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DEVELOPMENT AND INTEGRATION OF CANADIAN SCWR CONCEPT WITH COUNTER-FLOW FUEL ASSEMBLY

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DEVELOPMENT AND INTEGRATION OF CANADIAN SCWR CONCEPT WITH COUNTER-FLOW FUEL ASSEMBLY

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Abstract

Canada is developing a next generation (Gen IV) reactor concept, the Canadian Super-Critical Water-cooled Reactor (SCWR), which will meet the technology goals of the Generation-IV International Forum (GIF). These goals include enhanced safety features (inherent safe operation and deploying passive safety features), improved resource utilization (~40% more efficient than current nuclear power generating stations), sustainable fuel cycle, and greater proliferation resistance than Gen III reactors. The Canadian SCWR concept is a pressure-tube type reactor that uses supercritical water as a coolant, a separate low-pressure heavy water moderator, and a direct steam power cycle.

This paper presents the evolution of Canadian SCWR core concept, in particular the recently developed counter-flow fuel assembly and its impact on reactor core concept. Integration of the reactor core with the supporting safety systems is also described to address long term reactor heat removal at station blackout conditions.

1. Introduction

The Super-Critical Water-cooled Reactor (SCWR) is one of six next generation reactor systems selected by the Generation-IV International Forum (GIF). Employing the existing supercritical water technology used in coal plants for the balance-of-power systems, the SCWR concept development effort focuses mainly on the core configuration to generate supercritical steam, closely matching the conditions found in existing and planned high-pressure turbine designs (thereby markedly increasing the thermal efficiency compared to the conventional nuclear power plants and coming close to 50%). Canada is developing a 1200 MWe SCWR, which has evolved from the well-established pressure-tube type CANDU®[1] reactor. The original reactor core concept used a once-through fuel channel configuration [1], [2]. This paper presents the evolution of the reactor

[1] CANDU – Canada Deuterium Uranium, a registered trademark of Atomic Energy of Canada Limited (AECL).

core concept, describes the latest Canadian SCWR concept that features a counter-flow fuel channel and discusses its advantages for enhanced safety.

2. Reactor core

The proposed Canadian SCWR concept consists of 336 fuel channels, each housing a 5-m long fuel assembly. It is designed to generate 2540 MW of thermal power and about 1200 MW of electric power (assuming a 48% thermodynamic cycle efficiency of the plant). The average fuel channel power is 7.6 MW(t) and the core radial power profile factor is estimated to be 1.28. The lattice pitch is selected to be 250 mm based on recent optimization results for the fuel-to-moderator ratio to achieve a negative coolant void coefficient and high fuel burnup [3].

The reactor core design concept, shown in Figure 1 schematically, uses a pressurized inlet plenum (at the top) attached to a low-pressure calandria vessel (at the bottom) that contains heavy water moderator surrounding 336 fuel channels. Each fuel channel contains a fuel assembly with a central flow tube and a two-ring fuel-element configuration [3]. The fuel assembly has a two-pass counter-flow configuration, where the coolant flows downwards through a central flow tube and up through fuel elements. The reactor is oriented vertically for ease of batch refueling. The light water coolant enters the inlet plenum through inlet nozzles and then enters the fuel channels through several slots (which are designed (acting like orifices) to control the amount of coolant flowing into each channel).

