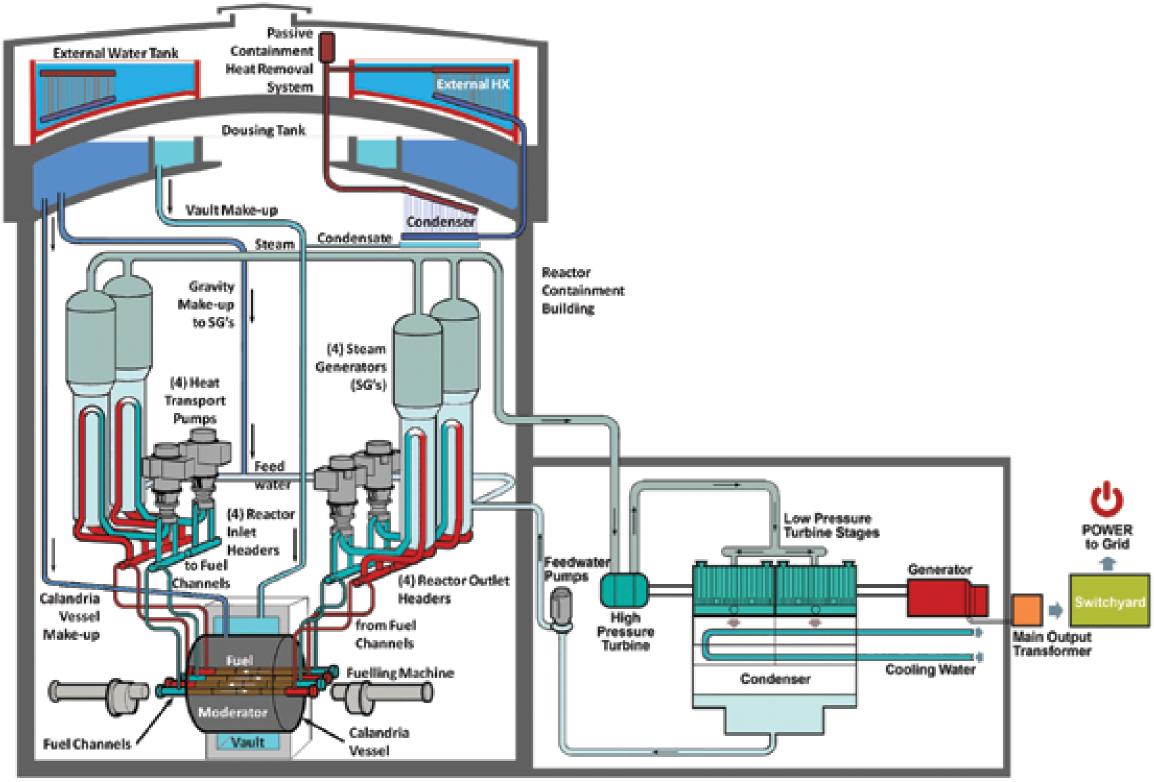
In addition, both active and passive measures can arrest containment pressure and remove decay heat from the containment. Specifically, the dousing system limits containment peak pressure for breaks inside containment by a gravity driven dousing spray. Local air coolers (LACs) remove the heat from the containment for long term.

Active and passive heat sinks ensure containment function for BDBAs. Specifically, active containment heat removal is provided by SARHRS for BDBAs (DECs). SARHRS can remove heat from containment for the long term. A PCHRS is a long term containment heat sink that removes heat from the containment by natural circulation with no operator intervention for 72 hours. Passive containment cooling is maintained by PCHRS as long as the water in the external water tank is available; operator action to provide water make-up to the PCHRS external water tank may be required after 72 hours.

The AFCR containment also contains passive and active provisions for hydrogen control and monitoring. These systems include:

- Passive autocatalytic recombiners (PARs)
- Hydrogen igniters
- On-line hydrogen monitoring system

The optional ECFVS is additional protection for the containment to avoid uncontrolled radioactive releases from the containment.



Overal AFCR Plant Flow Diagram with Key Passive Features

Reliable and Robust Design

Our AFCR is based on the reference Qinshan CANDU 6 design and is a further advancement of the EC6 design through the addition of new passive safety features and the use of alternative fuel (recycled uranium or thorium). The AFCR is Candu's latest and most advanced alternative fuel cycle pressurized heavy water reactor design for the international market.

Our AFCR design approach ensures safety during construction, commissioning and operation. All reasonably practicable design measures are taken into account to prevent accidents and to mitigate their consequences. We have ensured with a high level of confidence that, for all postulated accidents considered in the design including those of very low probability, radiological consequences would be below prescribed limits and that the likelihood of accidents with serious radiological consequences is extremely low. The intent of AFCR design is to practically eliminate accident sequences with a large or early release.

Fail Safe Design

Systems and components that are vital to safety are designed to fail to a safe state, as appropriate and to the extent practicable. Components fail to a safe state to lead the plant to a safe shutdown state and to maintain fission products barriers so that radioactive materials are confined to within regulatory limits. Components are designed, as far as practicable, to a safe state or be put in a safe state following a failure (e.g., where a loss of instrument air results in an unsafe failure, a back-up air supply is provided). Typical examples include the containment isolation system and shutdown systems.

Single Failure Criterion

The single failure criterion is taken into account in the AFCR design to ensure safety functions are performed despite one random failure of equipment independent of the initiating event. Account is taken of any consequential failure resulting from the single failure. This criterion applies to active components for which a single failure is postulated in both the short and long term. In the AFCR design, a system important to safety is capable of performing its intended safety functions credited in the design basis event analysis assuming a single failure within the system or in an associated system that supports its operation.

Diversity

To the extent practicable, diversity is applied to redundant systems that perform the same safety function by incorporating different attributes to reduce the potential for common-cause failures. The level of diversity provided is commensurate with the required reliability of performing the safety function.

Reliability

Reliability of the SSCs is achieved in design by:

- **Robustness** – minimizes probability of failure by adopting quality standards commensurate with their importance to safety
- **Qualification** – designed to withstand the loads and adverse environmental conditions induced by the design basis events (DBAs, including seismic event, fire, internal flooding, etc.)
- **Redundancy/diversity** – tolerant of both random and common mode failures

Grouping and Separation

Our AFCR is designed based on the CANDU “two group” design approach to achieve redundancy and independence. The unique CANDU two-group approach provides two sets of systems to accomplish the essential safety functions with redundancy to ensure reliability of mitigating safety functions. Each group can perform the essential safety functions and independently maintain the plant in a safe state. In addition, component redundancy is built in to the safety systems to satisfy the single failure criterion. Physical and functional system separation is designed into the two-group concept. The components of safety systems that perform similar functions are separated to the maximum practicable extent, and redundant components within systems are physically separated according to their susceptibility and common hazards.

Group 1 and Group 2 Concept

> AFCR’s two group design ensures there are two independent means to achieve the same safety functions.
>
> Group 1 and Group 2: functional and physical separation plus redundancy and diversity.

Seismic Qualification

Earthquakes are natural external common cause events, which are considered in the AFCR. The SSCs required to perform or support the performance of fundamental safety functions during and/or following an earthquake are seismically qualified.

Environmental Qualification

The safety equipment is environmentally qualified to ensure it performs the required safety function(s) without experiencing a common cause failure with the plant in a normal or abnormal operating condition, or during a DBA condition. Equipment credited to operate during BDBAs (including severe accidents (SAs)) and located in the environmental conditions resulting from these events is assessed for its survivability.

Ageing

To ensure the capability of the SSCs important to safety to perform the necessary safety function throughout their design life, relevant ageing and wear-out mechanisms and potential age related degradation have been taken into account and appropriate margins provided. Ageing and wear-out effects in all normal operating conditions, testing, maintenance, maintenance outages, and plant states in a postulated initiating event (PIE) and post-PIE have also been taken into account. All life-limiting factors are evaluated and addressed, in particular ageing effects. The effects of ageing are addressed in the AFCR safety analysis.

Radiation Protection

The AFCR design ensures workers and members of the public are provided with adequate protection from radiation throughout the operating life and into the decommissioning phase of the reactor. The radiation protection provisions ensure safety for all normal, abnormal, and accident conditions. Our AFCR complies with the recommendations of the International Commission on Radiological Protection (ICRP) and annual exposure limits as set out in ICRP-60.

AFCR design provisions ensure potential radiation doses to the public and site personnel do not exceed these limits. Overall risk to the public from all plant states is judged against the AFCR safety goals based on Generation III requirements. Measures are taken to ensure that the radiation protection and technical safety objectives are achieved, and that radiation doses to the public and to site personnel in all operational states, including maintenance and decommissioning, do not exceed prescribed limits, and are as low as reasonably achievable (ALARA).

The exposure of plant personnel to internal and external radiation is limited by layout and structural shielding arrangements, by control of access to areas of high activity or of possible contamination, and by combination of systems incorporated into the design. AFCR design ensures that the limits prescribed Chinese national standard GB6249 and recommendations provided in ICRP Publication 103 are met.

Human Factors

We integrate human factors into our design process to ensure:

- A thorough and consistent approach to system design
- Consideration of operating experience review information, so designs may be evolved with knowledge of past performance criteria
- Establishment of required human factors engineering (HFE) documentation for system design input
- Design effort towards definition and assessment of operator/maintainer system interface functionality, information and control needs, environmental issues, and equipment layout for special tool and staff accessibility and maintenance concerns (e.g., equipment replacement, removal, etc.)

The overall application of HFE ensures a design that supports safe, productive, efficient operating characteristics throughout all stages of construction, commissioning, operation, maintenance, testing, inspection, and decommissioning.

Out-of-Core Criticality Safety

The AFCR design emphasizes the prevention of out-of-core criticality and protection of individuals, society and the environment from harm. To that effect, our design follows the good safety practices described in the ANSI/ANS-8 series of standards, consistent with Chinese national standards GB15146-2008 series regarding nuclear criticality safety.

Provision for In-Service Testing, Maintenance, Repair, Inspection and Monitoring

AFCR structures, systems and components (SSCs) important to safety are designed to be calibrated, tested, maintained, repaired or replaced, inspected and monitored for their functional capability over the lifetime of the nuclear power plant to demonstrate reliability targets are being met. For the SSCs important to safety that cannot be designed to be able to be tested, inspected or monitored to the extent desirable, other proven alternative and/or indirect methods are specified; and conservative safety margins are applied or other appropriate precautions are taken to compensate for possible unanticipated failures.

Complementary Design Features to Enhance Safety Provisions

Complementary design features address BDBAs (Design Extension Conditions (DECs)), including the complementary prevention and mitigation measures provided in the EWS, SARHRS and PCHRS. Complementary design features in our AFCR design to address BDBAs (DECs) include:

- Provisions to remain in a safe shutdown state and to prevent criticality
- Provisions to prevent core damage
- Provisions to cool core debris
- Provisions to retain the core debris at in-vessel retention
- Provisions to maintain containment integrity
- Provisions to preclude uncontrolled radioactive material releases
- Hydrogen control and monitoring measures
- Provisions to maintain spent fuel cooling for extended periods
- Alternate AC power supply
- Alternative water supply

For BDBAs, AFCR has sufficient complementary design features to prevent accident progression and mitigate the consequences of severe accidents.

Severe Accident Recovery and Heat Removal System (SARHRS)

The AFCR incorporates a seismically qualified SARHRS to prevent and/or mitigate severe accidents. The purpose of SARHRS is to remove decay heat from the core during a BDBA event, and as such contributes to nuclear power plant (NPP) safety goals. SARHRS is a complementary design feature, and belongs to Level 4 defence in the defence-in-depth (DiD) concept.

SARHRS provides the following functions:

- Make-up water to the calandria vessel
- Make-up water to the calandria vault
- Removal of heat from the containment

The system is composed of a make-up pump, a cooling water pump, a heat exchanger, associated piping lines and valves. It provides a recovery and recirculation mode as a long-term heat removal provision after a BDBA. The system is powered by a SARHRS dedicated diesel generator (DG) for each unit. The SARHRS is a manually operated system. All the active components are located outside the containment for accessibility following a BDBA. All the valves are remotely controlled, and are available for local manual operation as well.

Passive Water Make-up to the Calandria Vessel

A passive moderator make-up function is also provided as a fourth level of defence-in-depth in the AFCR as part of the EWS. Gravity driven moderator make-up from the dousing tank maintains the moderator as a sustainable heat sink for decay heat removal from the core for BDBAs. It prevents accidents from progressing to a severe core damage accident (SCDA) for most BDBAs. The flow rate for the make-up from the dousing tank to the calandria vessel by gravity is selected based on the moderator boil-off rate required for decay heat removal with additional margin for leakage considerations though the failed bellows during accidents.

The EWS system passive moderator make-up function can provide water make-up to the calandria vessel for 24 hours for events without initiating ECCS. With the ECCS available, there is no concern of fuel cooling since decay heat can be effectively removed from the core by the ECCS.

Passive Calandria Vault Water Make-up

To ensure in-vessel retention (IVR) of core debris in severe accidents, the AFCR design includes provisions to provide water make-up to the calandria vault by gravity from a dedicated water tank at high elevation inside the containment. This ensures calandria vessel cooling from the outside by the water in the calandria vault and IVR. SARHRS provides a water make-up to the vault by pump to maintain the calandria vessel integrity. Whereas, a passive calandria vault make-up system (PCVMS) provides passive backup water make-up to the vault. As part of the PCVMS function, the condensate from the PCHRS condensers is also collected to feed the calandria vault by gravity.

Passive Containment Heat Removal System (PCHRS)

Our AFCR's PCHRS is another layer of defense for the containment and an important complementary design features to manage BDBAs (DECs), which provides a long-term containment heat sink following an accident. The PCHRS removes decay heat from the containment by natural circulation thereby reducing the containment pressure and temperature within the maximum allowable levels for BDBAs without operator intervention for 72 hours.

The major components of the PCHRS include the containment condensers inside the containment, the external containment heat exchangers (HXs), the connection pipes between the containment condensers and the external HXs and the cooling water tank. Under accident conditions, steam inside the containment atmosphere condenses at the surface of the containment condensers and heat is transferred the outside water by natural circulation. The water inside the condenser tubes is heated by heat transferred from steam condensation. The heated water has a higher temperature and less density. A natural circulation flow is established in the loop by the difference of the water density between the warm and cold water lines, driving the warm water up to the external containment HX through the warm water line and the cold water moving down to the containment condenser through the cold water line. The external containment HXs are submerged in the cooling water tank located on the top of the reactor building outside the containment. The warm water inside the HX tubes is cooled by the water in the cooling water tank.

The PCHRS also collects condensate and returns it directly to the calandria vault to maintain the water inventory in the vault. This water source supplements the PCVMS water make-up from the independent water source in the dousing tank. In-vessel retention is maintained as long as the vault water is sustained for cooling the calandria vessel from the outside.

The PCHRS meets the following:

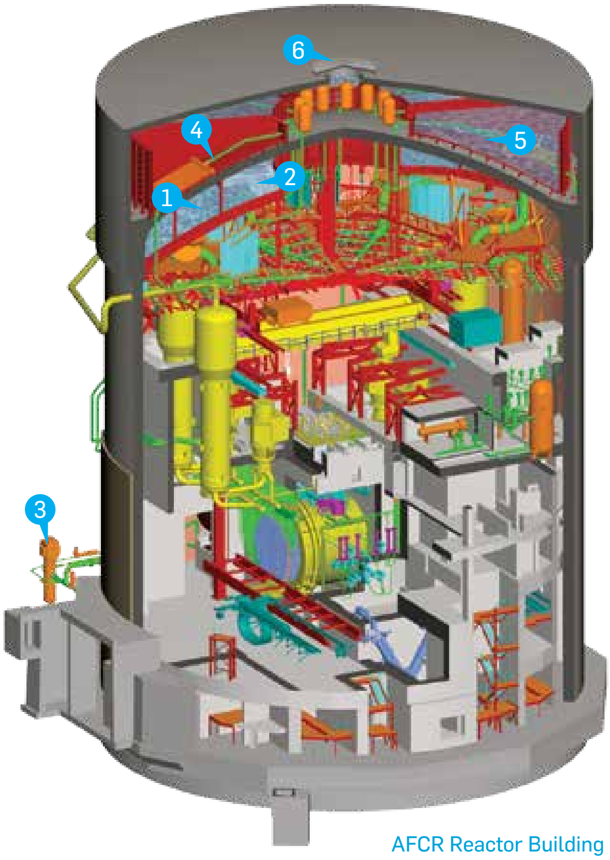
- Withstands effects of natural phenomena such as extreme weather, earthquakes, or floods
- Withstands dynamic effects of an accident and remains functional in accident environment conditions
- Automatically operates following a BDBA with no operator action required for 72 hours
- Passively and sufficiently removes decay heat from containment atmosphere to reduce containment pressure within its maximum allowable level for BDBAs
- Collects condensate and returns it to the calandria vault
- Provides water make-up to the cooling water tank after 72 hours

The PCHRS is designed in modules. Each module consists of one containment condenser, one external HX, associated piping line as well as isolation valves, an expansion tank and a cooling water tank.

The PCHRS design is based on representative accident conditions. Additional PCHRS testing is performed in the detailed design stage to confirm system performance meets design requirements.

Emergency Containment Filtered Venting System (ECFVS)

Containment is designed to minimize radioactive releases following a severe accident. The AFCR ECFVS is based on proven technology and is similar to the ECFVS installed in our other CANDU NPPs. The ECFVS allows containment depressurization to be performed while minimizing radioactive releases to the environment. Vented vapours from the containment atmosphere pass through a scrubber/filter vessel to remove high activity isotopes and aerosols to contain or control the radioactive releases. The system is fully passive and does not require any external electric or other power sources during standby or in operational mode (except monitoring). The ECFVS constitutes a last resort measure to prevent catastrophic failure of containment and is part of severe accident management guidelines (SAMG).



1	Dousing Tank
2	Calandria Vault Make-up Water
3	Severe Accident Recovery & Heat Removal System
4	Passive Containment Heat Removal System (PCHRS) Loop
5	PCHRS Cooling Tanks
6	PCHRS Vented Enclosure

AFCR Reactor Building

Safety and Safety Support Systems

Safety Systems

Reactor safety systems are designed to mitigate the consequences of plant process failures, and to ensure reactor shutdown, removal of decay heat, and prevention of radioactive releases. The safety systems in our AFCR design maintain the traditional CANDU reactor practice of providing:

- Independent shutdown systems 1 and 2
- An emergency core cooling system (ECCS)
- A containment system

The two-shutdown systems, the ECCS, and the containment boundary system, meet specified regulatory reliability targets with which the system design complies. The containment boundary includes the physical structures designed to prevent and control the release of radioactive substances.

Safety support systems are also provided to ensure reliable electrical power, cooling water and instrument air supplies to the safety systems. Standby generators are provided as a backup to station power for postulated loss of station power events.

Safety systems and their support services are designed to perform with a high degree of reliability and is achieved through stringent technical specifications, including seismic qualification and environmental qualification for accident conditions.

Shutdown Systems

The AFCR's two passive, fast acting, fully capable, diverse shutdown systems are physically and functionally independent of each other. This feature of the CANDU reactor design ensures defence in depth.

Emergency Core Cooling System

The ECCS is designed to supply emergency coolant to the reactor in three stages:

- The highpressure ECCS is designed to provide initial light water injection to the HTS from the ECC accumulator tanks pressurized by air/gas pressure
- Following termination of highpressure injection, the mediumpressure injection system supplies light water to the HTS from the dousing tank via the ECC pumps
- Following the termination of medium- pressure injection (upon depletion of the dousing tank), the long term automatic ECC injection is provided by collecting the mixture of heavy water and light water from the reactor building basement and recirculating into the HTS via the ECC pumps and heat exchanger

During normal operation, the ECC system is poised to detect any LOCA that results in a depletion of HTS inventory (i.e., reactor coolant) to such an extent that make-up by normal means is not assured.

The system maintains or reestablishes sufficient cooling of the fuel and fuel channels for the design basis events, so as to limit the release of fission products from the fuel and maintain fuel channel integrity. After reestablishing fuel cooling, the system provides sufficient cooling flow to prevent further damage to the fuel.

Containment System

The containment system forms a continuous, pressure-retaining envelope around the reactor core and the HTS. The containment structure protects the public and environment from all potential internal events, and is designed to withstand tornadoes, hurricanes, earthquakes, malevolent acts, large aircraft crash, etc., and to prevent the release of radioactive material to the environment.

The containment boundary consists of a steel-lined, pre-stressed concrete reactor building structure, access airlocks and a containment isolation system. Local air coolers remove heat from the containment atmosphere and are located to best maintain operating containment pressure and temperature.

The hydrogen control system in containment prevents build-up and uncontrolled burning of hydrogen. In addition, the containment internal structures are arranged to promote natural air mixing inside containment.

The dousing system is connected to the elevated dousing tank and reduces reactor building pressure and maintains containment integrity, if required, in the event of accidents.

The strength of the containment structure, including access openings and penetrations, has sufficient margins of safety to withstand potential positive internal pressures, negative pressures, temperatures, dynamic effects such as missile impacts, and forces anticipated to arise as a result of DBAs and BDBAs. The containment system consists of a post-tensioned pre-stressed concrete containment structure with a steel liner, energy sinks consisting of an automatically initiated dousing system and building local air coolers, access airlocks, hydrogen control system, and a containment isolation system consisting of valves and dampers in the system lines penetrating containment. Both active and passive design features are provided to remove decay heat from the containment for BDBAs. The ECFVS provides another layer of defence to protect the containment from overpressure and to prevent uncontrolled large radioactive release.

Safety Support Systems

The safety support system supports the operation of one or more safety systems.

Emergency Water Supply System

The EWS system provides cooling water to the ECC heat exchangers and provides makeup water to each HTS loop and steam generators to ensure fuel cooling after an event which causes the loss of normally operating systems, or to act as a backup source of cooling water in the long term after an event. The EWS also provides gravity water make-up to the calandria vessel from the dousing tank to maintain the moderator as a heat sink for BDBAs. If the calandria vessel moderator rupture discs burst, the EWS would provide the water make-up flow path from the dousing tank to the calandria vessel, to compensate the sudden loss of the moderator through flashing when the rupture disc burst, and/or the moderator leak. This action would prevent a severe core damage accident or delay the onset of severe core damage and provide more time for the operator to take mitigating action.

Each AFCR unit is equipped with a dedicated EWS and EWS reservoir. Each unit has two 100% pumps taking suction from each of the onsite EWS water reservoirs that are in a separate location from the main plant service water system intake. Under accident conditions the EWS would provide both active and passive water sources. Passive cooling water supply would last for more than 72 hours. The active supply would provide cooling water for the longer term.

Raw Service Water and Recirculated Cooling Water Systems

A closed-loop recirculated cooling water (RCW) system transfers heat to the open-loop raw service water (RSW) system, from which heat is transferred to the ultimate heat sink. The RSW system is composed of four raw service water pumps in parallel. During normal operation, three of the four pumps operate. Four RCW/RSW heat exchangers form the interface between the RCW and RSW systems. The RCW system is also composed of four pumps in parallel, with three of four pumps operating during normal operation.

Connectivity of the RCW supply lines is arranged with valves in place so supply can be partitioned into two separate trains, with each train supplying one ECC heat exchanger and one moderator cooling system heat exchanger. This improves reliability of RCW and the supported systems.

Emergency Power Supply System

The electrical power distribution systems are separated into Group 1 and Group 2 in accordance with the two group separation philosophy. The Group 1 electrical distribution system provides power to the process systems used for power production, systems important to safety and safety support systems. The Group 2 system is the emergency power supply (EPS) system. This system provides a seismically qualified back-up power source to selected safety systems and safety support systems, which are normally supplied from the Group 1 system.

The EPS system is designed to provide a Group 2 seismically qualified alternative source of electrical power supply to systems important to safety in the event that normal power supplies (Class IV, Class III) are lost. Each AFCR unit has a dedicated EPS to supply the necessary safety loads. The EPS system for each unit is composed of two duplicate, odd and even, automatically started, seismically qualified and functionally independent trains along with uninterruptible power supplies (UPS) and a distribution system.