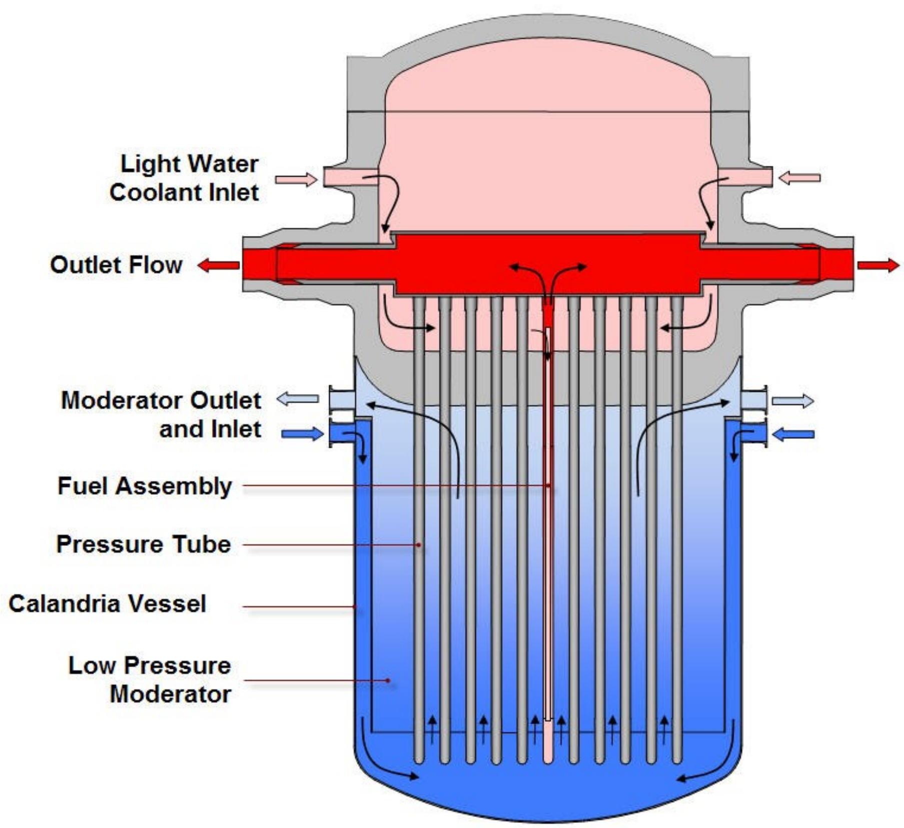


Figure 1 Canadian SCWR Reactor Core Schematic and Flow Streams

Figure 2 shows the details of flow stream entering the fuel assembly and the change of flow direction at the bottom of the assembly. The coolant enters the fuel channel at a subcritical temperature (slightly less than 350ºC) and at a supercritical pressure of about 26 MPa [1]. At the bottom of the fuel channel, the coolant exits the central flow tube (at the temperature below the critical temperature of 374ºC), changes flow direction and flows up through the fuel elements. While flowing up, the coolant temperature gradually becomes supercritical with the heat generated by the fuel. The supercritical water exiting the fuel channels combine and mix in the outlet plenum, which is located inside the inlet plenum, at an average target temperature of up to 625ºC and at a pressure of 25 MPa. The outlet temperature is chosen specifically to match the thermodynamic and flow conditions used for existing and upcoming SCW turbine designs in thermal power plants. Exit conditions are being optimized taking into account of issues related to other technology areas (such as material and chemistry).