Each EPS generating set consists of a diesel generator with battery starting system, brushless excitation system, governor and controls.

Postulated events specifically supported by the EPS system are:

- Design basis earthquake
- Total loss of electrical power (both Class IV and III)
- LOCA followed by site design earthquake after 24 hours

In case of an SBO, the seismically qualified UPS provides power to loads required for provision of a heat sink capable of supporting the safety critical loads for up to 24 hours.

An independent SARHRS diesel generator for each unit is a complementary design feature to power a limited number of loads for mitigation of severe accidents.

In addition, each reactor unit is provided with its own seismically qualified mobile diesel generator to cope with extended SBO events.

Two-Unit AFCR Plant Layout

AFCR Plant Siting and Layout

Our AFCR units are highly adaptable to different site conditions and can accommodate a wide range of geo-technical characteristics, meteorological conditions and owner requirements through its flexible design. The layout of the AFCR plant provides adequate separation by distance, elevations (different heights) and the use of barriers for SSCs important to safety that contribute to protection and safety. Security and physical protection have been enhanced in the AFCR design to meet the latest criteria required in response to potential common mode events (e.g., fires, aircraft crashes and malevolent acts). The plant is also tornado protected.

The layout for a two-unit plant is designed to achieve the shortest practical construction schedule while supporting shorter maintenance durations with longer intervals between maintenance outages. The buildings are arranged to minimize interferences during construction, with allowance for on-site fabrication of module assemblies. Open-top construction (before setting the roof of the RB in place), allows for the flexible sequence of installation of equipment and reduces the overall project schedule risk. Each unit is designed to operate independently during all operational conditions but with the capability to support each other during seismic events.

The size of the power block (plant foot-print) for a two-unit integrated AFCR plant is 48,000 square metres. The power block consists of two reactor buildings, two service buildings, two turbine buildings, two high-pressure emergency core cooling buildings, two secondary control areas and one heavy water upgrader building.

The AFCR is seismically designed to withstand an earthquake that would happen once in every 10,000 years with sufficient margin. It is robust enough to withstand other natural disasters such as flooding, tornados, tsunamis, or a typhoon.

The principal structures associated with each AFCR unit are the reactor, service and turbine buildings.

The RB internals are divided into three areas: accessible, restricted access and inaccessible. Systems and equipment requiring maintenance or access during on-power operations are located in areas that are safe for personnel to enter.

The service building is arranged so the main control room (MCR) and equipment areas are separated from the secondary control area (SCA) and its related support services by 180 degrees with the reactor building between them. This arrangement makes it virtually impossible for both control areas to be lost due to a common cause failure.

Within the service building, the spent fuel transfer and storage bays are located immediately adjacent to the reactor building. This arrangement keeps the length of the spent fuel transfer duct and mechanism as short as practical while locating the storage bay in an area remote from the rest of the service building.

The turbine building adjoins the service building with the turbine auxiliary bay providing the shortest length of inter-phasing piping and cables.

Auxiliary structures include the administration building, the condenser cooling water (CCW) pump house, water intake and discharge, the HPECC building, the SARHRS building, and the Emergency Water Supply (EWS) pump house.

A tritium splitter facility is also included as a part of the AFCR twin-unit plant.

Reactor Building

The AFCR RB houses the reactor, fuel-handling systems, HTS including the steam generators, and moderator system, together with their auxiliaries and the safety systems and complementary design features. It is a multilevel, reinforced concrete and steel structure that is seismically qualified, tornado protected, and protected against malevolent acts.

The RB is a pre-stressed, seismically qualified, concrete building and has been strengthened further compared to previous CANDU 6 designs to resist internal and external events, including a large aircraft crash. Pre-stressed concrete is reinforced with cables that are tightened to keep the structure under compression and to behave in an elastic manner under all design basis events, with a significant margin. The concrete containment structure has an inner steel liner that reduces leakage rates in the event of an accident. CANDU reactors inherently have lower containment pressures during postulated accidents. Despite this advantage, our AFCR has a thick walled containment structure similar to those of other Generation III PWR designs. This approach results in the greatest containment building design margins.

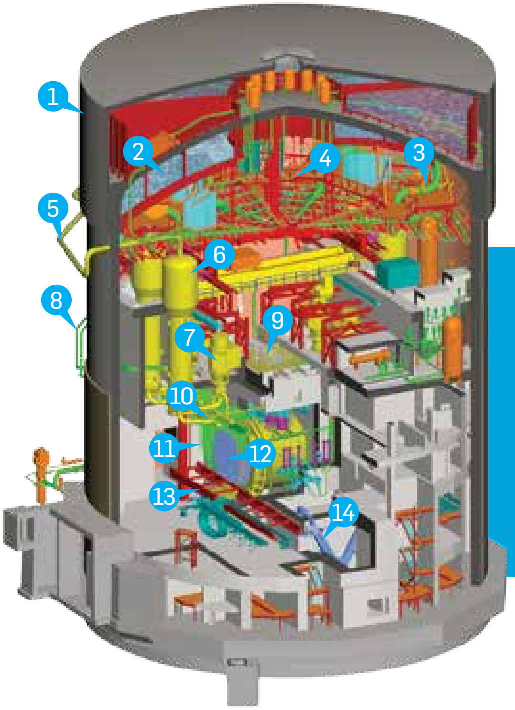
The entire structure, including concrete internal structures, is supported by a reinforced concrete base slab that ensures a fully-enclosed boundary for environmental protection and biological shielding which in turn reduces the level of radiation emitted outside the reactor building, during operation, design basis internal and external events and beyond design basis internal and external events, to values that are insignificant to human health.

Internal shielding allows personnel access during operation to specific areas for inspection and routine maintenance. These areas are designed to maintain temperatures that are suitable for personnel activities. Airlocks are designed as routine entry/exit doors.

Containment structure perimeter walls are separate from internal structures, eliminating any interdependence and providing flexibility in construction.

The AFCR containment building also includes a heat sink and the PCHRS, located on top of the containment structure, to remove heat from containment through passive means. Through this new feature, the AFCR is Candu's latest and most advanced alternative fuel cycle pressurized heavy water reactor designed with multiple layers of defence through both active and passive safety features.

In addition, an ECFVS is also provided as another layer of defence in depth.



1	Reactor Building
2	Dousing Tank
3	Dousing System Supply Pipe
4	Dousing System
5	Main Steam Line
6	Steam Generator
7	Heat Transport Pump
8	Main Feed Water Line
9	Reactivity Mechanism Deck
10	Headers
11	Feeder Pipes
12	Calandria
13	Fuelling Machine Bridge & Carriage
14	Spent Fuel Handling Mechanism

AFCR Reactor Building

Service Building

The AFCR service building is a multi-level, reinforced concrete structure that is seismically qualified and tornado missile protected. It accommodates the “umbilicals” that run between the principle structures, the electrical systems and the spent fuel bay and associated fuel-handling facilities. It houses the emergency core cooling pumps and heat exchangers.

The spent fuel bay is a water-filled pool for storing spent fuel. The AFCR spent fuel bay is located at grade level and the potential for leakage during various accidents is significantly reduced relative to other types of reactor designs.

Safety and isolation valves of the main steam lines are housed in a seismically qualified and tornado missile protected concrete structure that is located on top of the service building. The layout of the service building is optimized to ensure the highest level of ergonomics and operational ease based on feedback from other CANDU reactor operating stations.

The service building is designed to protect the spent fuel bay, secondary control area, airlocks and emergency power supply against a large aircraft crash.

Turbine Building

The AFCR turbine building is located on one side of the service building wherein the service building interfacing wall is tornado missile resistant. This location is optimal for access to the main control room; the piping and cable tray run to and from the service building; and the condenser cooling water ducts run to and from the main pump house. Access routes are provided between the turbine building and the service building.

The turbine building houses the turbine generator. It also houses the auxiliary systems, the condenser, the condensate and feedwater systems, the building heating plant, and any compressed gas required for the balance of plant. The balance of plant consists of the remaining systems, components and structures that comprise the complete power plant that are not included in the nuclear steam plant.

The heat from the reactor coolant converts the feedwater into steam in the steam generators. This steam drives the turbine, which in turn drives the generator to create electricity.

The condenser cools the steam from the steam generator and converts it back to water (condensate) to be converted into steam again.

Blowout panels in the walls and roof of the turbine building relieve the internal pressure in the turbine building in the event of a steam line break.

Nuclear Systems

The AFCR nuclear systems are located in the reactor building and the service building. These buildings are robust and shielded for added safety and security. Shielding is a protective barrier that reduces or eliminates the transfer of radiation from radioactive materials.

The nuclear systems are composed of:

> An HTS with heavy water reactor coolant, four steam generators, four heat transport pumps, four reactor outlet headers, four reactor inlet headers, feeders and interconnecting piping. This configuration is standard on all CANDU reactors

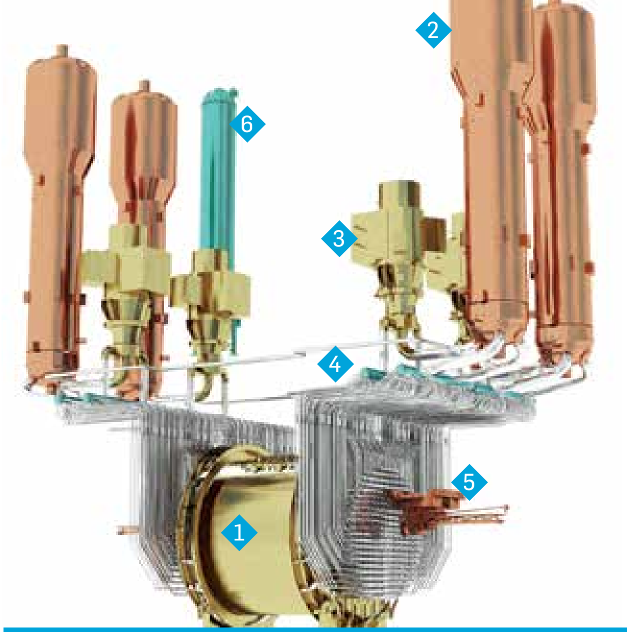
> A heavy water moderator system

> A reactor assembly that consists of a calandria vessel complete with fuel channels installed in a concrete vault

> A fuel handling system that consists of two fuelling machine heads, each mounted on a fuelling machine bridge that is supported by columns, which are located at each end of the reactor

> Two independent shutdown systems SDS1 and SDS2, the ECCS, the containment system and associated safety support systems

An illustration of the main nuclear systems that form the reactor coolant pressure boundary is shown below.



Main Nuclear Systems Schematic

1 Calandria
2 Steam Generator (4)
3 Heat Transport Pump (4)
4 Header (8)
5 Fuelling Machine (2)
6 Pressurizer

Heat Transport System

The AFCR HTS, similar to the reference CANDU 6 design, circulates pressurized heavy water coolant through the reactor fuel channels to remove heat produced by the nuclear fission chain reaction in the reactor core. The heated coolant is circulated through the steam generators to produce steam that drives the turbine generator system. The heat transport system consists of 380 horizontal fuel channels with associated corrosion-resistant feeders, four reactor inlet headers, four reactor outlet headers, four steam generators, four electrically-driven heat transport pumps and interconnecting piping and valves arranged in a two-loop, figure-of-eight configuration. The headers, steam generators and pumps are all located above the reactor.

While maintaining the CANDU 6 reactor-basis for reduced implementation risk, the AFCR incorporates a series of changes to ensure a minimum 60-year plant life at full capacity while having the features required for both recycled uranium and thorium fuel use.

The steam generator size has been incrementally increased to further enhance thermal and core physics margins by establishing sub-cooled conditions.

Our CANFLEX fuel bundle is a qualified and proven bundle configuration. In our AFCR, it is used both for DRU and thorium-based fuel applications for improved core thermalhydraulics and physics characteristics.

The thickness of the pressure tubes has been increased to ensure longer life, while the feeder pipes have been resized for improved flow distribution and reduced pressure drop.

Heat Transport System Key Design Parameters	
Reactor outlet header operating pressure [MPa(g)]	9.89
Reactor outlet header operating temperature [°C]	308
Reactor inlet header operating pressure [MPa(g)]	11.0
Reactor inlet header operating temperature [°C]	263
Maximum single-channel flow (nominal) [kg/s]	28.6

Steam Generators

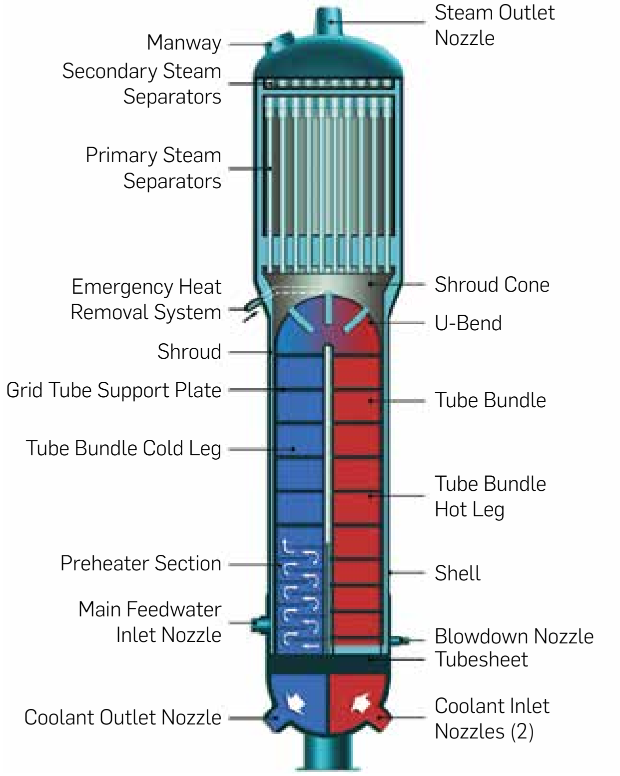
The AFCR SGs are slightly larger than those of the CANDU 6 reactor while still maintaining all the proven characteristics. The tubing is made of IncoloyTM800, a material proven in CANDU 6 reactor stations. The light water inside the steam generators, at a lower pressure than the hot heavy water reactor coolant, is converted into steam.

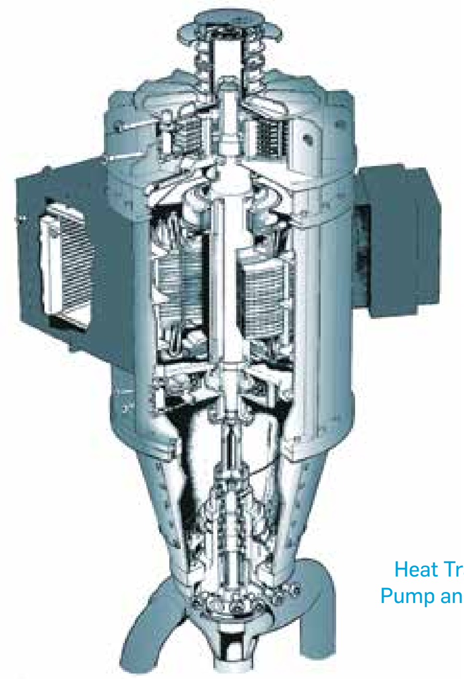
The SGs are designed for 60-year life with periodic primary and secondary side cleaning. Additional features have been included in the reactor design for ease of replacement, if required.

Steam wetness (ratio of vapour/liquid concentration in steam), has been reduced at the steam nozzle using the latest steam separator technology. This results in improved turbine cycle economics.

Steam Generator Design Data	
Number	4
Nominal tube diameter [mm]	15.9
Nominal steam temperature [°C]	260

Steam Generator





Heat Transport Pump and Motor

Heat Transport System Pumps

The four HTS pumps are vertical, single stage, double volute, single suction, double discharge centrifugal pumps. The AFCR HTS pumps retain the CANDU 6 mechanical multi-seal design, which allows for easy replacement. The heat transport pumps circulate reactor coolant through the fuel bundles in the reactor's fuel channels and through the steam generators. Electric motors drive the HTS pumps.

Cooling the pump seals lengthens the pump service life and the time that the pump will operate under accident conditions.

The AFCR HTS pumps are identical to those in CANDU 6 reactors, to reduce any implementation risk.

Heat Transport Pump Data	
Number	4
Rated flow [L/s]	2,228
Rated head [m]	215
Motor rating [MW]	6.7

Heat Transport Pressure and Inventory Control System

The heat transport pressure and inventory control system of our AFCR consists of a pressurizer, liquid relief valves, a degasser-condenser, two heavy water feed pumps, and feed and bleed valves. The system is designed for a 60-year life.

This system provides:

- Pressure and reactor coolant inventory control to each heat transport system loop
- Overpressure protection
- Degassing the HTS coolant

Moderator System

The AFCR moderator system is a low-pressure and low-temperature heavy water based system. It is independent of the heat transport system. The moderator system consists of pumps and heat exchangers that circulate heavy water moderator through the calandria and remove heat that is generated during reactor operation. The heavy water acts as both a moderator and reflector for the neutron flux in the reactor core.

The moderator slows down neutrons emitted from the fission chain reaction to increase the chances of the neutrons hitting another atom and causing further fission reactions. The reflector is the material layer around the reactor core that scatters neutrons and reflects them back into the reactor core to cause further fission chain reactions. This capability is one of the fundamental reasons behind the high fuel efficiency of the AFCR core and its ability to use multiple fuel types efficiently.

The moderator system fulfills a safety function that is unique to CANDU-type reactors. It also serves as a backup heat sink for absorbing the heat from the reactor core in the event of loss of fuel cooling (e.g., failure of the heat transport system) to mitigate core damage.

The AFCR maintains the proven CANDU 6 reactor dousing system, an elevated water tank that provides additional passive gravity-fed cooling water inventory to the calandria that houses the moderator. This connection extends core cooling and delays severe accident event progression. The moderator is not only a means of increasing fuel efficiency but it distinguishes the CANDU reactor from all other commercial reactor designs in terms of added passive safety.

The AFCR moderator system has minor variations from the C6 design, to use uranium, recycled uranium and thorium-based fuels to meet higher seismic requirements, to ensure longer operational life and to accommodate increased gamma heating.

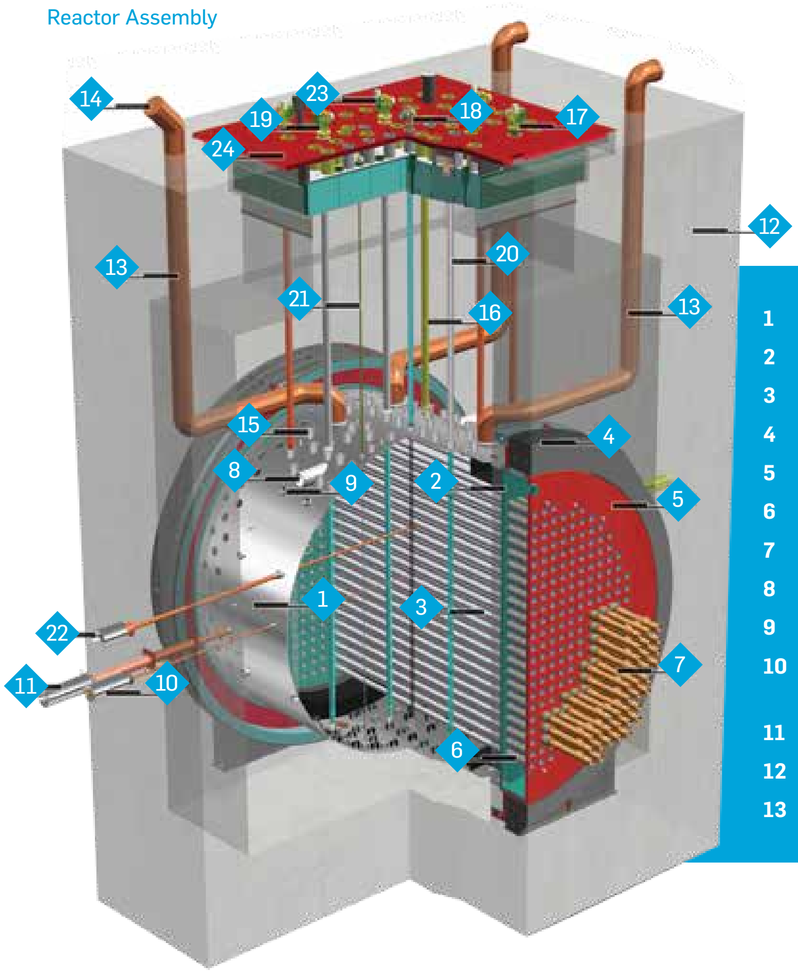
Reactor Assembly

The AFCR reactor assembly consists of a horizontal, cylindrical, low-pressure calandria and end-shield assembly. This enclosed assembly contains the heavy water moderator, the 380 fuel channel assemblies and the reactivity mechanisms. The reactor is supported within a concrete, light water-filled calandria vault. Fuel is enclosed in the fuel channels that pass through the calandria and end-shield assembly. Each fuel channel permits access for re-fuelling while the reactor is on power.

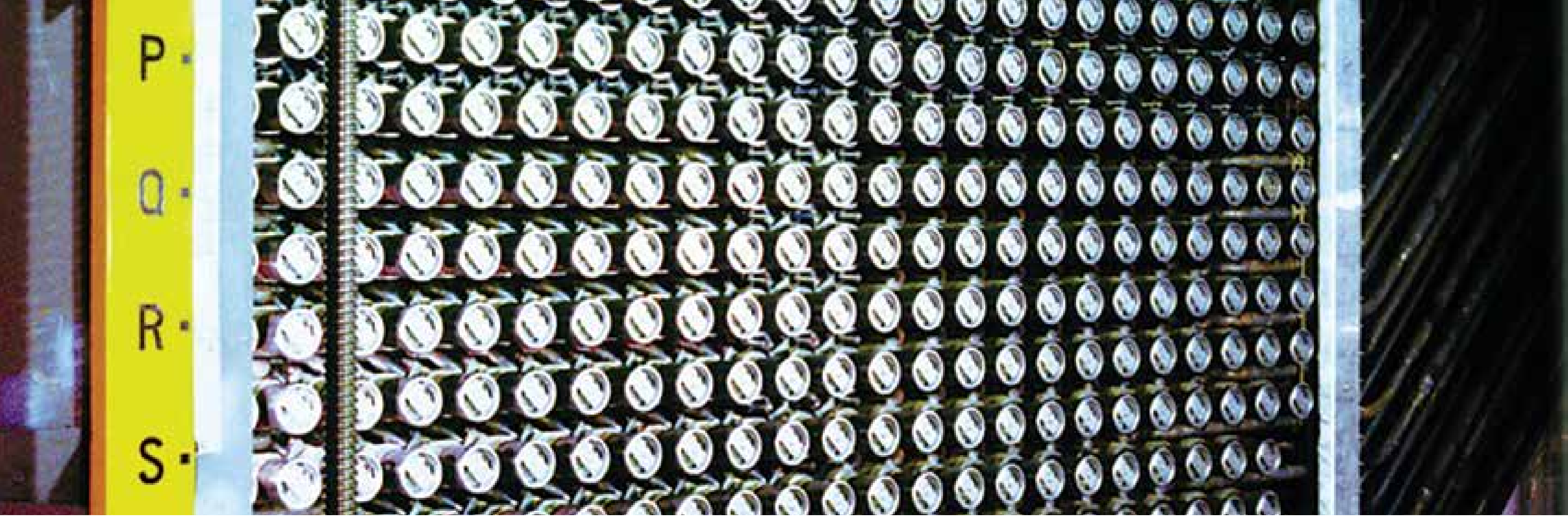
The ability to replace fuel while on power means minimal excess reactivity in the core at all times, an inherent safety feature. On-power fuelling creates operational flexibility (i.e., it improves outage planning as fixed cycle times are not required) and allows prompt removal of defective fuel bundles without shutting down the reactor. The horizontal fuel channels are made of zirconium niobium alloy pressurized tubes with 403 SS end-fittings.

Reactor Core Design Data	
Output [MW_{th}]	2,084
Coolant	D_2O
Moderator	D_2O
Fuel channels	380
Lattice pitch [mm]	285.75

Reactor Assembly



1 Calandria
2 Calandria Tubesheet
3 Calandria Tubes
4 Embedment Rings
5 Fuelling Tubesheet
6 End Shield Lattice Tubes
7 End Fittings
8 Moderator Outlet
9 Moderator Inlet
10 Horizontal Flux Detector Unit
11 Fission Chamber
12 Calandria Vault Wall
13 Pressure Relief Pipes
14 Rupture Disc
15 Reactivity Control Unit Nozzles
16 View Port
17 Shutoff Unit
18 Adjuster Unit
19 Control Absorber unit
20 Liquid Zone Control Unit
21 Vertical Flux Detector Unit
22 Liquid Injection Shutdown Unit
23 Supplementary Absorber Unit
24 Reactivity Mechanism Deck



Reactor Face

Reactor Power Control

The liquid zone control units provide the AFCR's primary control. Each liquid zone control assembly consists of independently adjustable liquid zones that introduce light water in zirconium alloy tubes into the reactor. Light water is a stronger absorber of neutrons than heavy water. Controlling the amount of light water controls the power of the reactor. On-power refuelling and zone-control actions provide reactivity control.

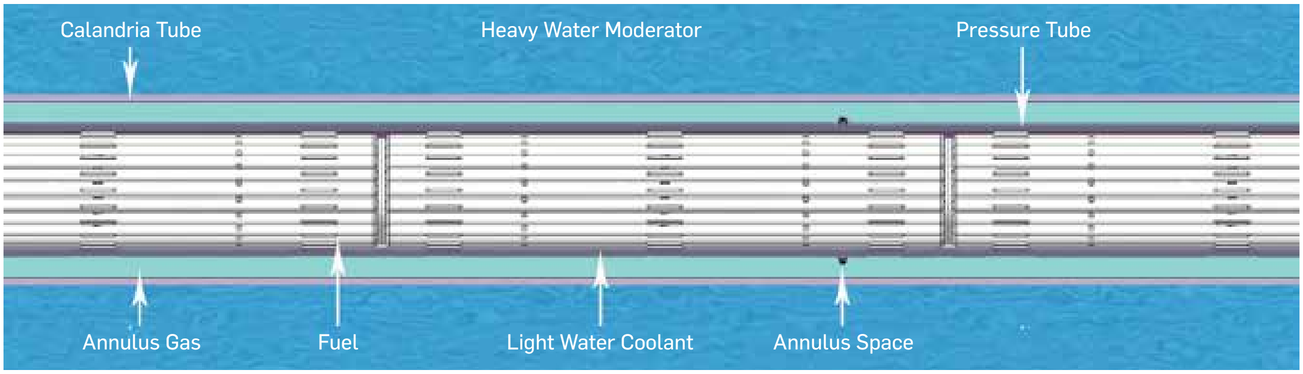
The reactor regulating system also includes control absorber units and adjusters that can be used to absorb neutrons and reduce reactor power if larger power reductions are required. The reactor power control systems of the AFCR are designed for both RU-based- and thorium-based fuel.

Fuel Channel Assembly

The AFCR fuel channel assemblies consist of a zirconium-niobium alloy Zr2.5wt%Nb pressure tubes, centred in a zirconium alloy calandria tubes. The pressure tube is roll-expanded into stainless steel end fittings at each end.

Each pressure tube is thermally insulated from the low-temperature moderator by the annulus gas between the pressure tube and the calandria tube. Tight-fitted spacers, positioned along the length of the pressure tube, maintain annular space and prevent contact between the two tubes. Each end fitting holds a liner tube, a fuel support plug and a channel closure. Reactor coolant flows through adjacent fuel channels in opposite directions. The AFCR pressure tubes are designed with added thickness to ensure longer operational life while utilizing both RU- and thorium-based fuels.

The AFCR is designed for a life of 60 years of operation with provision for life extension at the reactor's mid-life by replacement of fuel channels.



Fuel Channel Assembly

Fuel Handling and Storage System

The fuel handling and storage system of the AFCR consists of:

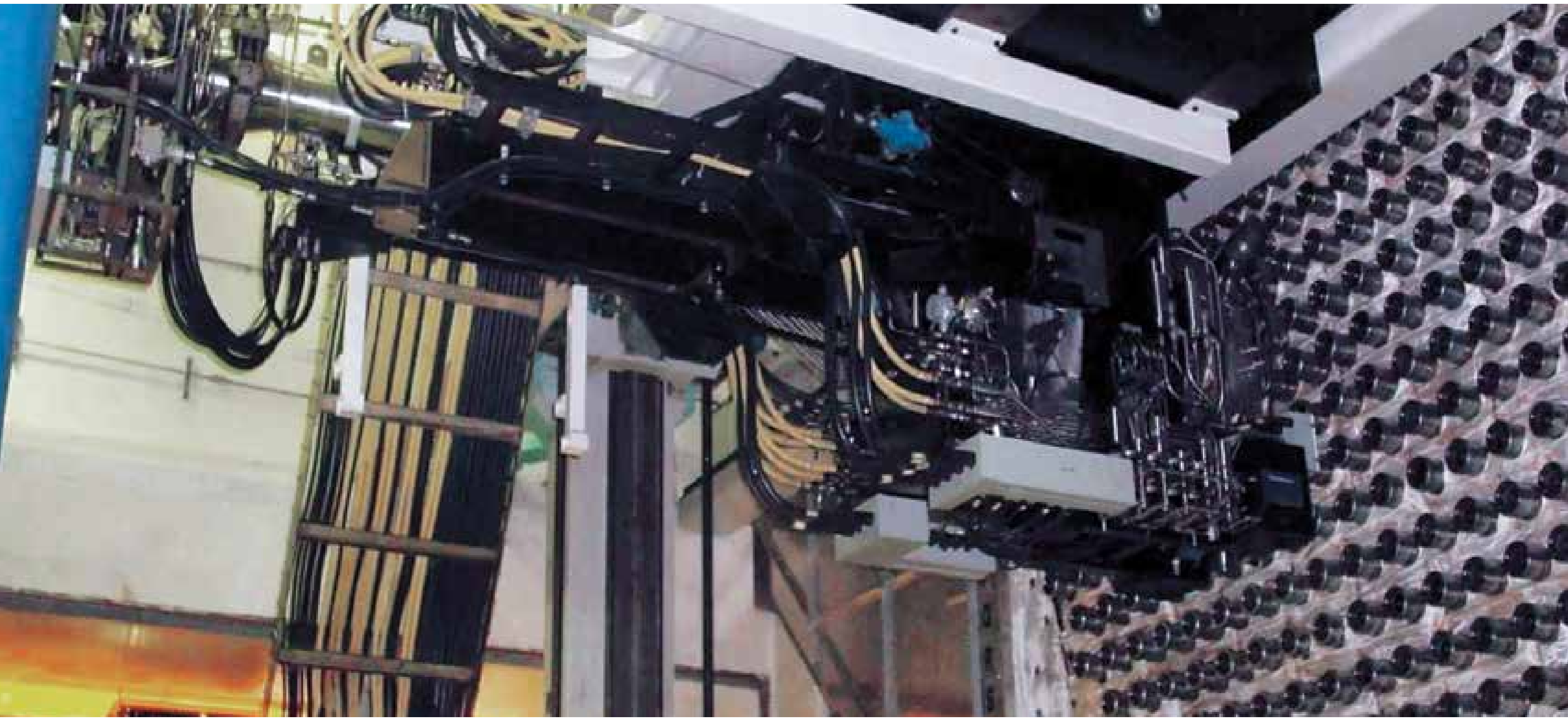
- New fuel transfer and storage
- Fuel changing
- Spent fuel transfer and storage

New fuel transfer and storage is designed for sufficient fuel storage capacity to maintain full-power operation for at least nine months. New fuel is transferred to the new fuel loading room in the reactor building as required, where the fuel is loaded into one of two new fuel transfer mechanisms for transfer into one of the fuelling machines via new fuel ports.

On-power fuelling is implemented by two remotely controlled fuelling machines, located on opposite sides of the reactor and mounted on bridges that are supported by columns. These machines maintain their proven basis while incorporating modernized elements, post-Fukushima requirements and increased seismic resistance.

Fresh fuel bundles are inserted at the inlet end of the fuel channel by one of the fuelling machines. The other fuelling machine removes irradiated fuel bundles from the outlet end of the same fuel channel and transfers it to the underwater spent fuel storage bay.

From the loading of fuel in the new-fuel mechanism to the discharge of irradiated fuel in the receiving bay, the fuelling process is automated and remotely controlled from the station control room. The AFCR spent fuel bay is at grade level and highly resistant to earthquakes and associated events.



Fuelling Machine

Turbine-Generator System

The turbine generator, and condensate and feedwater system are located in the turbine building and are part of the BOP. They are based on conventional designs and meet the design requirements specified by the NSP designer to assure the performance and integrity of the NSP. These include requirements for materials (e.g., titanium condenser tubes and absence of copper alloys in the feed train), chemistry control, feed train reliability, feedwater inventory, and turbine bypass capability.

Site differences affect the condenser cooling water (CCW) system design, such as temperatures, which in turn affect turbine exhaust conditions and the amount of energy it is possible to extract from the steam. In the event of loss of off-site power to the plant, the AFCR stays at power for the duration of the event using turbine generators that are disconnected from the grid. In this mode of operation, power is only supplied to internal auxiliaries as needed for the safe shutdown of the plant.

Turbine Generators

Steam is conveyed from the steam generators located in the RB to the turbine generator in the turbine building via four pipelines, one per steam generator. A main steam balance header is provided to receive the steam from each of the four steam generators and to equalize the pressures prior to entry to the turbine generator.

The turbine assembly normally consists of one single-flow high-pressure turbine, two double-flow low-pressure turbines, and two moisture separator reheaters with two stages of reheating.

Main Steam System

The main steam supply system conveys steam from the steam generator to the turbine and auxiliary systems and consists of the main steam safety valves, main steam isolation valves, atmospheric steam discharge valves, condenser steam discharge valves and associated piping. This steam is supplied to the turbine generator, turbine gland steam sealing system, second stage reheaters, and de-aerator.

Main steam safety valves provide the safety functions of overpressure protection of the secondary side of the steam generators and remove heat from the fuel during accident conditions (crash cooldown for loss of coolant). They can be used to prevent releases in the event of steam generator tube leaks to the secondary side of the steam generator.

Atmospheric steam discharge valves take into account pressure excursions in the main steam system during normal operation.

Condenser steam discharge valves are throttled for turbine trips at partial turbine power levels.

Condensing System

After expansion in the low-pressure turbines, steam is condensed in the main condenser by heat transferred to the CCW system. The condensate from the main condenser is de-aerated and returned to the steam generators via regenerative feedwater heating system.

The condenser consists of separate shells, one per low-pressure tubing casing. It is made of titanium tube sheets and tubes and is equipped with on-line tube cleaning system.

The CCW system supplies once-through cooling water to the main condensers. The system pumps cooling water through the main condensers to condense the turbine exhaust steam and to maintain rated backpressure conditions at the turbine exhaust. The system components and materials minimize deterioration of the condenser heat transfer capability under normal operating conditions and ensure a high degree of availability.

Condensate and Feedwater System

The condensate system provides condensate from the condenser hotwell to the deaerator through the low-pressure feedwater heaters under all conditions of operation. This system includes 2x100% condensate extraction pumps, one auxiliary condensate extraction pump, piping, and controls.

The feedwater system provides feedwater from the deaerator to the preheater section of the steam generators to maintain required water levels during various modes of operation. This system includes the 3x50% main feedwater pumps, two auxiliary feedwater pumps, feedwater control valves, piping, and controls.

Instrumentation and Control

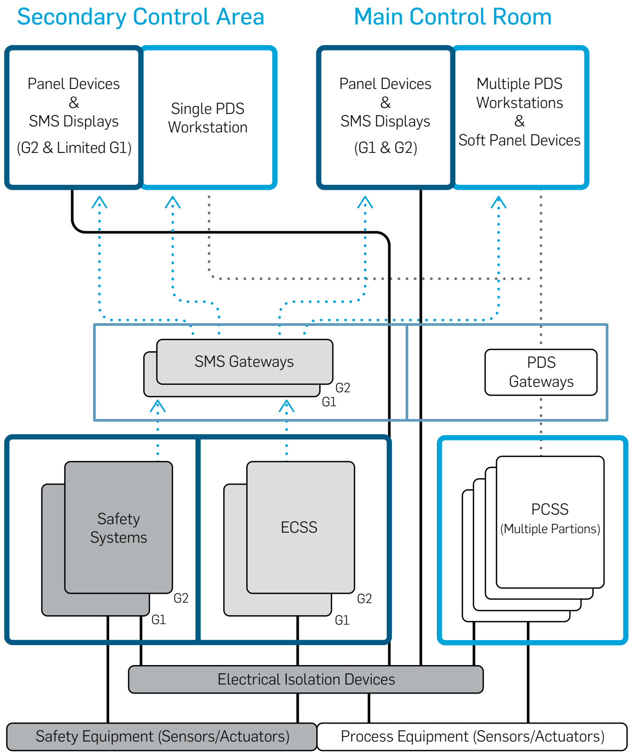
The instrumentation and control (I&C) systems are designed to give the operators in the MCR all necessary information and control capability to operate the reactor unit safely.

Most automated plant control functions are implemented in a modern distributed control system (DCS) using a network of modular, programmable digital controllers that communicate with one another using reliable, high-security data transmission methods.

The systems are also designed to handle certain upset conditions to return the plant to normal conditions or to safely shutdown the reactor in a controlled manner if required. Separated, independent control and instrumentation systems are designed for shutting down the unit and maintaining it in a shutdown state under accident conditions. Shutdown of the reactor and monitoring of its major safety parameters is also possible from the secondary control area (SCA) in case the MCR is unavailable.

Human factors engineering is rigorously applied at all stages of the design process to maximize operator responses to different plant conditions.

Plant surveillance is also centralized in the MCR. Instrumentation for closed-circuit television, meteorological sensing, fire detection and alarm, vibration monitoring, and access control are all indicated and controlled here. Communication networks such as telephone, public address, maintenance, and plastic suits are also centralized in the MCR.



AFCR Overall Instrumentation and Control Architecture

AFCR Control Centres

The AFCR control centres consist of:

- The main control area (MCA) which consists of the MCR, the work control area/operational support centre, and the control equipment room
- The SCA which includes the secondary control room (SCR) and the secondary control equipment room (SCER)
- The technical support centre (TSC)

The on-site emergency support centre (ESC) that is shared between two units for each two-unit plant.

The MCR and all the facilities required to support MCR operations are collectively located in an area referred to as the MCA.

The MCR features extensive use of visual display units, which offer selective presentation of information in diagrammatic formats. The use of computer-based displays, designed using modern human factors engineering, simplifies the control room panels and provides a uniform human-system interface (HSI) for all plant systems.

If for any reason the MCR becomes uninhabitable or unusable, the SCA provides operators with the needed displays through safety system panels and Group 2 control panels to safely shutdown and/or maintain the reactor in a safe shutdown state.

The technical support centre provides an assembly location for the technical support team who provide assistance to operating personnel in the MCR in responding to abnormal operating conditions. Access to information about radiological conditions in the plant and its surroundings, and about meteorological conditions in the plant vicinity is available in the TSC.

The on-site ESC is located separately from the MCR and SCA. It provides overall management of the owner's emergency response, coordination of radiological and environmental assessments, and determination of recommended public and protective actions, while coordinating emergency response activities with the different levels of government agencies.

MCR mockup facility

MCR mockup facility

Computer Control and Display System

The DCS implements the bulk of the control logic and data acquisition functions for the process control systems. Processing of this data for presentation to the operator is performed by the PDS and in some cases by the Safety Monitoring System (SMS).

The DCS is a modular distributed digital control system, which uses a number of programmable digital controllers connected to data communication networks that have been designed to provide very high reliability and data security. The system includes comprehensive fault detection, redundancy, and transfer of control features, to provide a very high degree of immunity to random component failures.

The DCS is divided into a number of independent functional partitions. This functional partitioning provides a defence against common mode faults and ensures separation, where needed, among different process controls, and between process controls and functions that mitigate the failure of these controls.

For enhanced reliability and ease of maintenance, redundancy, as appropriate, is employed at the modular level. A modular redundant system is defined as a system in which, on failure of any one module (central processing unit, input/output card, power supply, communications controller etc.), the functions of the failed module are taken over seamlessly by its modular redundant partner. Comprehensive and qualified self-diagnostics enable transfers of control between redundant modules. The transfer(s) of control are bumpless to minimize process and reactivity upsets.

Significant use is made of the programmable system's inherent ability to take intelligent action in response to detected faults. Most failures are detected without the need for intrusive testing. Self-checks are applied to standby components as well to ensure high availability.

The PDS is a computer based HSI system that supports integrated monitoring and supervisory control of functions, systems and equipment necessary for power production and the monitoring of functions, systems and equipment important to safety. One PDS exists for each unit in a multi-unit station. Each unitized PDS includes provisions to monitor and, if designated the responsible unit, control systems shared between units (common systems). A high level of redundancy is employed within PDS to ensure no single hardware failure affects safety or power production.

Reactor Regulating System

The reactor regulating system (RRS) is used to control bulk reactor power and flux tilts in the reactor core. It consists of the signal processing and control logic used to operate the various reactivity control mechanisms, including the liquid zone control units, mechanical control absorber rods, and adjusters. The RRS is used for all normal operating states, including start-up, shutdown, full power operation, and load cycling.

Reactor Safety Instrumentation

The instrumentation and control of each safety system consists of independent and triplicated measurements of each variable and initiation of protective action are provided when any two of the three channels are tripped.

Safety systems are implemented in digital controllers or hardwired logic, each separate and independent from the other safety systems and from the process control systems. The safety systems are provided with full test facilities to allow testing while the reactor is at power.

Safety Monitoring

Our AFCR has an inventory of discrete alarms, displays and controls that are designed to support post-accident monitoring (PAM), safe shutdown and all safety-significant credited manual operator actions.

The inventory selected for PAM is designed to enable operators to:

- Assess post-accident conditions of the plant and determine the nature and the course of the accident
- Determine whether or not the automated systems important to safety have performed or are performing the required protective actions
- Monitor the plant characteristics following the accident
- Determine the appropriate actions to be performed and monitor results of those actions, including the need to execute off-site emergency procedures

These alarms, displays and controls are complemented by a computer-based SMS which is designed to provide a concise display of critical safety parameters for the rapid and reliable determination of the safety state of the unit. The SMS is designed to integrate and validate information in an attempt to minimize erroneous information and improve human performance.

Critical safety parameters are selected to convey sufficient information on the critical safety functions necessary for the detection, diagnosis and mitigation of abnormal conditions including: transients, DBAs and BDBAs. The critical safety parameters provide information on the following critical safety functions:

- Reactivity control
- Reactor core cooling and heat removal from the primary circuit
- Reactor coolant system integrity
- Radioactivity control
- Containment integrity

The measurement and display of a PAM parameter is organized into distinct information chains consisting of three possible segments: sensor, processing and display. The information chains are qualified to allow operators to take credited actions based on the information presented and to remain operational during and following the events they are intended to monitor, including DBE events. The qualified information chains or segments thereof are distinctly presented or identified to clearly distinguish them from the nonqualified.

At least two independent information chains are provided for those important parameters that need to be monitored during DBAs. The SMS is provided with all qualified measurements and is itself qualified for post-accident use providing an independent display segment for any given parameter.

While the discrete alarms, displays and controls are limited to the MCR and SCR, the SMS displays are provided in the locations where operations and emergency response staff operate to detect and diagnose abnormal conditions. These locations include the MCR, SCR, TSC and the on-site ESC.

Electrical Power System

Our AFCR's electrical power system consists of connections to the off-site grid, the main turbine generator, the associated main output system, the on-site standby diesel generators, the battery power supplies, the UPS, and the electrical distribution equipment.

The electrical power distribution system provides safe and reliable electrical power to the unit in a manner that maintains the redundancy and separation requirements.

For reliability of operation, two 100% redundant power distribution systems are provided for the loads important to safety and triplicated power systems are provided for control and instrumentation purposes.

The electrical power distribution systems are separated into Group 1 and Group 2 in accordance with the two group separation philosophy. The Group 1 electrical distribution system provides power to the process systems used for power production, systems important to safety and safety support systems. The Group 2 system is the seismically qualified emergency power supply which is a back-up power source to selected safety systems and safety support systems.

The Group 1 system is divided into four classes of power based on availability:

- Class IV from the main generator or grid
- Class III from standby diesel generators
- Class II from UPS
- Class I delivered from batteries

The Group 2 EPS system has a seismically-qualified UPS and batteries with a mission time as required by the safety systems when normal electrical supplies are unavailable.

In case of an SBO, a seismically qualified UPS is provided to power loads required for provision of a heat sink capable of supporting the safety critical loads for up to 24 hours.

The independent SARHRS diesel generator at each unit is a complementary design feature to power a limited number of loads for mitigation of severe accidents.

In addition, each reactor unit has its own seismically qualified mobile diesel generator for extended SBO events.

Conventional Plant Services

Conventional plant services include water supply, heating, ventilation, and air conditioning (HVAC), chlorination (if required), fire protection, compressed gases and electric power systems.

Service Water Systems

The BOP service water systems provide cooling water, demineralized water and domestic water to the nuclear power plant users. The systems include the CCW system and water treatment facility.

Heating, Ventilation and Cooling Systems

HVAC and chilled water are supplied to our AFCR buildings to ensure a suitable environment for personnel and equipment during all seasons. Dedicated, separate ventilation systems are provided for the MCR and SCA.

The building heating plant provides the steam and hot water demands of the entire AFCR HVAC systems. Steam extracted from the turbine is used as the steam source for normal building heating.

Fire Protection System

Water supply for the main fire protection system comes from a fresh water source. The main system provides fire protection for the entire plant. The AFCR also has a seismically-qualified water supply pump house and distribution system.

The fire protection system also includes standpipe and fire hose systems, portable fire extinguishers for fire suppression, and a fire detection and alarm system covering all buildings and areas.

Fire-resistant barriers for fire mitigation are provided, where necessary, to isolate and localize fire hazards and to prevent the spread of fire to other equipment and areas. The fire protection system design complies with CSA N293 and N285.0.

Modular Air-Cooled Storage (MACSTOR®)

Radioactive Waste Management

The AFCR waste management systems minimize radiological exposure to operating staff and to the public. Radiological exposure for workers from the plant is monitored and controlled to ensure exposure is within the limits recommended by the ICRP. The systems have been proven over many years at other CANDU sites and provide for the collection, transfer and storage of all radioactive gases, liquids and solids, including spent fuel and wastes generated within the plant.

Wastes are handled as follows:

- Gaseous radioactive wastes (gases, vapours or airborne particulates) are monitored and filtered. The off-gas management system treats radioactive noble gases. Tritium releases are collected by a vapour recovery system and stored on-site
- Liquid radioactive wastes are stored in concrete tanks that are located in the service building. Any liquid, including spills that require removal of radioactivity are treated using cartridge filters and ion exchange resins
- Solid radioactive waste can be classified in five main groups: spent fuel; spent ion exchange resins; spent filter cartridges; compactable solids; and non-compactable solids. Each type of waste is processed and moved using specially designed transporting devices if necessary. After processing, the wastes are collected and prepared for on-site storage by the utility or for transport to an offsite storage location

AFCR radioactive waste management systems have been optimized using best available techniques (BAT) in support of the ALARA principle.

In addition, the plant owner/operator maintains an environmental monitoring program to verify the adequacy and proper operation of the radiological effluent monitoring systems that monitor and control release of effluents at the release point.

Modular Air-Cooled Storage (MACSTOR)

Our patented spent fuel dry storage technology, the MACSTOR®, consists of concrete canisters that hold spent CANDU reactor fuel bundles in a modular, air-cooled concrete above ground canister. The largest design, the MACSTOR-400, has four rows of storage cylinders and provides a capacity of 24,000 NU bundles stored in 400 baskets.

AFCR Project Delivery

Through customer feedback on our previous construction projects, we have optimized key project elements. The AFCR plant construction schedule, from first containment concrete to in-service, is 57 months. The second unit can be in service six months later. Deployment of the AFCR requires the coordination and timely delivery of key project elements including licensing programs; environmental assessments; design engineering; procurement, construction; and commissioning start-up programs.

Design Engineering

Preliminary design and development programs of the AFCR plant are executed in parallel with the environmental assessment and licensing programs to ensure continuous improvement and plant configuration is maintained. The final design program ensures that plant reliability, and equipment and component maintainability and constructability requirements are maximized.

Licensing

Our AFCR builds on the successful CANDU track record of accommodating the requirements of offshore jurisdictions in various customers' countries while retaining the standard nuclear platform. The CANDU 6 reactor has been licensed in Europe, Asia and North and South America. The AFCR incorporates improvements to meet the latest regulatory requirements in Canada and internationally.

Licensing programs are executed and coordinated with the engineering design programs and environmental assessment and are structured to support regulatory process requirements.

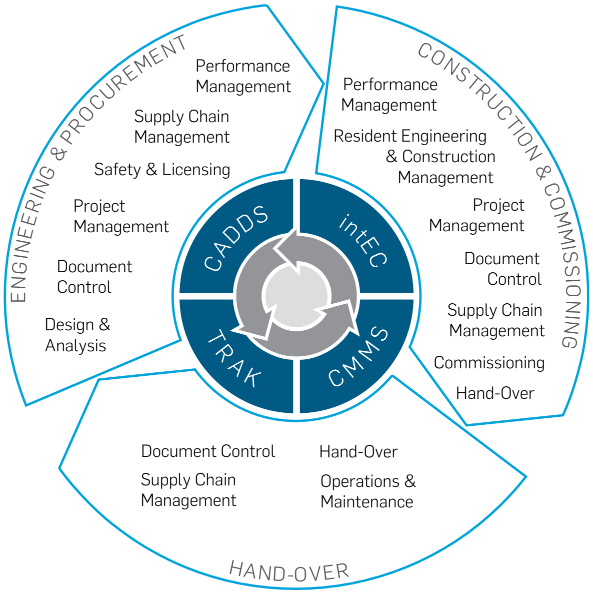
Configuration Management

The AFCR makes use of the latest computer technology for managing the complete plant configuration from design to construction, and turnover to the plant owner/operator. State-of-the-art electronic drafting tools are integrated with material management, wiring and device design, and other technology applications.

Project Management

The AFCR project management structure provides fully integrated project management solutions. Performance management programs are executed from project concept, through a project readiness mode, to project closeout.

The project management framework consists of three key elements: total project execution planning; a critical decision framework to control each phase of the project lifecycle; and a comprehensive risk management program.



Design Engineering and Project Tools

Qinshan construction

Procurement

Standardized procurement and supply processes are implemented to support time, cost, and performance benefits to the project, such as efficiency through variety control (e.g., standardization) and economy in manufacturing and servicing.

Construction Programs

Constructability programs are implemented to ensure project simplification by:

- Maximizing concurrent construction to increase construction productivity
- Minimizing construction rework to decrease equipment costs
- Minimizing unscheduled activities to reduce capital costs and construction risk

Construction Strategy

The main features of AFCR construction are:

- Open-top construction method using a very-heavy-lift crane
- Concurrent construction
- Modularization and prefabrication
- Use of advanced technologies to minimize interferences

This construction strategy has contributed to the successful completion of CANDU 6 units around the world, delivered on budget and on/or ahead of schedule.

Qinshan CANDU 6 Project Performance Record

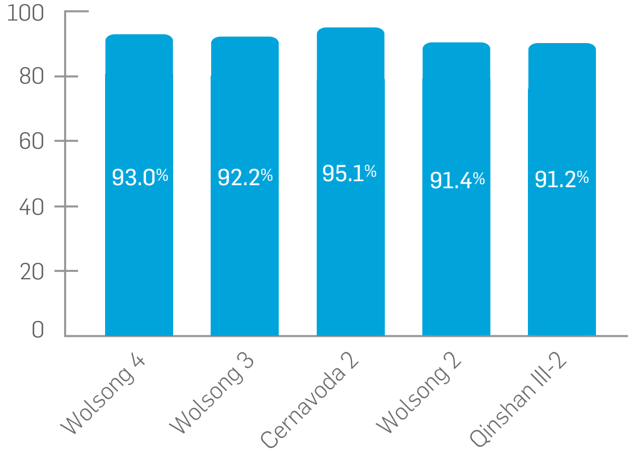
Milestone	Unit 1
First concrete	4 days ahead of schedule
Containment pressure test	20 days ahead of schedule
Fuel load licence	6 days ahead of schedule
Unit 1 complete	37 days ahead of schedule

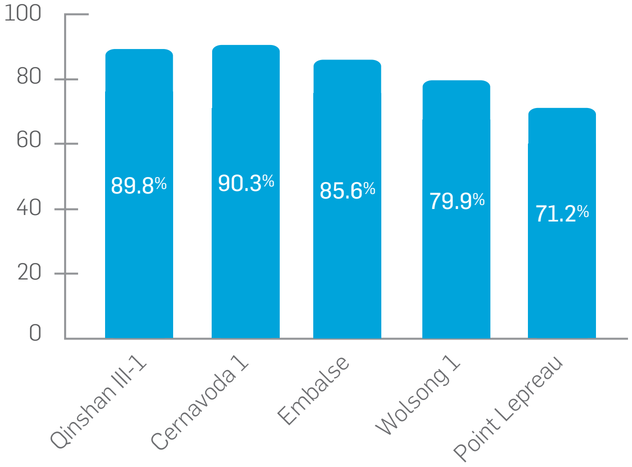
Operations and Maintenance

Plant Performance

The target operating capacity factor for the AFCR is >90% over the operating life of 60 years. This expectation is based on the proven track record of our CANDU 6 customers.

Lifetime Unit Capability Factor as of December 31, 2014





Features to Enhance Operating Performance

Incorporation of feedback from utilities operating reactors (both CANDU and other reactor designs) is an integral part of our design process. Various new features and maintenance improvement opportunities have been incorporated to enhance operating performance throughout the station life.

Major AFCR enhancements:

- Use of improved material and plant chemistry specifications based on operating experience from CANDU plants
- Implementation of advanced computer control and interaction systems for monitoring, display, diagnostics and annunciation

Features that Facilitate Maintenance

The number and duration of maintenance outages impact plant capacity factors. The traditional CANDU outage duration has been improved in the AFCR design by incorporating the following enhancements:

- Service building layout enhancements for ease of maintenance
- A maintenance-based design strategy that incorporates lessons learned and ensures maintainability of systems and components
- Improved plant maintenance with provisions for electrical, water and air supplies that are built in for on-power and normal shutdown maintenance
- Shielding in radiological-controlled areas is provided to minimize worker exposure and occupational dose
- Improved equipment selection and system design based on probabilistic safety evaluations and specific outage intervals

Technology Transfer and Localization

CANDU technology transfer and localization is the most effective in the nuclear industry and is capable of achieving the highest level of local content in the shortest time. In South Korea, we achieved up to 75% local content by the fourth unit. Such accelerated results are possible due to innovative design, as well as extensive experience in project management and technology transfer.

This approach allows our customers great success in achieving self-sufficiency and self-reliance. The resulting partnerships we develop provide our customer with the "know-why" and "know-how" to effectively serve domestic needs.

Further fine-tuning has been done in this area for the AFCR design through a variety of measures, including equipment standardization and optimization.

Program Details

A successful technology transfer and localization program is largely dependent upon technical information as well as personnel development and partnership in recipient organizations. Our experience has shown that success in a technology transfer program and subsequent localization involves the recognition of and preparation for the following factors:

- **People:** The availability of trained personnel to interpret the documentation and implement the design
- **Training:** A necessary ingredient as not all of the technology resides in document form – much of it can only be transferred through personnel communication
- **Practice:** The technology transfer and localization program runs concurrently to a nuclear build project, allowing customers to practice their skills as they learn. Such an approach prevents knowledge dissipation and relearning
- **Technology flexibility:** Adjustments and modifications of manufacturing techniques, equipment and skills are often essential
- **Environmental and cultural differences:** Recognition of differences is an important consideration in any international endeavor
- **Potential conflict resolution:** Recognition of project priorities must occur between all parties in order to prevent possible conflicts, maintain project schedules and minimize overall costs
- **Coordination:** As there are often several recipients of technology transfer, coordination is required in order to:
  - Ensure the necessary infrastructure is in place to provide adequately trained personnel
  - Determine priorities for technology to be transferred and to ensure sufficient allocation of funds and human resources
  - Determine the most suitable recipients to receive and eventually develop the technology
  - Monitor and coordinate the actual technology transfer process

Expert Panel Review of the AFCR in China concluded:

- Recycled Uranium in AFCR significantly increases China's nuclear fuel resources
- AFCR forms a synergy with PWRs and reprocessing plants; consistent with China's nuclear power development strategy
- AFCR is based on proven technology and meets Gen III requirements
- AFCR reactor is designed to utilize RU and Thorium based fuels

The experts recommended the following:

- The current design should be completed for project implementation
- Select proper time to initiate the construction of AFCR to unlock and utilize its various advantages

Building on past success to power the future with advanced fuel cycles

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The AFCR is a 740 MWe heavy water moderated and cooled pressure tube reactor. Heavy water (D_2O) is a natural form of water used as a moderator to effectively slow neutrons in the reactor, enabling the use of natural uranium (NU) as well as other alternatives as fuel. This feature of high neutron economy is unique to CANDU reactors. The choice of D_2O as the moderator is the key enabler for the use of alternative fuel cycles (recycled uranium and thorium-based fuels) in CANDU reactors.

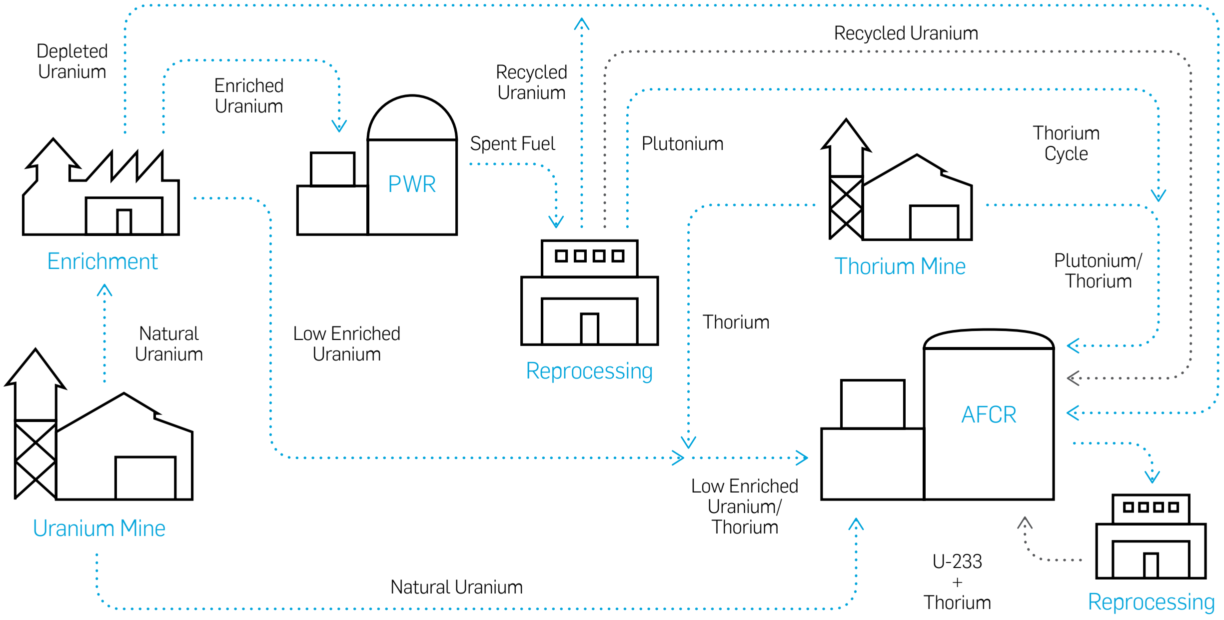
AFCR maintains the traditional CANDU inherent safety design features and includes further safety enhancements to meet the latest safety standards and post-Fukushima requirements.

Key safety features include:

- Core features such as a practically zero power coefficient of reactivity, negative fuel temperature coefficient and better distributed channel and bundle power profiles
- Two independent passive shutdown systems, each capable of safely shutting down the reactor with no human intervention
- Two group design to ensure two independent means to achieve the same safety functions
- Refuelling during on-power operation reduces the excess reactivity level needed for reactor control. Reactor characteristics are constant and no additional measures, such as the addition of boron to the reactor coolant (and its radioactive removal), are required
- Natural circulation capability in the reactor cooling system for temperature transients (changes) due to loss of forced flow
- Reactivity control devices cannot be ejected by high pressure because they are located in the low-pressure moderator and do not penetrate the AFCR coolant pressure boundary
- Moderator as a back-up heat sink, unique for CANDU design, maintains core coolability for loss-of-coolant accidents even when combined with unavailability of emergency core cooling
- Elevated water tanks located in the upper level of the reactor building deliver (gravity fed) passive dousing water spray into containment and make-up cooling water to the calandria vessel to remove decay heat. The gravity fed makeup water from the dousing tank to the steam generators for Station Blackout (SBO) events is designed to last for at least 72 hours
- A large concrete reactor vault surrounding the reactor core in the calandria contains a large volume of light water to further slow down or arrest severe core damage progression by providing a second passive core heat sink. Passive water make-up to the calandria vault mitigates severe core damage accidents for 72 hours
- Calandria vault plus shield cooling system or the severe accident recovery and heat removal system (SARHRS) is used to arrest severe core damage progression within the calandria vessel
- Passive capability of the containment itself ensures containment integrity is maintained while an offsite emergency response plan is implemented following onset of severe core damage. A new passive containment heat removal system (PCHRS) maintains the containment integrity for the longer term

All reasonably practicable design measures are taken into account in the AFCR design to prevent accidents and to mitigate their consequences. Our AFCR is designed with both active and passive containment heat sinks to ensure the containment function under severe accident conditions. The AFCR's inherent safety with new passive and active design features aims to practically eliminate plant states that could lead to early or large radioactive releases.

Qinshan CANDU Reactors in Haiyan, China



Alternative Fuel Cycles for AFCR-type Reactors

AFCR Advantages for Advanced Fuel Cycles

Current CANDU reactors, as a result of favourable reactor core physics characteristics and on-power fuelling, use approximately 30% less natural uranium per each kilowatt-hour of electricity as compared to PWR designs. Our unique technology has unequalled flexibility for using alternative fuels, such as recycled uranium and thorium-based fuels. This capability results from a versatile pressure tube design, simple fuel bundle, on-power refuelling, and high neutron economy.

The AFCR uses advanced fuels specifically direct use of recycled uranium (DRU) fuel or low enriched uranium/thorium (LEU/Th) fuel. DRU fuel represents a gradual transition from NU-based fuels that are used in current CANDU 6 reactors. DRU fuel is similar to the already proven natural uranium equivalent (NUE) fuel in that it is composed of RU, from reprocessed pressurized water reactor (PWR) spent fuel but has a slightly higher fissile content (contains about 0.95%wt. ^{235}U) than the NUE fuel.

Our AFCR, although specifically designed for DRU and LEU/Th fuels, retains the ability to easily adapt to various fuel cycle options, such as NU, NUE and Pu/Th.

CANFLEX Fuel Bundle

Fuel

Our AFCR uses the CANFLEX® 43-element fuel bundle design. The increased subdivision of this bundle design improves thermalhydraulic margins and enables the use of RU and Th-based fuels. Each fuel element consists of a column of either sintered (RU or RU/dysprosium in DRU; or LEU or thorium in LEU/Th) fuel pellets inside a sealed zirconium alloy tube. The ends of a circular array of the 43 fuel elements are welded to zirconium alloy support plates to form an integral fuel bundle assembly. Each fuel bundle is approximately 50 cm long and 10 cm in diameter. Its compact size and weight facilitates automated and on-power fuel handling.

All types of CANDU reactor fuel bundles, with fewer components than other reactor types, are easy to manufacture allowing all countries with CANDU reactors to manufacture their own fuel. Excellent uranium utilization and a simple fuel bundle design help minimize the CANDU reactor fuel cycle unit energy cost, in absolute terms, relative to other reactor types. The efficient use of neutrons in CANDU reactors contributes to its fuel cycle flexibility, and consequent reduction in volume of irradiated fuel relative to earlier CANDU reactor designs.

Direct use of Recycled Uranium Fuel

The DRU fuel is recycled uranium (RU) based fuel, arranged in a 43-element CANFLEX fuel bundle. The nominal enrichment of the RU is 0.95 wt% 235U to achieve a target burnup of 10,000 MWd/tHE. The use of higher fissile content RU fuel compared to NU fuel has greater economic advantages due to higher fuel utilization. RU fuel is in the form of sintered uranium pellets.

Low-Enriched Uranium (LEU) and Thorium (Th) Fuel

The low-enriched uranium (LEU) and thorium (Th) fuel is a heterogeneous combination of the constituent fuels arranged in a 43-element CANFLEX fuel bundle. The fuel is designed to achieve a target burnup of 20,000 MWd/tHE.

43-Element Fuel Bundle Design Characteristics

Fuel	DRU	LEU and Th
Average fuel burnup [MWd/tHE]	10,000	20,000
Bundles per fuel channel	12	12
Reference fuelling scheme	4-bundle shift	2-bundle shift

Economic Value Using Advanced Fuel Cycles

The use of DRU and LEU/Th fuels in the AFCR core increases the CANDU advantage even further with fuel requirements as low as 50-60% of PWR baseline designs. In addition, CANDU reactor fuel bundles are small and, therefore easier to modify relative to more complex fuel assemblies of other nuclear reactor technologies. This allows advantages for current or future fuel development and verification testing programs compared to other reactor types.

Adopting alternative fuel cycles such as NUE, DRU, and LEU/Th significantly improves the uranium utilization rates while meeting nuclear power generation requirements. In fact, an AFCR twin-unit plant using DRU fuel would save approximately 10,000 tonnes of natural uranium over its 60-year design life.

The AFCR has the advantage of not requiring reactor shutdown for batch fuelling, and conversely, uses easy-to-handle fuel bundles, which are inserted/removed in the reactor core on-demand, with the aid of on-power fuelling capability. The small sized fuel bundles and on-power fuelling allow the establishment of optimal core configurations with minimal effort and without relying on the use of liquid neutron absorbers to suppress excess reactivity, as is the case with PWR designs. Absorbers can have adverse fuel cost and system chemistry impacts.

The cumulative effect of these CANDU reactor technology specific features results in the following capabilities of the AFCR:

a) Re-using PWR used fuel stream in the immediate term in the form of DRU fuel, in a cost effective manner

b) Introducing new fertile material into the fuel stream with the first new build reactors (LEU/Th)

c) Approaching “closed” fuel cycles, requiring sequentially less new fuel material with each next generation CANDU reactor unit —a major market and technology change potential

The AFCR features offer a cost effective solution, is available in the short term and is suitable for meeting intermediate and long-term aspirations for sustainable fuel supply, without requiring major investments or technological risks.

Safety is at Our Core

The AFCR incorporates the proven principles and characteristics of the reference CANDU 6 design and the extensive knowledge base of CANDU reactor technology gained over decades of successful operation. It has been enhanced to reflect and comply with the latest regulatory requirements, including Canadian and Chinese safety requirements as well as International Atomic Energy Agency (IAEA) codes and standards.

AFCR Safety Design Philosophy

> Evolutionary design based on proven design and experience feedback

> Meet Generation III reactor safety goals

> Strengthen defense in depth

> Increase safety margins

> Apply two group safety design philosophy

> Incorporate post-Fukushima requirements

> Extend plant design to cope with BDBAs through inherent safety design with robust complementary design features

> Ensure rugged plant design against malevolent acts and external events

> Minimize environmental impact

> Advanced active and passive safety features for practical elimination of large releases

AFCR Safety Design Philosophy

The AFCR is designed based on the “defence-in-depth” safety philosophy applied to all CANDU plants with enhancements to further improve overall safety. These enhancements include core design incorporating a practically zero power coefficient of reactivity, improved performance of safety systems, inherent safety design for resistance of accidents, a combination of active and passive safety features for prevention of core damage and mitigation of consequences of accidents, and a robust containment design to minimize the risk to the public and the environment.

Our AFCR is an advanced CANDU reactor plant to meet Generation III reactor standards, including:

> Ample thermal and safety margins for safe operation

> More rugged design and higher availability with a plant life of 60 years

> Resistance of accident through inherent safety design features

> Physical and functional separation of safety systems

> Simplified, more reliable systems

> A combination of passive and active safety designs for accident prevention and mitigation

> Further reduced probability of severe core damage

> Very low large release frequency to minimize the risk to the public

> Higher burn-up to use alternative fuel more efficiently and reduce the amount of waste

> Robustness of the plant against malevolent acts and external events

AFCR Safety Goals

Safety goals are established to effectively implement fundamental nuclear safety objectives and to ensure that nuclear power plant operation poses no significant additional risk to public health, safety, security, and the environment in comparison with other risks to which the public is normally exposed. Establishment of safety goals for the AFCR is based on the Generation III requirements. It achieves the following quantitative design target safety goals with ample margins:

- The occurrence frequency of events that may lead to severe core damage is less than 10^{-6} events per operating reactor year
- The frequency of events that may result in a large radioactive release is less than 10^{-7} events per operating reactor year

The design approach for the AFCR ensures safety during construction, commissioning and operation. All reasonably practicable design measures, including those for design extension conditions, are taken into account in the AFCR design to prevent accidents and to mitigate their consequences. Our AFCR ensures with a high level of confidence that, for all postulated accidents considered in the design including those of very low probability, radiological consequences would be below prescribed limits. The AFCR design features ensure that the likelihood of accidents with serious radiological consequences is extremely low. The intent is to practically eliminate accident sequences with a large or early release.

Defence-in-Depth

Consistent with the overall safety concept of defence-in-depth, the AFCR aims to prevent, as far as practicable, challenges to the integrity of physical barriers; failure of a barrier when challenged, and failure of a barrier as a consequence of the failure of another barrier. This approach is structured in five levels consistent with regulatory documents CNSC REGDOC-2.5.2, IAEA SSR2/1, and NNSA HAF102-2004 as presented below:

- **Level 1** – Prevention of deviations from normal operation and failures of structures, systems and components (SSCs) by conservative design and high-quality construction
- **Level 2** – Detection and control of deviations from normal operation in order to prevent anticipated operational occurrences (AOOs) from escalating to accident conditions and to return the plant to a state of normal operation by using inherent and engineered design features to minimize or exclude uncontrolled transients to the extent possible
- **Level 3** – Minimize the consequences of accidents by providing inherent safety features, fail-safe design, additional equipment, and mitigating procedures
- **Level 4** – Control of severe plant conditions in which the design basis may be exceeded, including the prevention of accident progression and mitigation of the consequences of severe accidents, by providing equipment and procedures to manage accidents and mitigate their consequences as far as practicable
- **Level 5** – Mitigation of radiological consequences of potential releases of radioactive substances by adequately equipped emergency support centre and on-site and off-site emergency response

Levels of defence are implemented such that the reliability of each protection level is preserved commensurate with the expected frequency and consequence of challenges. Should one level fail, it is compensated or corrected by the subsequent level.

Measures of the first three levels of defence are considered within the design basis to ensure integrity of fission product barriers and to limit potential radiation hazards to members of the public. Measures of the fourth level of defence are considered beyond design basis to keep the likelihood and radioactive releases of severe plant conditions as low as practicable. The fifth level of defence deals with off-site emergency response.

During normal operation, the built in level of defence ensures the plant operates safely and reliably by incorporating substantial design margins, adopting high-quality standards and by advanced reliable control systems to accommodate plant transients and arrest the progression of the transients once they start. Following a design basis accident (DBA), the safety systems and equipment automatically start to shut down the reactor and maintain it in a safe shutdown condition indefinitely.

Safety systems, which perform the safety functions, follow the design principles of separation, diversity and reliability. High degrees of redundancy within systems are provided to ensure the safety functions can be carried out assuming a single failure with the systems. Protection against external events and internal hazards (e.g., seismic events, tornadoes, floods, fire, and malevolent acts) is also provided, ensuring independence of systems or components performing safety and highly reliable and effective mitigation of postulated events, including severe accidents.

The AFCR has inherent design robustness against severe core damage, including preventing severe core damage at high pressure and precluding high pressure melt and direct containment heating. In general, the progression of a severe core damage accident in a CANDU reactor would be slow because the fuel is surrounded by a large quantity of light and heavy water, which acts as a heat sink to remove the decay heat. Furthermore, the creep mechanical deformation mechanism leading to disassembly of the core is a slow process.

The AFCR design incorporates four major physical barriers to the release of radioactive materials from the reactor core to the environment:

- The fuel matrix. The bulk of the fission products generated are contained within the fuel grains or on the grain boundaries, and are not readily available to be released even if the fuel sheath fails
- The fuel sheath. There are large margins to fuel sheath failure under normal operating conditions
- The Heat Transport System (HTS). Even if fission products are released from the fuel, they are contained within the HTS. The HTS can withstand pressures and temperatures resulting from accident conditions. Adequate margins to fuel sheath failure are maintained, taking credit for the protective actions of the engineered safety features
- Containment. In the event of an accident that released fission products into the reactor building, automatic containment isolation will occur; ensuring subsequent release of radioactivity to the environment is controlled

CANDU Isotope Production Advantage

CANDU reactors can also produce isotope products. Cobalt-60 is produced using the adjusters in CANDU reactors. The favourable conditions of high neutron flux mean high production rates of Co-60 are realized quickly. Cobalt-60 is used in the industrial and health care fields for sterilization and sanitization applications.

Designed Based on Post-Fukushima Requirements

To make nuclear safety in the post-Fukushima era more robust and effective, the lessons learned from the Fukushima nuclear accident, including applicable recommendations from the Canadian Nuclear Safety Commission (CNSC) Fukushima Task Force Report have been implemented into the AFCR. We have also incorporated:

- NNSA post-Fukushima requirements
- CNSC regulatory requirements relating to the Fukushima accident
- IAEA, US Nuclear Regulatory Commission (NRC) and World Association of Nuclear Operators (WANO) recommendations relating to lessons learned from the Fukushima accident

The AFCR incorporates key features to prevent and mitigate severe accidents including passive and active provisions that provide water make-up to the steam generators, to the calandria vessel, to the calandria vault and passively and actively remove heat from the containment for the long term. A PCHRS is provided as a long term containment heat sink. The PCHRS removes heat from the containment by natural circulation with no operator intervention for 72 hours. Sufficient provisions are provided to protect the containment function during severe accidents for the AFCR.

Provisions to prevent accident progression and mitigate the accident consequences are taken into account in the AFCR together with consideration of CANDU reactor safety features. The AFCR maintains the CANDU reactor's built-in severe accident prevention and mitigation features, including the moderator as emergency heat sink to maintain core coolability, and presence of a large water source around the calandria to cool potential debris. Each safety function is performed by at least two independent means in the AFCR. Active and passive safety provisions are provided to ensure the fundamental safety functions (reactivity control, fuel cooling and containment of radioactive material) are achieved for all plant states. For any design basis or severe-accident, the reactor can be shut down by two independent shutdown systems, in addition to the control system. Safety enhancements for severe accident prevention and mitigation measures include independent passive and active make-up to the calandria vessel and calandria vault to maintain coolability in the calandria and reactor vault.

To ensure calandria vessel cooling from the outside via the water in the calandria vault and in-vessel retention (IVR), both active and passive measures are provided for the calandria vault make-up. The passive water make-up to the calandria vault is provided by gravity from a dedicated water tank at a high elevation inside the containment. Also the condensate from the PCHRS internal condensers is collected to feed the calandria vault. The water make-up to the calandria vault by pump action is provided by the SARHRS.

Our AFCR has an optional emergency containment filtered venting system (ECFVS) based on proven technology and similar to ECFVSs that have been installed in the other CANDU units. The ECFVS constitutes an additional layer of defence to prevent catastrophic failure of containment and is part of severe accident management guidelines (SAMG).

AFCR Fundamental Safety Function Features

Nuclear safety requires that radioactive products from the nuclear fission process are contained both within the systems for the protection of the workers and outside the structures for the protection of the public. The AFCR achieves this requirement at all times through the following fundamental safety functions:

1. Control of reactivity: Controlling the reactor power and, when necessary, shutting down the reactor
2. Removal of heat from the fuel: Removing heat from the reactor core, including decay heat following shutdown, to prevent fuel overheating and removing heat from the irradiated fuel in the spent fuel bay
3. Confinement of radioactive material and control of operational discharges, as well as limiting accidental releases
4. Containing radioactive products that are normally produced and existing in the fuel as well as in the process systems; and providing controlled, filtered and monitored releases of radioactive materials during normal operation, AOOs and accident conditions

The AFCR also provides sufficient means for monitoring safety critical parameters to guide operator actions at all times to ensure that the fundamental safety functions are being carried out. Fundamental safety functions are fulfilled for all plant states.

These nuclear safety functions are carried out to a very high degree of reliability in the AFCR by applying the following principles:

- The use of high-quality components and installations
- The use of inherent safety features to the extent practical
- The use of two Group safety design philosophy
- Implementing multiple defense-in-depth barriers for prevention of radioactive release
- Providing engineered safety features to prevent and mitigate the consequences of design basis accidents (DBAs)
- Providing complementary features to prevent and mitigate the consequences of beyond design basis accidents (BDBAs), including severe accidents

Reactivity Control

The AFCR has three methods for reactivity control: reactor power control and two independent safety shutdown systems. Reactor power control is carried out by the AFCR's reactor regulating system (RRS). The RRS controls the reactor power within stipulated limits in various operational states. The system operates independently of the two shutdown systems. The RRS includes liquid zone control units to adjust the flux level in the reactor and control absorber and adjuster units that absorb neutrons and optimize reactor power output and fuel burnup. This system allows for a setback function to reduce power at a controlled rate and also a stepback function to enable fast power reduction in the core.

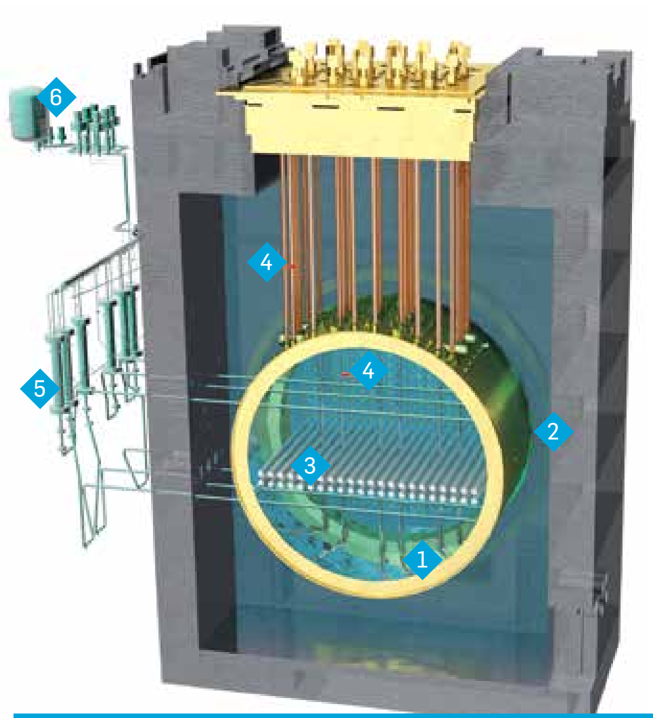
Shutdown system 1 (SDS1) consists of 32 cadmium vertical shutoff rods which fall into the core by gravity with initial spring assist. All shutoff rods are introduced into the core via guide tubes permanently positioned in the low pressure and low-temperature moderator environment. There are no mechanisms for rapidly ejecting any shutoff rods due to their placement in the low pressure moderator (a distinctive safety feature of the pressure-tube reactor design). The design of the shutoff rods is based on the proven CANDU 6 reactor design and includes enhancements for our AFCR.

Shutdown system 2 (SDS2) consists of six high-pressure gadolinium (neutron absorber) tanks for injection into the moderator through six horizontally oriented nozzles. The negative reactivity is introduced by highpressure injection of the gadolinium solution into the moderator in the calandria quickly rendering the reactor core subcritical, effectively stopping the fission chain reaction. The gadolinium nitrate solution is dispersed uniformly throughout the reactor, thus maximizing the shutdown effectiveness.

SDS1 and SDS2 are fully redundant, independent, diverse, separated shutdown systems, providing fast shutdown means in addition to the RRS. SDS1 and SDS2 are physically, logically, and functionally separated, and do not share devices with each other or with the control system. Each shutdown system has two diverse trip parameters, where practical, which are effective for each accident.

Reactivity control in the AFCR is a triple layer of defence that ensures reactor shutdown at all times (no loss of shutdown event).

Reactivity Control



1 Moderator
2 Reactor
3 Calandria Tubes (Not all are shown in illustration)

Shutdown System 1
4 Shutoff Units
Shutdown System 2
5 Gadolinium Tanks
6 Helium Tank

Fuel Cooling

Sufficient fuel cooling in the AFCR is provided for all plant states from normal operations through to design extension conditions. These plant states and the various conditions are described individually below.

Normal Operations

Heat Transport System (HTS) pumps circulate D_2O coolant to transfer heat from the fuel to the feedwater on the secondary side of the steam generators.

Shutdown State

Shutdown Cooling System removes decay heat from the core under full HTS pressure and temperature.

Forced Circulation Lost in Heat Transport System

The AFCR ensures that fuel is effectively cooled by the primary HTS thermosyphoning. Decay heat is continuously removed from the core as long as a source of feedwater is available to the steam generators.

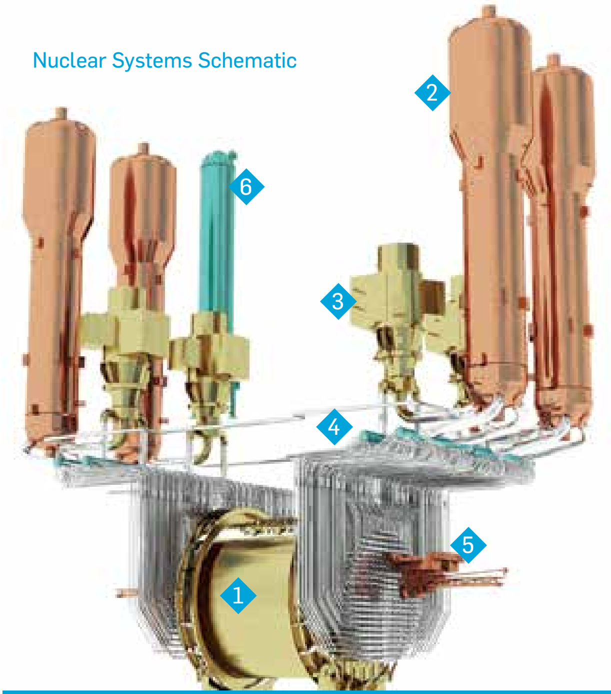
Loss of Feedwater Supply to the Steam Generators

The emergency water supply (EWS) system provides passive make-up water supply to the steam generators.

Non-Loss of Coolant Accident (LOCA) Events

Gravity make-up to the steam generators is provided by the EWS system to effectively remove decay heat from the core for at least 72 hours.

Nuclear Systems Schematic



1 Calandria
2 Steam Generator (4)
3 Heat Transport Pump (4)
4 Header (8)
5 Fuelling Machine (2)
6 Pressurizer

Station Blackout

Reactor core cooling via the steam generators is maintained for at least 72 hours with no operator intervention required. For long-term cooling, make-up water to the steam generators is provided by the EWS system pump. Each independent EWS reservoir contains enough water to remove decay heat for at least nine days for each unit.

Loss of Coolant Accident (LOCA) Events

The emergency core cooling system (ECCS) effectively cools the fuel and maintains fuel channel integrity. The ECCS provides water injection to the HTS in three phases:

- High-pressure emergency core injection (ECI) from accumulators;
- Medium-pressure ECI from the dousing tank; and
- Low-pressure ECC recovers, recirculates and cools the water from the reactor building basement

LOCA Combined with loss of ECC event

The moderator provides an emergency heat sink to maintain core coolability by effectively removing decay heat from core. The decay heat is sufficiently removed by moderator boil off, even when moderator cooling is unavailable. The moderator is an effective heat sink that stops accidents at the fuel channel boundary.

The AFCR provides large quantities of moderator water (260 m^3) plus passive and active water make-up to the calandria vessel to prevent severe core damage accidents:

- Passive water make up from the dousing tank to the calandria vessel by gravity
- Active moderator make-up by a dedicated severe accident prevention and mitigation system to cool the core for the long term

Calandria vault water provides for in-vessel retention (IVR) of core debris. The shield water system has sufficient thermal capacity to slow down the progression of a severe accident. Accident progression in a CANDU reactor would be slow due to the significant quantity of heat sinks surrounding the core. The water in the calandria vault ensures calandria vessel cooling to maintain core debris IVR.

The AFCR has both passive and active provisions to ensure water inventory in the calandria vault is maintained for calandria vessel cooling. This includes two passive systems for make-up water to calandria vault ensuring calandria vessel cooling for at least 72 hours:

- Independent water is provided for passive make-up to calandria vault only
- Condensate from the PCHRS is collected and returned to the calandria vault

Active make-up water is also provided to the calandria vault by the SARHRS using the water from either the EWS reservoir or the basement for long term cooling. The calandria vault water heat sink stops accidents at the calandria vessel boundary.

CANDU Spent Fuel Bay

Spent Fuel Cooling

The AFCR's spent fuel bay (SFB) ensures spent fuel cooling is maintained for 15 days without being dependent on operator action. Spent fuel is sufficiently cooled as long as it is covered by the water in the bay. The SFB has a redundant spent fuel bay make-up and cooling system, status monitoring and leakage detection. In addition, the SFB has mitigation measures for emergency spent fuel cooling including provisions for pool water make up and pool cooling. It is located at grade level and therefore potential for leakage during various accidents is significantly reduced relative to other reactor designs.

AFCR's Major Passive Heat Sinks

Four major passive heat sinks in the AFCR ensure decay heat removal from the reactor core and from containment:

- Gravity fed dousing water to fill fuel channels, SGs and calandria vessel
  - AFCR dousing water inventory is increased from CANDU 6 design to 2350 m^3
- Moderator volume is 260 m^3
- Shielding cooling water volume is 520 m^3
- Independent water source from the dousing water combined with condensate from passive containment heat removal system (PCHRS) fills calandria vault by gravity
  - Additional independent 600 m^3 of water is added to the dousing tank dedicated for calandria vault make-up only
  - Condensate from PCHRS is collected for calandria vault make-up

Containment

The AFCR has a robust containment to address DBAs and BDBAs. AFCR containment design pressure at 200 kPa(g) covers all DBAs, including a LOCA and a main steam line break (MSLB). The maximum containment pressure for DBAs is about 140 kPa(g). AFCR containment can withstand accident pressure of 400 kPa(g) with margin. The AFCR contains a steel liner to reduce leakage rate and minimize potential radioactive releases.

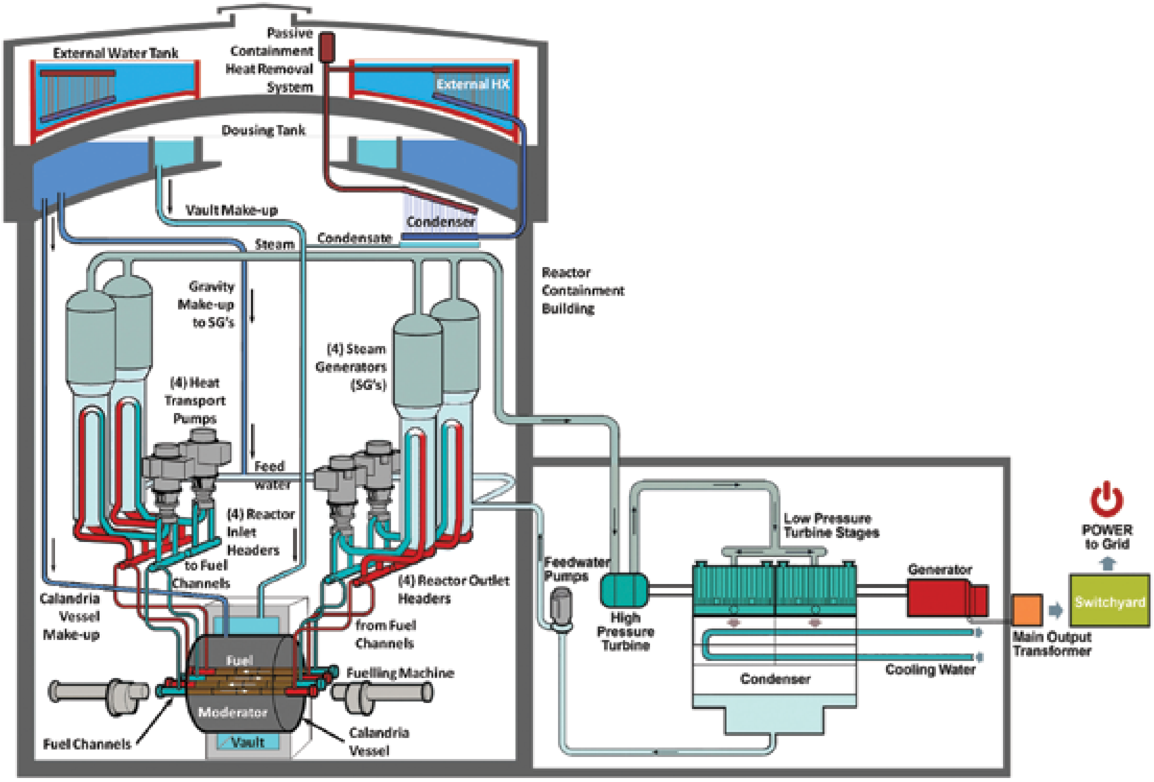
In addition, both active and passive measures can arrest containment pressure and remove decay heat from the containment. Specifically, the dousing system limits containment peak pressure for breaks inside containment by a gravity driven dousing spray. Local air coolers (LACs) remove the heat from the containment for long term.

Active and passive heat sinks ensure containment function for BDBAs. Specifically, active containment heat removal is provided by SARHRS for BDBAs (DECs). SARHRS can remove heat from containment for the long term. A PCHRS is a long term containment heat sink that removes heat from the containment by natural circulation with no operator intervention for 72 hours. Passive containment cooling is maintained by PCHRS as long as the water in the external water tank is available; operator action to provide water make-up to the PCHRS external water tank may be required after 72 hours.

The AFCR containment also contains passive and active provisions for hydrogen control and monitoring. These systems include:

- Passive autocatalytic recombiners (PARs)
- Hydrogen igniters
- On-line hydrogen monitoring system

The optional ECFVS is additional protection for the containment to avoid uncontrolled radioactive releases from the containment.



Overal AFCR Plant Flow Diagram with Key Passive Features

Reliable and Robust Design

Our AFCR is based on the reference Qinshan CANDU 6 design and is a further advancement of the EC6 design through the addition of new passive safety features and the use of alternative fuel (recycled uranium or thorium). The AFCR is Candu's latest and most advanced alternative fuel cycle pressurized heavy water reactor design for the international market.

Our AFCR design approach ensures safety during construction, commissioning and operation. All reasonably practicable design measures are taken into account to prevent accidents and to mitigate their consequences. We have ensured with a high level of confidence that, for all postulated accidents considered in the design including those of very low probability, radiological consequences would be below prescribed limits and that the likelihood of accidents with serious radiological consequences is extremely low. The intent of AFCR design is to practically eliminate accident sequences with a large or early release.

Fail Safe Design

Systems and components that are vital to safety are designed to fail to a safe state, as appropriate and to the extent practicable. Components fail to a safe state to lead the plant to a safe shutdown state and to maintain fission products barriers so that radioactive materials are confined to within regulatory limits. Components are designed, as far as practicable, to a safe state or be put in a safe state following a failure (e.g., where a loss of instrument air results in an unsafe failure, a back-up air supply is provided). Typical examples include the containment isolation system and shutdown systems.

Single Failure Criterion

The single failure criterion is taken into account in the AFCR design to ensure safety functions are performed despite one random failure of equipment independent of the initiating event. Account is taken of any consequential failure resulting from the single failure. This criterion applies to active components for which a single failure is postulated in both the short and long term. In the AFCR design, a system important to safety is capable of performing its intended safety functions credited in the design basis event analysis assuming a single failure within the system or in an associated system that supports its operation.

Diversity

To the extent practicable, diversity is applied to redundant systems that perform the same safety function by incorporating different attributes to reduce the potential for common-cause failures. The level of diversity provided is commensurate with the required reliability of performing the safety function.

Reliability

Reliability of the SSCs is achieved in design by:

- **Robustness** – minimizes probability of failure by adopting quality standards commensurate with their importance to safety
- **Qualification** – designed to withstand the loads and adverse environmental conditions induced by the design basis events (DBAs, including seismic event, fire, internal flooding, etc.)
- **Redundancy/diversity** – tolerant of both random and common mode failures

Grouping and Separation

Our AFCR is designed based on the CANDU “two group” design approach to achieve redundancy and independence. The unique CANDU two-group approach provides two sets of systems to accomplish the essential safety functions with redundancy to ensure reliability of mitigating safety functions. Each group can perform the essential safety functions and independently maintain the plant in a safe state. In addition, component redundancy is built in to the safety systems to satisfy the single failure criterion. Physical and functional system separation is designed into the two-group concept. The components of safety systems that perform similar functions are separated to the maximum practicable extent, and redundant components within systems are physically separated according to their susceptibility and common hazards.

Group 1 and Group 2 Concept

AFCR’s two group design ensures there are two independent means to achieve the same safety functions.

Group 1 and Group 2: functional and physical separation plus redundancy and diversity.

Seismic Qualification

Earthquakes are natural external common cause events, which are considered in the AFCR. The SSCs required to perform or support the performance of fundamental safety functions during and/or following an earthquake are seismically qualified.

Environmental Qualification

The safety equipment is environmentally qualified to ensure it performs the required safety function(s) without experiencing a common cause failure with the plant in a normal or abnormal operating condition, or during a DBA condition. Equipment credited to operate during BDBAs (including severe accidents (SAs)) and located in the environmental conditions resulting from these events is assessed for its survivability.

Ageing

To ensure the capability of the SSCs important to safety to perform the necessary safety function throughout their design life, relevant ageing and wear-out mechanisms and potential age related degradation have been taken into account and appropriate margins provided. Ageing and wear-out effects in all normal operating conditions, testing, maintenance, maintenance outages, and plant states in a postulated initiating event (PIE) and post-PIE have also been taken into account. All life-limiting factors are evaluated and addressed, in particular ageing effects. The effects of ageing are addressed in the AFCR safety analysis.

Radiation Protection

The AFCR design ensures workers and members of the public are provided with adequate protection from radiation throughout the operating life and into the decommissioning phase of the reactor. The radiation protection provisions ensure safety for all normal, abnormal, and accident conditions. Our AFCR complies with the recommendations of the International Commission on Radiological Protection (ICRP) and annual exposure limits as set out in ICRP-60.

AFCR design provisions ensure potential radiation doses to the public and site personnel do not exceed these limits. Overall risk to the public from all plant states is judged against the AFCR safety goals based on Generation III requirements. Measures are taken to ensure that the radiation protection and technical safety objectives are achieved, and that radiation doses to the public and to site personnel in all operational states, including maintenance and decommissioning, do not exceed prescribed limits, and are as low as reasonably achievable (ALARA).

The exposure of plant personnel to internal and external radiation is limited by layout and structural shielding arrangements, by control of access to areas of high activity or of possible contamination, and by combination of systems incorporated into the design. AFCR design ensures that the limits prescribed Chinese national standard GB6249 and recommendations provided in ICRP Publication 103 are met.

Human Factors

We integrate human factors into our design process to ensure:

> A thorough and consistent approach to system design

> Consideration of operating experience review information, so designs may be evolved with knowledge of past performance criteria

> Establishment of required human factors engineering (HFE) documentation for system design input

> Design effort towards definition and assessment of operator/maintainer system interface functionality, information and control needs, environmental issues, and equipment layout for special tool and staff accessibility and maintenance concerns (e.g., equipment replacement, removal, etc.)

The overall application of HFE ensures a design that supports safe, productive, efficient operating characteristics throughout all stages of construction, commissioning, operation, maintenance, testing, inspection, and decommissioning.

Out-of-Core Criticality Safety

The AFCR design emphasizes the prevention of out-of-core criticality and protection of individuals, society and the environment from harm. To that effect, our design follows the good safety practices described in the ANSI/ANS-8 series of standards, consistent with Chinese national standards GB15146-2008 series regarding nuclear criticality safety.

Provision for In-Service Testing, Maintenance, Repair, Inspection and Monitoring

AFCR structures, systems and components (SSCs) important to safety are designed to be calibrated, tested, maintained, repaired or replaced, inspected and monitored for their functional capability over the lifetime of the nuclear power plant to demonstrate reliability targets are being met. For the SSCs important to safety that cannot be designed to be able to be tested, inspected or monitored to the extent desirable, other proven alternative and/or indirect methods are specified; and conservative safety margins are applied or other appropriate precautions are taken to compensate for possible unanticipated failures.

Complementary Design Features to Enhance Safety Provisions

Complementary design features address BDBAs (Design Extension Conditions (DECs)), including the complementary prevention and mitigation measures provided in the EWS, SARHRS and PCHRS. Complementary design features in our AFCR design to address BDBAs (DECs) include:

- Provisions to remain in a safe shutdown state and to prevent criticality
- Provisions to prevent core damage
- Provisions to cool core debris
- Provisions to retain the core debris at in-vessel retention
- Provisions to maintain containment integrity
- Provisions to preclude uncontrolled radioactive material releases
- Hydrogen control and monitoring measures
- Provisions to maintain spent fuel cooling for extended periods
- Alternate AC power supply
- Alternative water supply

For BDBAs, AFCR has sufficient complementary design features to prevent accident progression and mitigate the consequences of severe accidents.

Severe Accident Recovery and Heat Removal System (SARHRS)

The AFCR incorporates a seismically qualified SARHRS to prevent and/or mitigate severe accidents. The purpose of SARHRS is to remove decay heat from the core during a BDBA event, and as such contributes to nuclear power plant (NPP) safety goals. SARHRS is a complementary design feature, and belongs to Level 4 defence in the defence-in-depth (DiD) concept.

SARHRS provides the following functions:

- Make-up water to the calandria vessel
- Make-up water to the calandria vault
- Removal of heat from the containment

The system is composed of a make-up pump, a cooling water pump, a heat exchanger, associated piping lines and valves. It provides a recovery and recirculation mode as a long-term heat removal provision after a BDBA. The system is powered by a SARHRS dedicated diesel generator (DG) for each unit. The SARHRS is a manually operated system. All the active components are located outside the containment for accessibility following a BDBA. All the valves are remotely controlled, and are available for local manual operation as well.

Passive Water Make-up to the Calandria Vessel

A passive moderator make-up function is also provided as a fourth level of defence-in-depth in the AFCR as part of the EWS. Gravity driven moderator make-up from the dousing tank maintains the moderator as a sustainable heat sink for decay heat removal from the core for BDBAs. It prevents accidents from progressing to a severe core damage accident (SCDA) for most BDBAs. The flow rate for the make-up from the dousing tank to the calandria vessel by gravity is selected based on the moderator boil-off rate required for decay heat removal with additional margin for leakage considerations though the failed bellows during accidents.

The EWS system passive moderator make-up function can provide water make-up to the calandria vessel for 24 hours for events without initiating ECCS. With the ECCS available, there is no concern of fuel cooling since decay heat can be effectively removed from the core by the ECCS.

Passive Calandria Vault Water Make-up

To ensure in-vessel retention (IVR) of core debris in severe accidents, the AFCR design includes provisions to provide water make-up to the calandria vault by gravity from a dedicated water tank at high elevation inside the containment. This ensures calandria vessel cooling from the outside by the water in the calandria vault and IVR. SARHRS provides a water make-up to the vault by pump to maintain the calandria vessel integrity. Whereas, a passive calandria vault make-up system (PCVMS) provides passive backup water make-up to the vault. As part of the PCVMS function, the condensate from the PCHRS condensers is also collected to feed the calandria vault by gravity.

Passive Containment Heat Removal System (PCHRS)

Our AFCR's PCHRS is another layer of defense for the containment and an important complementary design features to manage BDBAs (DECs), which provides a long-term containment heat sink following an accident. The PCHRS removes decay heat from the containment by natural circulation thereby reducing the containment pressure and temperature within the maximum allowable levels for BDBAs without operator intervention for 72 hours.

The major components of the PCHRS include the containment condensers inside the containment, the external containment heat exchangers (HXs), the connection pipes between the containment condensers and the external HXs and the cooling water tank. Under accident conditions, steam inside the containment atmosphere condenses at the surface of the containment condensers and heat is transferred the outside water by natural circulation. The water inside the condenser tubes is heated by heat transferred from steam condensation. The heated water has a higher temperature and less density. A natural circulation flow is established in the loop by the difference of the water density between the warm and cold water lines, driving the warm water up to the external containment HX through the warm water line and the cold water moving down to the containment condenser through the cold water line. The external containment HXs are submerged in the cooling water tank located on the top of the reactor building outside the containment. The warm water inside the HX tubes is cooled by the water in the cooling water tank.

The PCHRS also collects condensate and returns it directly to the calandria vault to maintain the water inventory in the vault. This water source supplements the PCVMS water make-up from the independent water source in the dousing tank. In-vessel retention is maintained as long as the vault water is sustained for cooling the calandria vessel from the outside.

The PCHRS meets the following:

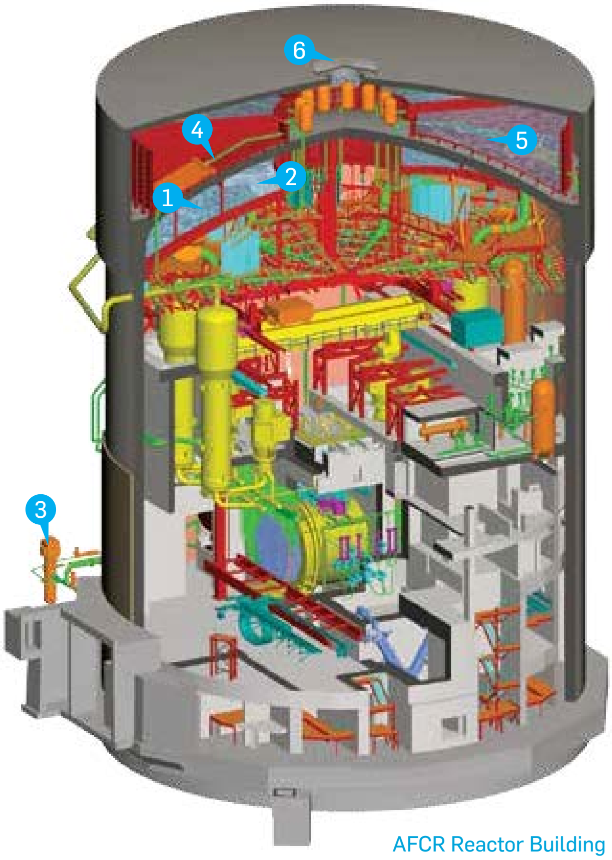
- Withstands effects of natural phenomena such as extreme weather, earthquakes, or floods
- Withstands dynamic effects of an accident and remains functional in accident environment conditions
- Automatically operates following a BDBA with no operator action required for 72 hours
- Passively and sufficiently removes decay heat from containment atmosphere to reduce containment pressure within its maximum allowable level for BDBAs
- Collects condensate and returns it to the calandria vault
- Provides water make-up to the cooling water tank after 72 hours

The PCHRS is designed in modules. Each module consists of one containment condenser, one external HX, associated piping line as well as isolation valves, an expansion tank and a cooling water tank.

The PCHRS design is based on representative accident conditions. Additional PCHRS testing is performed in the detailed design stage to confirm system performance meets design requirements.

Emergency Containment Filtered Venting System (ECFVS)

Containment is designed to minimize radioactive releases following a severe accident. The AFCR ECFVS is based on proven technology and is similar to the ECFVS installed in our other CANDU NPPs. The ECFVS allows containment depressurization to be performed while minimizing radioactive releases to the environment. Vented vapours from the containment atmosphere pass through a scrubber/filter vessel to remove high activity isotopes and aerosols to contain or control the radioactive releases. The system is fully passive and does not require any external electric or other power sources during standby or in operational mode (except monitoring). The ECFVS constitutes a last resort measure to prevent catastrophic failure of containment and is part of severe accident management guidelines (SAMG).



1 Dousing Tank
2 Calandria Vault Make-up Water
3 Severe Accident Recovery & Heat Removal System
4 Passive Containment Heat Removal System (PCHRS) Loop
5 PCHRS Cooling Tanks
6 PCHRS Vented Enclosure

AFCR Reactor Building

Safety and Safety Support Systems

Safety Systems

Reactor safety systems are designed to mitigate the consequences of plant process failures, and to ensure reactor shutdown, removal of decay heat, and prevention of radioactive releases. The safety systems in our AFCR design maintain the traditional CANDU reactor practice of providing:

- Independent shutdown systems 1 and 2
- An emergency core cooling system (ECCS)
- A containment system

The two-shutdown systems, the ECCS, and the containment boundary system, meet specified regulatory reliability targets with which the system design complies. The containment boundary includes the physical structures designed to prevent and control the release of radioactive substances.

Safety support systems are also provided to ensure reliable electrical power, cooling water and instrument air supplies to the safety systems. Standby generators are provided as a backup to station power for postulated loss of station power events.

Safety systems and their support services are designed to perform with a high degree of reliability and is achieved through stringent technical specifications, including seismic qualification and environmental qualification for accident conditions.

Shutdown Systems

The AFCR's two passive, fast acting, fully capable, diverse shutdown systems are physically and functionally independent of each other. This feature of the CANDU reactor design ensures defence in depth.

Emergency Core Cooling System

The ECCS is designed to supply emergency coolant to the reactor in three stages:

- The highpressure ECCS is designed to provide initial light water injection to the HTS from the ECC accumulator tanks pressurized by air/gas pressure
- Following termination of highpressure injection, the mediumpressure injection system supplies light water to the HTS from the dousing tank via the ECC pumps
- Following the termination of medium- pressure injection (upon depletion of the dousing tank), the long term automatic ECC injection is provided by collecting the mixture of heavy water and light water from the reactor building basement and recirculating into the HTS via the ECC pumps and heat exchanger

During normal operation, the ECC system is poised to detect any LOCA that results in a depletion of HTS inventory (i.e., reactor coolant) to such an extent that make-up by normal means is not assured.

The system maintains or reestablishes sufficient cooling of the fuel and fuel channels for the design basis events, so as to limit the release of fission products from the fuel and maintain fuel channel integrity. After reestablishing fuel cooling, the system provides sufficient cooling flow to prevent further damage to the fuel.

Containment System

The containment system forms a continuous, pressure-retaining envelope around the reactor core and the HTS. The containment structure protects the public and environment from all potential internal events, and is designed to withstand tornadoes, hurricanes, earthquakes, malevolent acts, large aircraft crash, etc., and to prevent the release of radioactive material to the environment.

The containment boundary consists of a steel-lined, pre-stressed concrete reactor building structure, access airlocks and a containment isolation system. Local air coolers remove heat from the containment atmosphere and are located to best maintain operating containment pressure and temperature.

The hydrogen control system in containment prevents build-up and uncontrolled burning of hydrogen. In addition, the containment internal structures are arranged to promote natural air mixing inside containment.

The dousing system is connected to the elevated dousing tank and reduces reactor building pressure and maintains containment integrity, if required, in the event of accidents.

The strength of the containment structure, including access openings and penetrations, has sufficient margins of safety to withstand potential positive internal pressures, negative pressures, temperatures, dynamic effects such as missile impacts, and forces anticipated to arise as a result of DBAs and BDBAs. The containment system consists of a post-tensioned pre-stressed concrete containment structure with a steel liner, energy sinks consisting of an automatically initiated dousing system and building local air coolers, access airlocks, hydrogen control system, and a containment isolation system consisting of valves and dampers in the system lines penetrating containment. Both active and passive design features are provided to remove decay heat from the containment for BDBAs. The ECFVS provides another layer of defence to protect the containment from overpressure and to prevent uncontrolled large radioactive release.

Safety Support Systems

The safety support system supports the operation of one or more safety systems.

Emergency Water Supply System

The EWS system provides cooling water to the ECC heat exchangers and provides makeup water to each HTS loop and steam generators to ensure fuel cooling after an event which causes the loss of normally operating systems, or to act as a backup source of cooling water in the long term after an event. The EWS also provides gravity water make-up to the calandria vessel from the dousing tank to maintain the moderator as a heat sink for BDBAs. If the calandria vessel moderator rupture discs burst, the EWS would provide the water make-up flow path from the dousing tank to the calandria vessel, to compensate the sudden loss of the moderator through flashing when the rupture disc burst, and/or the moderator leak. This action would prevent a severe core damage accident or delay the onset of severe core damage and provide more time for the operator to take mitigating action.

Each AFCR unit is equipped with a dedicated EWS and EWS reservoir. Each unit has two 100% pumps taking suction from each of the onsite EWS water reservoirs that are in a separate location from the main plant service water system intake. Under accident conditions the EWS would provide both active and passive water sources. Passive cooling water supply would last for more than 72 hours. The active supply would provide cooling water for the longer term.

Raw Service Water and Recirculated Cooling Water Systems

A closed-loop recirculated cooling water (RCW) system transfers heat to the open-loop raw service water (RSW) system, from which heat is transferred to the ultimate heat sink. The RSW system is composed of four raw service water pumps in parallel. During normal operation, three of the four pumps operate. Four RCW/RSW heat exchangers form the interface between the RCW and RSW systems. The RCW system is also composed of four pumps in parallel, with three of four pumps operating during normal operation.

Connectivity of the RCW supply lines is arranged with valves in place so supply can be partitioned into two separate trains, with each train supplying one ECC heat exchanger and one moderator cooling system heat exchanger. This improves reliability of RCW and the supported systems.

Emergency Power Supply System

The electrical power distribution systems are separated into Group 1 and Group 2 in accordance with the two group separation philosophy. The Group 1 electrical distribution system provides power to the process systems used for power production, systems important to safety and safety support systems. The Group 2 system is the emergency power supply (EPS) system. This system provides a seismically qualified back-up power source to selected safety systems and safety support systems, which are normally supplied from the Group 1 system.

The EPS system is designed to provide a Group 2 seismically qualified alternative source of electrical power supply to systems important to safety in the event that normal power supplies (Class IV, Class III) are lost. Each AFCR unit has a dedicated EPS to supply the necessary safety loads. The EPS system for each unit is composed of two duplicate, odd and even, automatically started, seismically qualified and functionally independent trains along with uninterruptible power supplies (UPS) and a distribution system.

Each EPS generating set consists of a diesel generator with battery starting system, brushless excitation system, governor and controls.

Postulated events specifically supported by the EPS system are:

- Design basis earthquake
- Total loss of electrical power (both Class IV and III)
- LOCA followed by site design earthquake after 24 hours

In case of an SBO, the seismically qualified UPS provides power to loads required for provision of a heat sink capable of supporting the safety critical loads for up to 24 hours.

An independent SARHRS diesel generator for each unit is a complementary design feature to power a limited number of loads for mitigation of severe accidents.

In addition, each reactor unit is provided with its own seismically qualified mobile diesel generator to cope with extended SBO events.

Two-Unit AFCR Plant Layout

AFCR Plant Siting and Layout

Our AFCR units are highly adaptable to different site conditions and can accommodate a wide range of geotechnical characteristics, meteorological conditions and owner requirements through its flexible design. The layout of the AFCR plant provides adequate separation by distance, elevations (different heights) and the use of barriers for SSCs important to safety that contribute to protection and safety. Security and physical protection have been enhanced in the AFCR design to meet the latest criteria required in response to potential common mode events (e.g., fires, aircraft crashes and malevolent acts). The plant is also tornado protected.

The layout for a two-unit plant is designed to achieve the shortest practical construction schedule while supporting shorter maintenance durations with longer intervals between maintenance outages. The buildings are arranged to minimize interferences during construction, with allowance for on-site fabrication of module assemblies. Open-top construction (before setting the roof of the RB in place), allows for the flexible sequence of installation of equipment and reduces the overall project schedule risk. Each unit is designed to operate independently during all operational conditions but with the capability to support each other during seismic events.

The size of the power block (plant foot-print) for a two-unit integrated AFCR plant is 48,000 square metres. The power block consists of two reactor buildings, two service buildings, two turbine buildings, two high-pressure emergency core cooling buildings, two secondary control areas and one heavy water upgrader building.

The AFCR is seismically designed to withstand an earthquake that would happen once in every 10,000 years with sufficient margin. It is robust enough to withstand other natural disasters such as flooding, tornados, tsunamis, or a typhoon.

The principal structures associated with each AFCR unit are the reactor, service and turbine buildings.

The RB internals are divided into three areas: accessible, restricted access and inaccessible. Systems and equipment requiring maintenance or access during on-power operations are located in areas that are safe for personnel to enter.

The service building is arranged so the main control room (MCR) and equipment areas are separated from the secondary control area (SCA) and its related support services by 180 degrees with the reactor building between them. This arrangement makes it virtually impossible for both control areas to be lost due to a common cause failure.

Within the service building, the spent fuel transfer and storage bays are located immediately adjacent to the reactor building. This arrangement keeps the length of the spent fuel transfer duct and mechanism as short as practical while locating the storage bay in an area remote from the rest of the service building.

The turbine building adjoins the service building with the turbine auxiliary bay providing the shortest length of inter-phasing piping and cables.

Auxiliary structures include the administration building, the condenser cooling water (CCW) pump house, water intake and discharge, the HPECC building, the SARHRS building, and the Emergency Water Supply (EWS) pump house.

A tritium splitter facility is also included as a part of the AFCR twin-unit plant.

Reactor Building

The AFCR RB houses the reactor, fuel-handling systems, HTS including the steam generators, and moderator system, together with their auxiliaries and the safety systems and complementary design features. It is a multilevel, reinforced concrete and steel structure that is seismically qualified, tornado protected, and protected against malevolent acts.

The RB is a pre-stressed, seismically qualified, concrete building and has been strengthened further compared to previous CANDU 6 designs to resist internal and external events, including a large aircraft crash. Pre-stressed concrete is reinforced with cables that are tightened to keep the structure under compression and to behave in an elastic manner under all design basis events, with a significant margin. The concrete containment structure has an inner steel liner that reduces leakage rates in the event of an accident. CANDU reactors inherently have lower containment pressures during postulated accidents. Despite this advantage, our AFCR has a thick walled containment structure similar to those of other Generation III PWR designs. This approach results in the greatest containment building design margins.

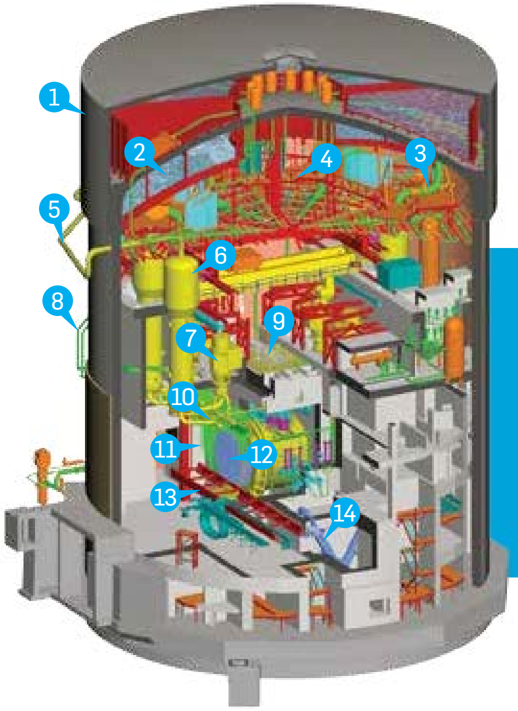
The entire structure, including concrete internal structures, is supported by a reinforced concrete base slab that ensures a fully-enclosed boundary for environmental protection and biological shielding which in turn reduces the level of radiation emitted outside the reactor building, during operation, design basis internal and external events and beyond design basis internal and external events, to values that are insignificant to human health.

Internal shielding allows personnel access during operation to specific areas for inspection and routine maintenance. These areas are designed to maintain temperatures that are suitable for personnel activities. Airlocks are designed as routine entry/exit doors.

Containment structure perimeter walls are separate from internal structures, eliminating any interdependence and providing flexibility in construction.

The AFCR containment building also includes a heat sink and the PCHRS, located on top of the containment structure, to remove heat from containment through passive means. Through this new feature, the AFCR is Candu's latest and most advanced alternative fuel cycle pressurized heavy water reactor designed with multiple layers of defence through both active and passive safety features.

In addition, an ECFVS is also provided as another layer of defence in depth.



1	Reactor Building	**8**	Main Feed Water Line
2	Dousing Tank	**9**	Reactivity Mechanism Deck
3	Dousing System Supply Pipe	**10**	Headers
4	Dousing System	**11**	Feeder Pipes
5	Main Steam Line	**12**	Calandria
6	Steam Generator	**13**	Fuelling Machine Bridge & Carriage
7	Heat Transport Pump	**14**	Spent Fuel Handling Mechanism

AFCR Reactor Building

Service Building

The AFCR service building is a multi-level, reinforced concrete structure that is seismically qualified and tornado missile protected. It accommodates the "umbilicals" that run between the principle structures, the electrical systems and the spent fuel bay and associated fuel-handling facilities. It houses the emergency core cooling pumps and heat exchangers.

The spent fuel bay is a water-filled pool for storing spent fuel. The AFCR spent fuel bay is located at grade level and the potential for leakage during various accidents is significantly reduced relative to other types of reactor designs.

Safety and isolation valves of the main steam lines are housed in a seismically qualified and tornado missile protected concrete structure that is located on top of the service building. The layout of the service building is optimized to ensure the highest level of ergonomics and operational ease based on feedback from other CANDU reactor operating stations.

The service building is designed to protect the spent fuel bay, secondary control area, airlocks and emergency power supply against a large aircraft crash.

Turbine Building

The AFCR turbine building is located on one side of the service building wherein the service building interfacing wall is tornado missile resistant. This location is optimal for access to the main control room; the piping and cable tray run to and from the service building; and the condenser cooling water ducts run to and from the main pump house. Access routes are provided between the turbine building and the service building.

The turbine building houses the turbine generator. It also houses the auxiliary systems, the condenser, the condensate and feedwater systems, the building heating plant, and any compressed gas required for the balance of plant. The balance of plant consists of the remaining systems, components and structures that comprise the complete power plant that are not included in the nuclear steam plant.

The heat from the reactor coolant converts the feedwater into steam in the steam generators. This steam drives the turbine, which in turn drives the generator to create electricity.

The condenser cools the steam from the steam generator and converts it back to water (condensate) to be converted into steam again.

Blowout panels in the walls and roof of the turbine building relieve the internal pressure in the turbine building in the event of a steam line break.

Nuclear Systems

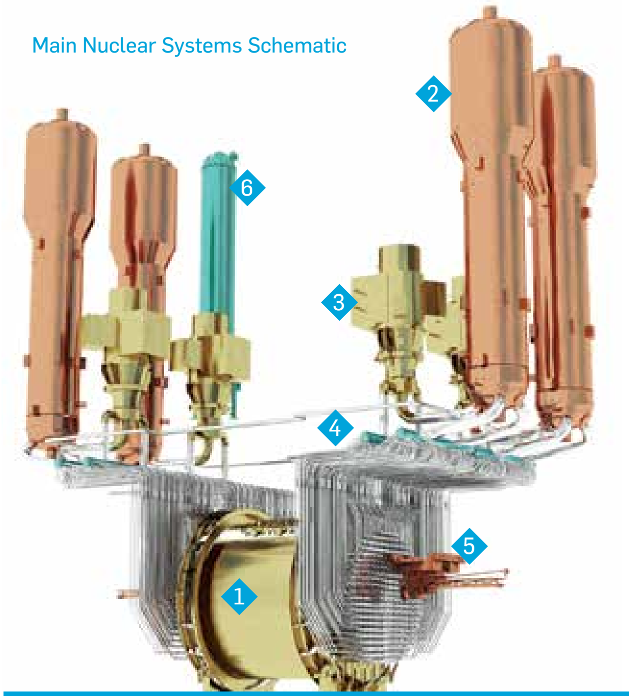
The AFCR nuclear systems are located in the reactor building and the service building. These buildings are robust and shielded for added safety and security. Shielding is a protective barrier that reduces or eliminates the transfer of radiation from radioactive materials.

The nuclear systems are composed of:

- An HTS with heavy water reactor coolant, four steam generators, four heat transport pumps, four reactor outlet headers, four reactor inlet headers, feeders and interconnecting piping. This configuration is standard on all CANDU reactors
- A heavy water moderator system
- A reactor assembly that consists of a calandria vessel complete with fuel channels installed in a concrete vault
- A fuel handling system that consists of two fuelling machine heads, each mounted on a fuelling machine bridge that is supported by columns, which are located at each end of the reactor
- Two independent shutdown systems SDS1 and SDS2, the ECCS, the containment system and associated safety support systems

An illustration of the main nuclear systems that form the reactor coolant pressure boundary is shown below.

Main Nuclear Systems Schematic



1 Calandria
2 Steam Generator (4)
3 Heat Transport Pump (4)
4 Header (8)
5 Fuelling Machine (2)
6 Pressurizer

Heat Transport System

The AFCR HTS, similar to the reference CANDU 6 design, circulates pressurized heavy water coolant through the reactor fuel channels to remove heat produced by the nuclear fission chain reaction in the reactor core. The heated coolant is circulated through the steam generators to produce steam that drives the turbine generator system. The heat transport system consists of 380 horizontal fuel channels with associated corrosion-resistant feeders, four reactor inlet headers, four reactor outlet headers, four steam generators, four electrically-driven heat transport pumps and interconnecting piping and valves arranged in a two-loop, figure-of-eight configuration. The headers, steam generators and pumps are all located above the reactor.

While maintaining the CANDU 6 reactor-basis for reduced implementation risk, the AFCR incorporates a series of changes to ensure a minimum 60-year plant life at full capacity while having the features required for both recycled uranium and thorium fuel use.

The steam generator size has been incrementally increased to further enhance thermal and core physics margins by establishing sub-cooled conditions.

Our CANFLEX fuel bundle is a qualified and proven bundle configuration. In our AFCR, it is used both for DRU and thorium-based fuel applications for improved core thermalhydraulics and physics characteristics.

The thickness of the pressure tubes has been increased to ensure longer life, while the feeder pipes have been resized for improved flow distribution and reduced pressure drop.

Heat Transport System Key Design Parameters	
Reactor outlet header operating pressure [MPa(g)]	9.89
Reactor outlet header operating temperature [°C]	308
Reactor inlet header operating pressure [MPa(g)]	11.0
Reactor inlet header operating temperature [°C]	263
Maximum single-channel flow (nominal) [kg/s]	28.6

Steam Generators

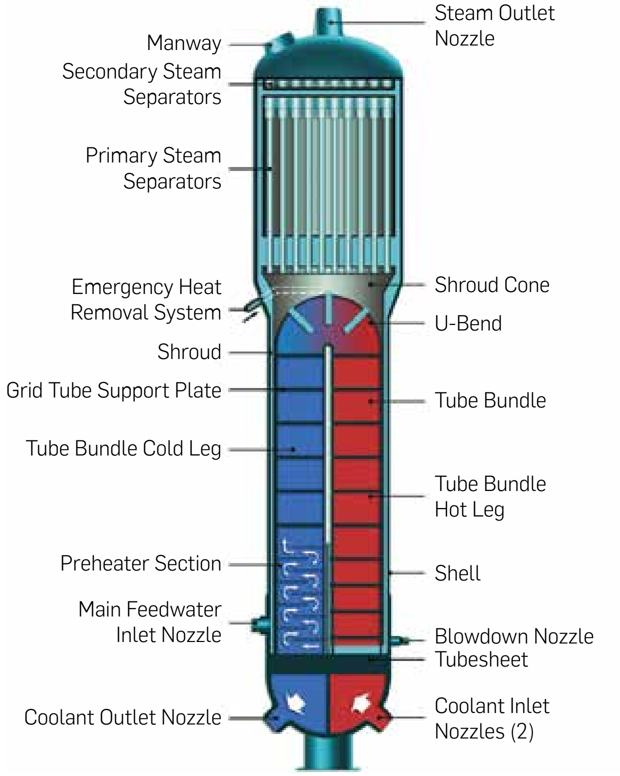
The AFCR SGs are slightly larger than those of the CANDU 6 reactor while still maintaining all the proven characteristics. The tubing is made of IncoloyTM800, a material proven in CANDU 6 reactor stations. The light water inside the steam generators, at a lower pressure than the hot heavy water reactor coolant, is converted into steam.

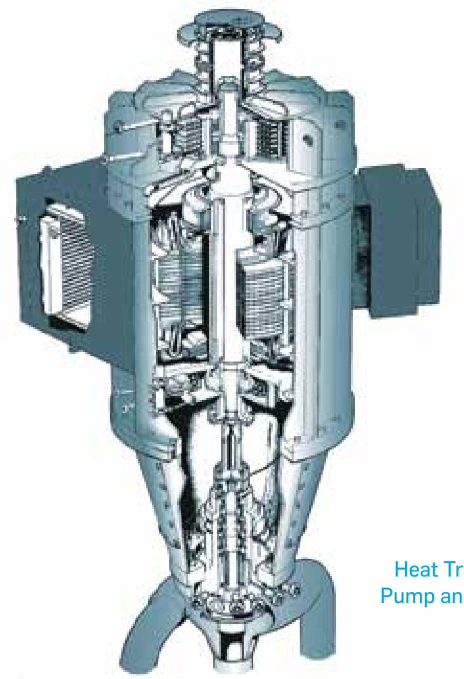
The SGs are designed for 60-year life with periodic primary and secondary side cleaning. Additional features have been included in the reactor design for ease of replacement, if required.

Steam wetness (ratio of vapour/liquid concentration in steam), has been reduced at the steam nozzle using the latest steam separator technology. This results in improved turbine cycle economics.

Steam Generator Design Data	
Number	4
Nominal tube diameter [mm]	15.9
Nominal steam temperature [˚C]	260

Steam Generator





Heat Transport Pump and Motor

Heat Transport System Pumps

The four HTS pumps are vertical, single stage, double volute, single suction, double discharge centrifugal pumps. The AFCR HTS pumps retain the CANDU 6 mechanical multi-seal design, which allows for easy replacement. The heat transport pumps circulate reactor coolant through the fuel bundles in the reactor's fuel channels and through the steam generators. Electric motors drive the HTS pumps.

Cooling the pump seals lengthens the pump service life and the time that the pump will operate under accident conditions.

The AFCR HTS pumps are identical to those in CANDU 6 reactors, to reduce any implementation risk.

Heat Transport Pump Data	
Number	4
Rated flow [L/s]	2,228
Rated head [m]	215
Motor rating [MW]	6.7

Heat Transport Pressure and Inventory Control System

The heat transport pressure and inventory control system of our AFCR consists of a pressurizer, liquid relief valves, a degasser-condenser, two heavy water feed pumps, and feed and bleed valves. The system is designed for a 60-year life.

This system provides:

> Pressure and reactor coolant inventory control to each heat transport system loop

> Overpressure protection

> Degassing the HTS coolant

Moderator System

The AFCR moderator system is a low-pressure and low-temperature heavy water based system. It is independent of the heat transport system. The moderator system consists of pumps and heat exchangers that circulate heavy water moderator through the calandria and remove heat that is generated during reactor operation. The heavy water acts as both a moderator and reflector for the neutron flux in the reactor core.

The moderator slows down neutrons emitted from the fission chain reaction to increase the chances of the neutrons hitting another atom and causing further fission reactions. The reflector is the material layer around the reactor core that scatters neutrons and reflects them back into the reactor core to cause further fission chain reactions. This capability is one of the fundamental reasons behind the high fuel efficiency of the AFCR core and its ability to use multiple fuel types efficiently.

The moderator system fulfills a safety function that is unique to CANDU-type reactors. It also serves as a backup heat sink for absorbing the heat from the reactor core in the event of loss of fuel cooling (e.g., failure of the heat transport system) to mitigate core damage.

The AFCR maintains the proven CANDU 6 reactor dousing system, an elevated water tank that provides additional passive gravity-fed cooling water inventory to the calandria that houses the moderator. This connection extends core cooling and delays severe accident event progression. The moderator is not only a means of increasing fuel efficiency but it distinguishes the CANDU reactor from all other commercial reactor designs in terms of added passive safety.

The AFCR moderator system has minor variations from the C6 design, to use uranium, recycled uranium and thorium-based fuels to meet higher seismic requirements, to ensure longer operational life and to accommodate increased gamma heating.

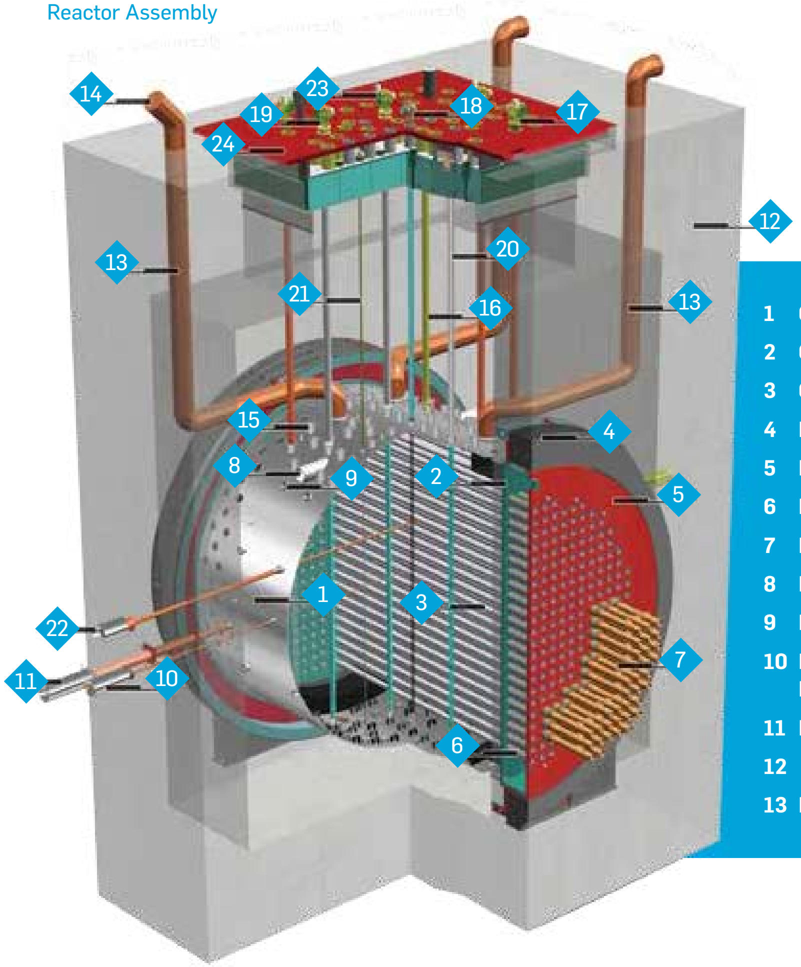
Reactor Assembly

The AFCR reactor assembly consists of a horizontal, cylindrical, low-pressure calandria and end-shield assembly. This enclosed assembly contains the heavy water moderator, the 380 fuel channel assemblies and the reactivity mechanisms. The reactor is supported within a concrete, light water-filled calandria vault. Fuel is enclosed in the fuel channels that pass through the calandria and end-shield assembly. Each fuel channel permits access for re-fuelling while the reactor is on power.

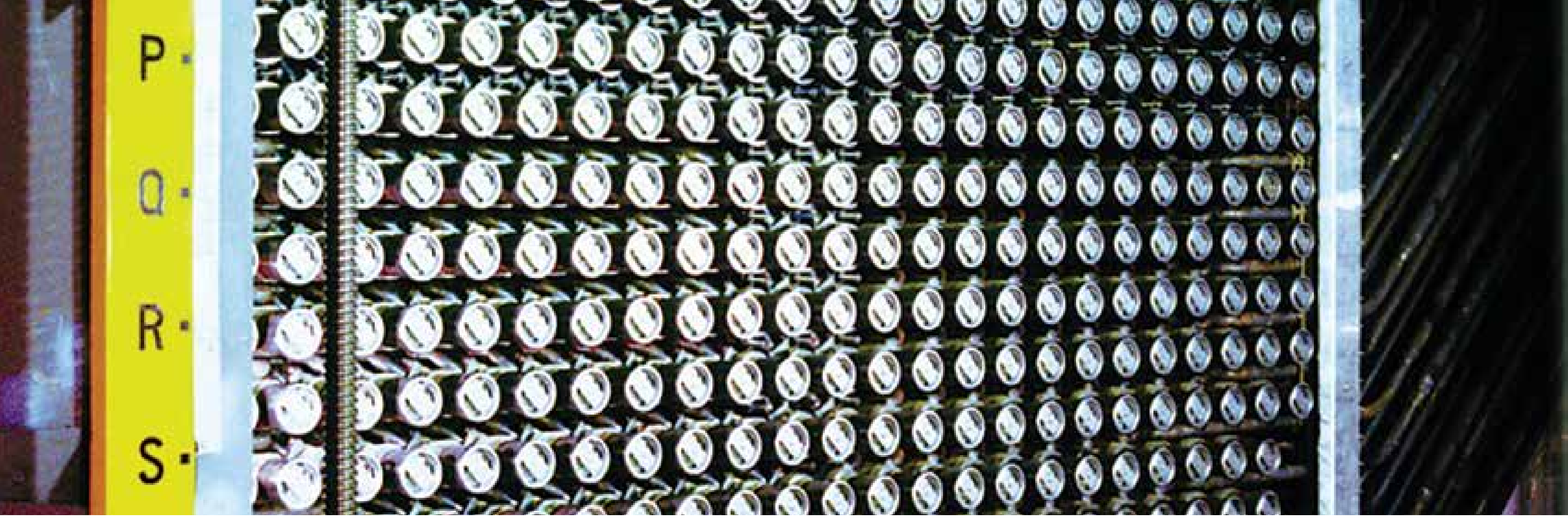
The ability to replace fuel while on power means minimal excess reactivity in the core at all times, an inherent safety feature. On-power fuelling creates operational flexibility (i.e., it improves outage planning as fixed cycle times are not required) and allows prompt removal of defective fuel bundles without shutting down the reactor. The horizontal fuel channels are made of zirconium niobium alloy pressurized tubes with 403 SS end-fittings.

Reactor Core Design Data	
Output [MW_{th}]	2,084
Coolant	D_2O
Moderator	D_2O
Fuel channels	380
Lattice pitch [mm]	285.75

Reactor Assembly



1 Calandria
2 Calandria Tubesheet
3 Calandria Tubes
4 Embedment Rings
5 Fuelling Tubesheet
6 End Shield Lattice Tubes
7 End Fittings
8 Moderator Outlet
9 Moderator Inlet
10 Horizontal Flux Detector Unit
11 Fission Chamber
12 Calandria Vault Wall
13 Pressure Relief Pipes
14 Rupture Disc
15 Reactivity Control Unit Nozzles
16 View Port
17 Shutoff Unit
18 Adjuster Unit
19 Control Absorber unit
20 Liquid Zone Control Unit
21 Vertical Flux Detector Unit
22 Liquid Injection Shutdown Unit
23 Supplementary Absorber Unit
24 Reactivity Mechanism Deck



Reactor Face

Reactor Power Control

The liquid zone control units provide the AFCR's primary control. Each liquid zone control assembly consists of independently adjustable liquid zones that introduce light water in zirconium alloy tubes into the reactor. Light water is a stronger absorber of neutrons than heavy water. Controlling the amount of light water controls the power of the reactor. On-power refuelling and zone-control actions provide reactivity control.

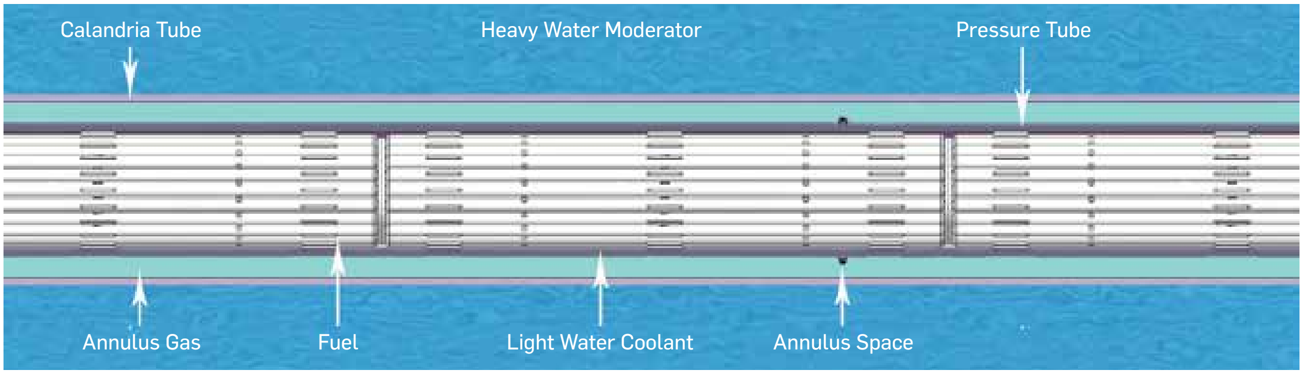
The reactor regulating system also includes control absorber units and adjusters that can be used to absorb neutrons and reduce reactor power if larger power reductions are required. The reactor power control systems of the AFCR are designed for both RU-based- and thorium-based fuel.

Fuel Channel Assembly

The AFCR fuel channel assemblies consist of a zirconium-niobium alloy Zr2.5wt%Nb pressure tubes, centred in a zirconium alloy calandria tubes. The pressure tube is roll-expanded into stainless steel end fittings at each end.

Each pressure tube is thermally insulated from the low-temperature moderator by the annulus gas between the pressure tube and the calandria tube. Tight-fitted spacers, positioned along the length of the pressure tube, maintain annular space and prevent contact between the two tubes. Each end fitting holds a liner tube, a fuel support plug and a channel closure. Reactor coolant flows through adjacent fuel channels in opposite directions. The AFCR pressure tubes are designed with added thickness to ensure longer operational life while utilizing both RU- and thorium-based fuels.

The AFCR is designed for a life of 60 years of operation with provision for life extension at the reactor's mid-life by replacement of fuel channels.



Fuel Channel Assembly

Fuel Handling and Storage System

The fuel handling and storage system of the AFCR consists of:

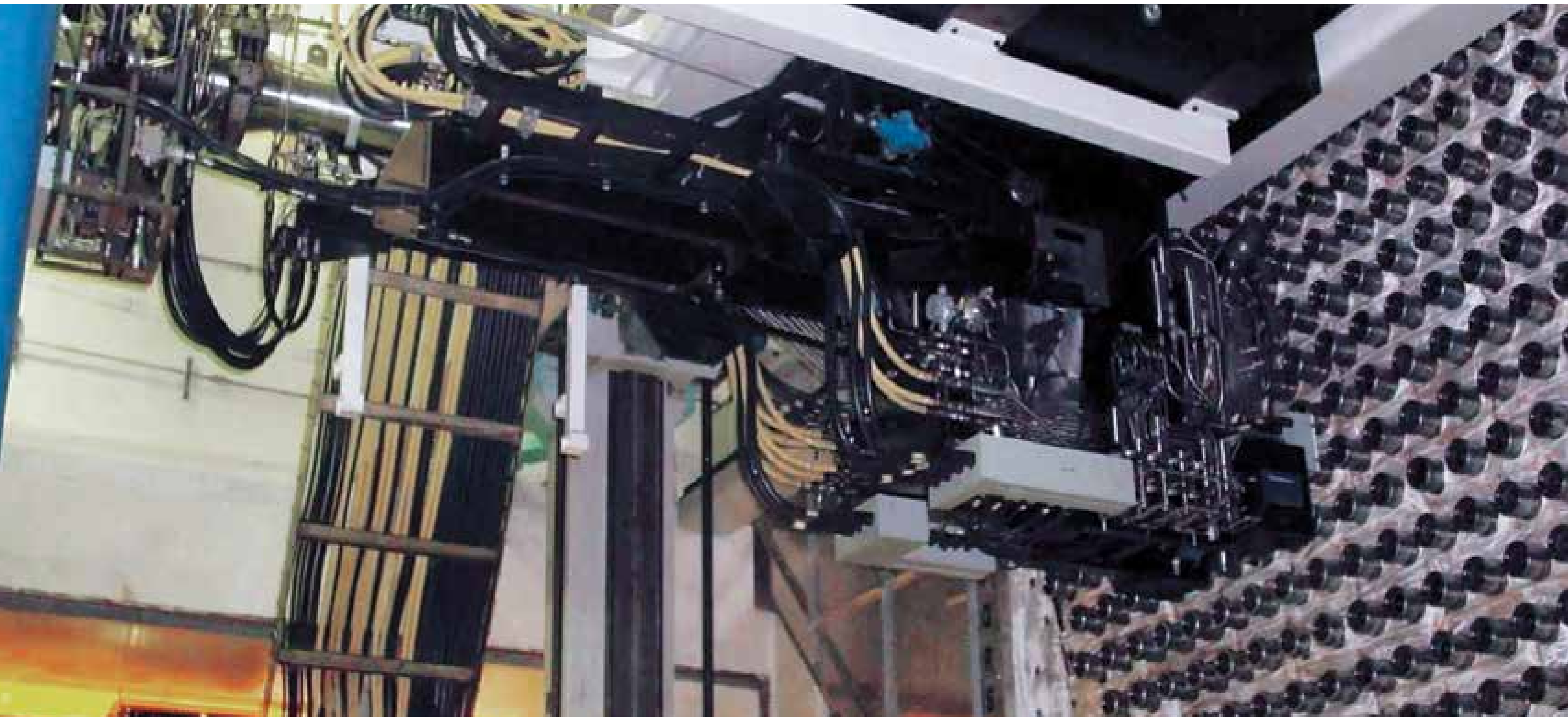
- New fuel transfer and storage
- Fuel changing
- Spent fuel transfer and storage

New fuel transfer and storage is designed for sufficient fuel storage capacity to maintain full-power operation for at least nine months. New fuel is transferred to the new fuel loading room in the reactor building as required, where the fuel is loaded into one of two new fuel transfer mechanisms for transfer into one of the fuelling machines via new fuel ports.

On-power fuelling is implemented by two remotely controlled fuelling machines, located on opposite sides of the reactor and mounted on bridges that are supported by columns. These machines maintain their proven basis while incorporating modernized elements, post-Fukushima requirements and increased seismic resistance.

Fresh fuel bundles are inserted at the inlet end of the fuel channel by one of the fuelling machines. The other fuelling machine removes irradiated fuel bundles from the outlet end of the same fuel channel and transfers it to the underwater spent fuel storage bay.

From the loading of fuel in the new-fuel mechanism to the discharge of irradiated fuel in the receiving bay, the fuelling process is automated and remotely controlled from the station control room. The AFCR spent fuel bay is at grade level and highly resistant to earthquakes and associated events.



Fuelling Machine

Turbine-Generator System

The turbine generator, and condensate and feedwater system are located in the turbine building and are part of the BOP. They are based on conventional designs and meet the design requirements specified by the NSP designer to assure the performance and integrity of the NSP. These include requirements for materials (e.g., titanium condenser tubes and absence of copper alloys in the feed train), chemistry control, feed train reliability, feedwater inventory, and turbine bypass capability.

Site differences affect the condenser cooling water (CCW) system design, such as temperatures, which in turn affect turbine exhaust conditions and the amount of energy it is possible to extract from the steam. In the event of loss of off-site power to the plant, the AFCR stays at power for the duration of the event using turbine generators that are disconnected from the grid. In this mode of operation, power is only supplied to internal auxiliaries as needed for the safe shutdown of the plant.

Turbine Generators

Steam is conveyed from the steam generators located in the RB to the turbine generator in the turbine building via four pipelines, one per steam generator. A main steam balance header is provided to receive the steam from each of the four steam generators and to equalize the pressures prior to entry to the turbine generator.

The turbine assembly normally consists of one single-flow high-pressure turbine, two double-flow low-pressure turbines, and two moisture separator reheaters with two stages of reheating.

Main Steam System

The main steam supply system conveys steam from the steam generator to the turbine and auxiliary systems and consists of the main steam safety valves, main steam isolation valves, atmospheric steam discharge valves, condenser steam discharge valves and associated piping. This steam is supplied to the turbine generator, turbine gland steam sealing system, second stage reheaters, and de-aerator.

Main steam safety valves provide the safety functions of overpressure protection of the secondary side of the steam generators and remove heat from the fuel during accident conditions (crash cooldown for loss of coolant). They can be used to prevent releases in the event of steam generator tube leaks to the secondary side of the steam generator.

Atmospheric steam discharge valves take into account pressure excursions in the main steam system during normal operation.

Condenser steam discharge valves are throttled for turbine trips at partial turbine power levels.

Condensing System

After expansion in the low-pressure turbines, steam is condensed in the main condenser by heat transferred to the CCW system. The condensate from the main condenser is de-aerated and returned to the steam generators via regenerative feedwater heating system.

The condenser consists of separate shells, one per low-pressure tubing casing. It is made of titanium tube sheets and tubes and is equipped with on-line tube cleaning system.

The CCW system supplies once-through cooling water to the main condensers. The system pumps cooling water through the main condensers to condense the turbine exhaust steam and to maintain rated backpressure conditions at the turbine exhaust. The system components and materials minimize deterioration of the condenser heat transfer capability under normal operating conditions and ensure a high degree of availability.

Condensate and Feedwater System

The condensate system provides condensate from the condenser hotwell to the deaerator through the low-pressure feedwater heaters under all conditions of operation. This system includes 2x100% condensate extraction pumps, one auxiliary condensate extraction pump, piping, and controls.

The feedwater system provides feedwater from the deaerator to the preheater section of the steam generators to maintain required water levels during various modes of operation. This system includes the 3x50% main feedwater pumps, two auxiliary feedwater pumps, feedwater control valves, piping, and controls.

Instrumentation and Control

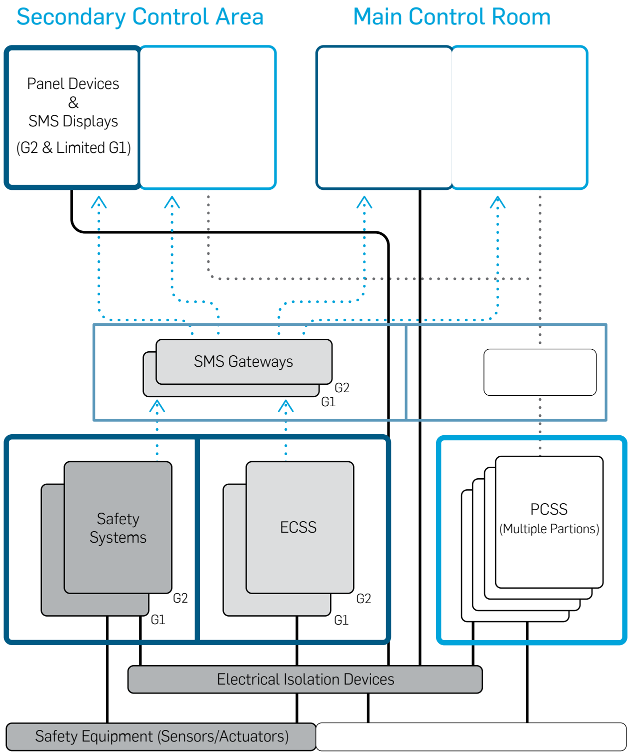
The instrumentation and control (I&C) systems are designed to give the operators in the MCR all necessary information and control capability to operate the reactor unit safely.

Most automated plant control functions are implemented in a modern distributed control system (DCS) using a network of modular, programmable digital controllers that communicate with one another using reliable, high-security data transmission methods.

The systems are also designed to handle certain upset conditions to return the plant to normal conditions or to safely shutdown the reactor in a controlled manner if required. Separated, independent control and instrumentation systems are designed for shutting down the unit and maintaining it in a shutdown state under accident conditions. Shutdown of the reactor and monitoring of its major safety parameters is also possible from the secondary control area (SCA) in case the MCR is unavailable.

Human factors engineering is rigorously applied at all stages of the design process to maximize operator responses to different plant conditions.

Plant surveillance is also centralized in the MCR. Instrumentation for closed-circuit television, meteorological sensing, fire detection and alarm, vibration monitoring, and access control are all indicated and controlled here. Communication networks such as telephone, public address, maintenance, and plastic suits are also centralized in the MCR.



AFCR Overall Instrumentation and Control Architecture

AFCR Control Centres

The AFCR control centres consist of:

> The main control area (MCA) which consists of the MCR, the work control area/operational support centre, and the control equipment room
> The SCA which includes the secondary control room (SCR) and the secondary control equipment room (SCER)
> The technical support centre (TSC)

The on-site emergency support centre (ESC) that is shared between two units for each two-unit plant.

The MCR and all the facilities required to support MCR operations are collectively located in an area referred to as the MCA.

The MCR features extensive use of visual display units, which offer selective presentation of information in diagrammatic formats. The use of computer-based displays, designed using modern human factors engineering, simplifies the control room panels and provides a uniform human-system interface (HSI) for all plant systems.

If for any reason the MCR becomes uninhabitable or unusable, the SCA provides operators with the needed displays through safety system panels and Group 2 control panels to safely shutdown and/or maintain the reactor in a safe shutdown state.

The technical support centre provides an assembly location for the technical support team who provide assistance to operating personnel in the MCR in responding to abnormal operating conditions. Access to information about radiological conditions in the plant and its surroundings, and about meteorological conditions in the plant vicinity is available in the TSC.

The on-site ESC is located separately from the MCR and SCA. It provides overall management of the owner's emergency response, coordination of radiological and environmental assessments, and determination of recommended public and protective actions, while coordinating emergency response activities with the different levels of government agencies.

MCR mockup facility

MCR mockup facility

Computer Control and Display System

The DCS implements the bulk of the control logic and data acquisition functions for the process control systems. Processing of this data for presentation to the operator is performed by the PDS and in some cases by the Safety Monitoring System (SMS).

The DCS is a modular distributed digital control system, which uses a number of programmable digital controllers connected to data communication networks that have been designed to provide very high reliability and data security. The system includes comprehensive fault detection, redundancy, and transfer of control features, to provide a very high degree of immunity to random component failures.

The DCS is divided into a number of independent functional partitions. This functional partitioning provides a defence against common mode faults and ensures separation, where needed, among different process controls, and between process controls and functions that mitigate the failure of these controls.

For enhanced reliability and ease of maintenance, redundancy, as appropriate, is employed at the modular level. A modular redundant system is defined as a system in which, on failure of any one module (central processing unit, input/output card, power supply, communications controller etc.), the functions of the failed module are taken over seamlessly by its modular redundant partner. Comprehensive and qualified self-diagnostics enable transfers of control between redundant modules. The transfer(s) of control are bumpless to minimize process and reactivity upsets.

Significant use is made of the programmable system's inherent ability to take intelligent action in response to detected faults. Most failures are detected without the need for intrusive testing. Self-checks are applied to standby components as well to ensure high availability.

The PDS is a computer based HSI system that supports integrated monitoring and supervisory control of functions, systems and equipment necessary for power production and the monitoring of functions, systems and equipment important to safety. One PDS exists for each unit in a multi-unit station. Each unitized PDS includes provisions to monitor and, if designated the responsible unit, control systems shared between units (common systems). A high level of redundancy is employed within PDS to ensure no single hardware failure affects safety or power production.

Reactor Regulating System

The reactor regulating system (RRS) is used to control bulk reactor power and flux tilts in the reactor core. It consists of the signal processing and control logic used to operate the various reactivity control mechanisms, including the liquid zone control units, mechanical control absorber rods, and adjusters. The RRS is used for all normal operating states, including start-up, shutdown, full power operation, and load cycling.

Reactor Safety Instrumentation

The instrumentation and control of each safety system consists of independent and triplicated measurements of each variable and initiation of protective action are provided when any two of the three channels are tripped.

Safety systems are implemented in digital controllers or hardwired logic, each separate and independent from the other safety systems and from the process control systems. The safety systems are provided with full test facilities to allow testing while the reactor is at power.

Safety Monitoring

Our AFCR has an inventory of discrete alarms, displays and controls that are designed to support post-accident monitoring (PAM), safe shutdown and all safety-significant credited manual operator actions.

The inventory selected for PAM is designed to enable operators to:

- Assess post-accident conditions of the plant and determine the nature and the course of the accident
- Determine whether or not the automated systems important to safety have performed or are performing the required protective actions
- Monitor the plant characteristics following the accident
- Determine the appropriate actions to be performed and monitor results of those actions, including the need to execute off-site emergency procedures

These alarms, displays and controls are complemented by a computer-based SMS which is designed to provide a concise display of critical safety parameters for the rapid and reliable determination of the safety state of the unit. The SMS is designed to integrate and validate information in an attempt to minimize erroneous information and improve human performance.

Critical safety parameters are selected to convey sufficient information on the critical safety functions necessary for the detection, diagnosis and mitigation of abnormal conditions including: transients, DBAs and BDBAs. The critical safety parameters provide information on the following critical safety functions:

- Reactivity control
- Reactor core cooling and heat removal from the primary circuit
- Reactor coolant system integrity
- Radioactivity control
- Containment integrity

The measurement and display of a PAM parameter is organized into distinct information chains consisting of three possible segments: sensor, processing and display. The information chains are qualified to allow operators to take credited actions based on the information presented and to remain operational during and following the events they are intended to monitor, including DBE events. The qualified information chains or segments thereof are distinctly presented or identified to clearly distinguish them from the nonqualified.

At least two independent information chains are provided for those important parameters that need to be monitored during DBAs. The SMS is provided with all qualified measurements and is itself qualified for post-accident use providing an independent display segment for any given parameter.

While the discrete alarms, displays and controls are limited to the MCR and SCR, the SMS displays are provided in the locations where operations and emergency response staff operate to detect and diagnose abnormal conditions. These locations include the MCR, SCR, TSC and the on-site ESC.

Electrical Power System

Our AFCR's electrical power system consists of connections to the off-site grid, the main turbine generator, the associated main output system, the on-site standby diesel generators, the battery power supplies, the UPS, and the electrical distribution equipment.

The electrical power distribution system provides safe and reliable electrical power to the unit in a manner that maintains the redundancy and separation requirements.

For reliability of operation, two 100% redundant power distribution systems are provided for the loads important to safety and triplicated power systems are provided for control and instrumentation purposes.

The electrical power distribution systems are separated into Group 1 and Group 2 in accordance with the two group separation philosophy. The Group 1 electrical distribution system provides power to the process systems used for power production, systems important to safety and safety support systems. The Group 2 system is the seismically qualified emergency power supply which is a back-up power source to selected safety systems and safety support systems.

The Group 1 system is divided into four classes of power based on availability:

> Class IV from the main generator or grid
> Class III from standby diesel generators
> Class II from UPS
> Class I delivered from batteries

The Group 2 EPS system has a seismically-qualified UPS and batteries with a mission time as required by the safety systems when normal electrical supplies are unavailable.

In case of an SBO, a seismically qualified UPS is provided to power loads required for provision of a heat sink capable of supporting the safety critical loads for up to 24 hours.

The independent SARHRS diesel generator at each unit is a complementary design feature to power a limited number of loads for mitigation of severe accidents.

In addition, each reactor unit has its own seismically qualified mobile diesel generator for extended SBO events.

Conventional Plant Services

Conventional plant services include water supply, heating, ventilation, and air conditioning (HVAC), chlorination (if required), fire protection, compressed gases and electric power systems.

Service Water Systems

The BOP service water systems provide cooling water, demineralized water and domestic water to the nuclear power plant users. The systems include the CCW system and water treatment facility.

Heating, Ventilation and Cooling Systems

HVAC and chilled water are supplied to our AFCR buildings to ensure a suitable environment for personnel and equipment during all seasons. Dedicated, separate ventilation systems are provided for the MCR and SCA.

The building heating plant provides the steam and hot water demands of the entire AFCR HVAC systems. Steam extracted from the turbine is used as the steam source for normal building heating.

Fire Protection System

Water supply for the main fire protection system comes from a fresh water source. The main system provides fire protection for the entire plant. The AFCR also has a seismically-qualified water supply pump house and distribution system.

The fire protection system also includes standpipe and fire hose systems, portable fire extinguishers for fire suppression, and a fire detection and alarm system covering all buildings and areas.

Fire-resistant barriers for fire mitigation are provided, where necessary, to isolate and localize fire hazards and to prevent the spread of fire to other equipment and areas. The fire protection system design complies with CSA N293 and N285.0.

Modular Air-Cooled Storage (MACSTOR®)

Radioactive Waste Management

The AFCR waste management systems minimize radiological exposure to operating staff and to the public. Radiological exposure for workers from the plant is monitored and controlled to ensure exposure is within the limits recommended by the ICRP. The systems have been proven over many years at other CANDU sites and provide for the collection, transfer and storage of all radioactive gases, liquids and solids, including spent fuel and wastes generated within the plant.

Wastes are handled as follows:

- Gaseous radioactive wastes (gases, vapours or airborne particulates) are monitored and filtered. The off-gas management system treats radioactive noble gases. Tritium releases are collected by a vapour recovery system and stored on-site
- Liquid radioactive wastes are stored in concrete tanks that are located in the service building. Any liquid, including spills that require removal of radioactivity are treated using cartridge filters and ion exchange resins
- Solid radioactive waste can be classified in five main groups: spent fuel; spent ion exchange resins; spent filter cartridges; compactable solids; and non-compactable solids. Each type of waste is processed and moved using specially designed transporting devices if necessary. After processing, the wastes are collected and prepared for on-site storage by the utility or for transport to an offsite storage location

AFCR radioactive waste management systems have been optimized using best available techniques (BAT) in support of the ALARA principle.

In addition, the plant owner/operator maintains an environmental monitoring program to verify the adequacy and proper operation of the radiological effluent monitoring systems that monitor and control release of effluents at the release point.

Modular Air-Cooled Storage (MACSTOR)

Our patented spent fuel dry storage technology, the MACSTOR®, consists of concrete canisters that hold spent CANDU reactor fuel bundles in a modular, air-cooled concrete above ground canister. The largest design, the MACSTOR-400, has four rows of storage cylinders and provides a capacity of 24,000 NU bundles stored in 400 baskets.

AFCR Project Delivery

Through customer feedback on our previous construction projects, we have optimized key project elements. The AFCR plant construction schedule, from first containment concrete to in-service, is 57 months. The second unit can be in service six months later. Deployment of the AFCR requires the coordination and timely delivery of key project elements including licensing programs; environmental assessments; design engineering; procurement, construction; and commissioning start-up programs.

Design Engineering

Preliminary design and development programs of the AFCR plant are executed in parallel with the environmental assessment and licensing programs to ensure continuous improvement and plant configuration is maintained. The final design program ensures that plant reliability, and equipment and component maintainability and constructability requirements are maximized.

Licensing

Our AFCR builds on the successful CANDU track record of accommodating the requirements of offshore jurisdictions in various customers' countries while retaining the standard nuclear platform. The CANDU 6 reactor has been licensed in Europe, Asia and North and South America. The AFCR incorporates improvements to meet the latest regulatory requirements in Canada and internationally.

Licensing programs are executed and coordinated with the engineering design programs and environmental assessment and are structured to support regulatory process requirements.

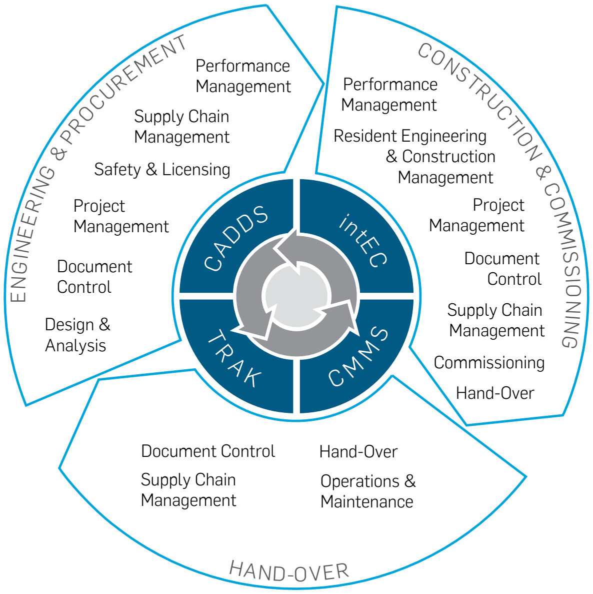
Configuration Management

The AFCR makes use of the latest computer technology for managing the complete plant configuration from design to construction, and turnover to the plant owner/operator. State-of-the-art electronic drafting tools are integrated with material management, wiring and device design, and other technology applications.

Project Management

The AFCR project management structure provides fully integrated project management solutions. Performance management programs are executed from project concept, through a project readiness mode, to project closeout.

The project management framework consists of three key elements: total project execution planning; a critical decision framework to control each phase of the project lifecycle; and a comprehensive risk management program.



Design Engineering and Project Tools

Qinshan construction

Procurement

Standardized procurement and supply processes are implemented to support time, cost, and performance benefits to the project, such as efficiency through variety control (e.g., standardization) and economy in manufacturing and servicing.

Construction Programs

Constructability programs are implemented to ensure project simplification by:

- Maximizing concurrent construction to increase construction productivity
- Minimizing construction rework to decrease equipment costs
- Minimizing unscheduled activities to reduce capital costs and construction risk

Construction Strategy

The main features of AFCR construction are:

- Open-top construction method using a very-heavy-lift crane
- Concurrent construction
- Modularization and prefabrication
- Use of advanced technologies to minimize interferences

This construction strategy has contributed to the successful completion of CANDU 6 units around the world, delivered on budget and on/or ahead of schedule.

Qinshan CANDU 6 Project Performance Record

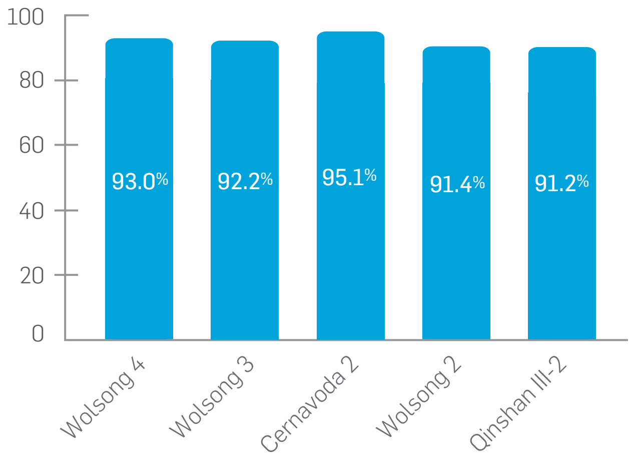
Milestone	Unit 1
First concrete	4 days ahead of schedule
Containment pressure test	20 days ahead of schedule
Fuel load licence	6 days ahead of schedule
Unit 1 complete	37 days ahead of schedule

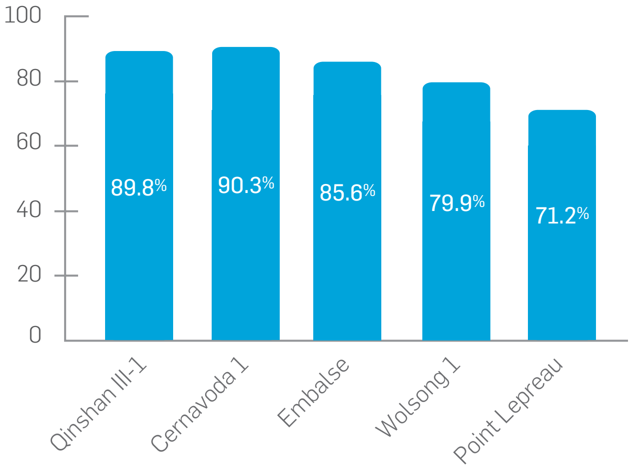
Operations and Maintenance

Plant Performance

The target operating capacity factor for the AFCR is >90% over the operating life of 60 years. This expectation is based on the proven track record of our CANDU 6 customers.

Lifetime Unit Capability Factor as of December 31, 2014





Features to Enhance Operating Performance

Incorporation of feedback from utilities operating reactors (both CANDU and other reactor designs) is an integral part of our design process. Various new features and maintenance improvement opportunities have been incorporated to enhance operating performance throughout the station life.

Major AFCR enhancements:

- Use of improved material and plant chemistry specifications based on operating experience from CANDU plants
- Implementation of advanced computer control and interaction systems for monitoring, display, diagnostics and annunciation

Features that Facilitate Maintenance

The number and duration of maintenance outages impact plant capacity factors. The traditional CANDU outage duration has been improved in the AFCR design by incorporating the following enhancements:

- Service building layout enhancements for ease of maintenance
- A maintenance-based design strategy that incorporates lessons learned and ensures maintainability of systems and components
- Improved plant maintenance with provisions for electrical, water and air supplies that are built in for on-power and normal shutdown maintenance
- Shielding in radiological-controlled areas is provided to minimize worker exposure and occupational dose
- Improved equipment selection and system design based on probabilistic safety evaluations and specific outage intervals

Technology Transfer and Localization

CANDU technology transfer and localization is the most effective in the nuclear industry and is capable of achieving the highest level of local content in the shortest time. In South Korea, we achieved up to 75% local content by the fourth unit. Such accelerated results are possible due to innovative design, as well as extensive experience in project management and technology transfer.

This approach allows our customers great success in achieving self-sufficiency and self-reliance. The resulting partnerships we develop provide our customer with the “know-why” and “know-how” to effectively serve domestic needs.

Further fine-tuning has been done in this area for the AFCR design through a variety of measures, including equipment standardization and optimization.

Program Details

A successful technology transfer and localization program is largely dependent upon technical information as well as personnel development and partnership in recipient organizations. Our experience has shown that success in a technology transfer program and subsequent localization involves the recognition of and preparation for the following factors:

- **People:** The availability of trained personnel to interpret the documentation and implement the design
- **Training:** A necessary ingredient as not all of the technology resides in document form – much of it can only be transferred through personnel communication
- **Practice:** The technology transfer and localization program runs concurrently to a nuclear build project, allowing customers to practice their skills as they learn. Such an approach prevents knowledge dissipation and relearning
- **Technology flexibility:** Adjustments and modifications of manufacturing techniques, equipment and skills are often essential
- **Environmental and cultural differences:** Recognition of differences is an important consideration in any international endeavor
- **Potential conflict resolution:** Recognition of project priorities must occur between all parties in order to prevent possible conflicts, maintain project schedules and minimize overall costs
- **Coordination:** As there are often several recipients of technology transfer, coordination is required in order to:
    - Ensure the necessary infrastructure is in place to provide adequately trained personnel
    - Determine priorities for technology to be transferred and to ensure sufficient allocation of funds and human resources
    - Determine the most suitable recipients to receive and eventually develop the technology
    - Monitor and coordinate the actual technology transfer process

Expert Panel Review of the AFCR in China concluded:

- Recycled Uranium in AFCR significantly increases China's nuclear fuel resources
- AFCR forms a synergy with PWRs and reprocessing plants; consistent with China's nuclear power development strategy
- AFCR is based on proven technology and meets Gen III requirements
- AFCR reactor is designed to utilize RU and Thorium based fuels

The experts recommended the following:

- The current design should be completed for project implementation
- Select proper time to initiate the construction of AFCR to unlock and utilize its various advantages

Building on past success to power the future with advanced fuel cycles

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