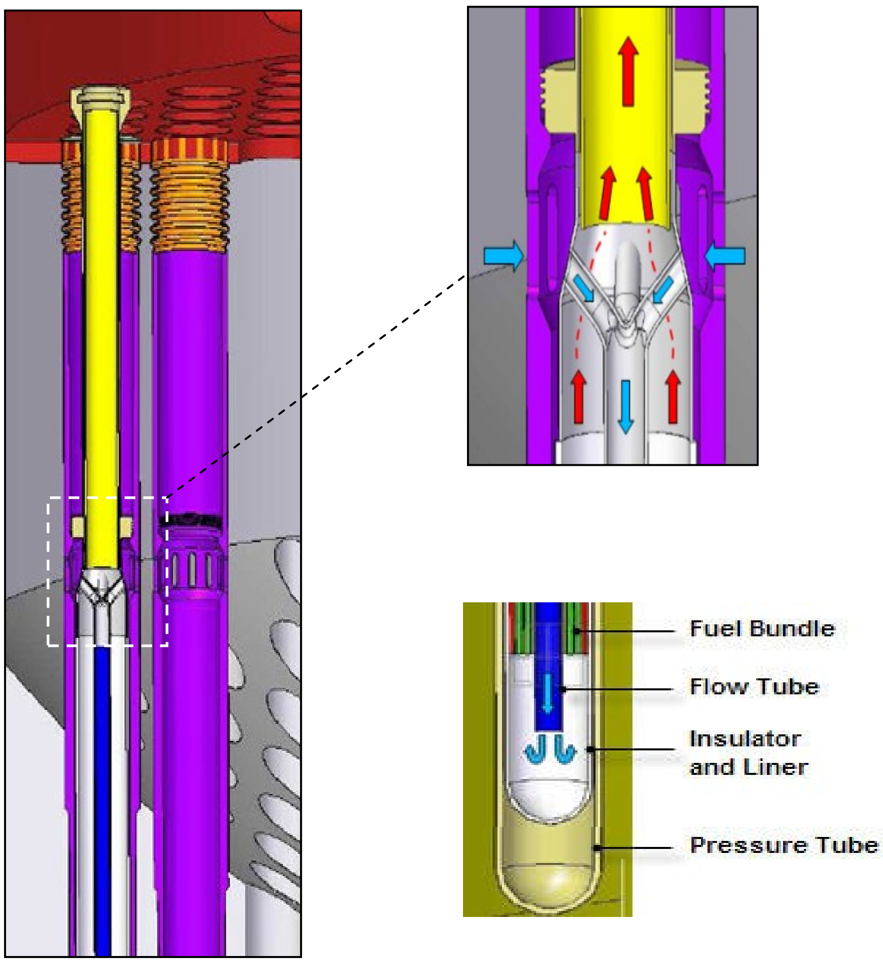
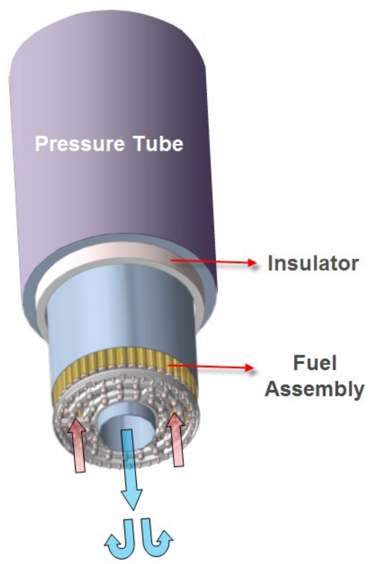


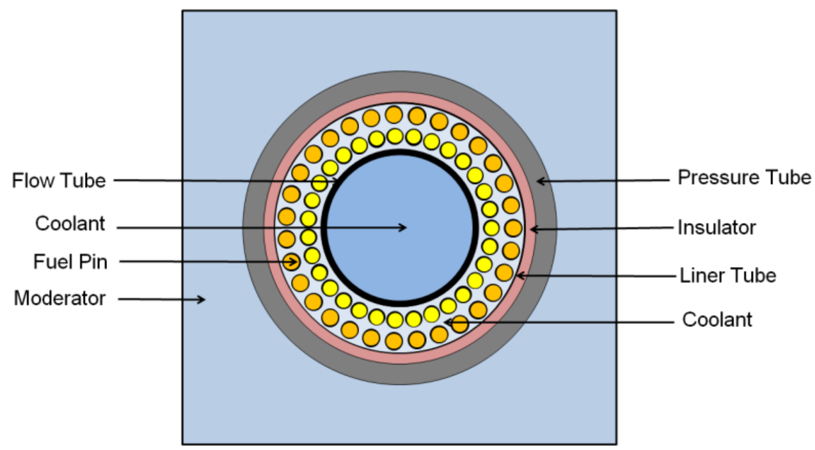
Figure 2 Canadian SCWR Fuel Channel Schematic and Flow Streams

The candidate inlet plenum material is forged SA508, a quenched and tempered vacuum-treated steel. It is cladded with austenitic stainless steel to minimize corrosion. The bottom of the inlet plenum, called the tubesheet, is machined to form a square array of holes slightly larger than the pressure tubes. Fuel channels are connected to the tubesheet in a leak-tight manner.

Each fuel channel consists of a pressure tube of outer diameter of 181-mm OD, which is in direct contact with the moderator and is made from a zirconium alloy with low neutron cross-section. A ceramic insulator, yttrium-stabilized zirconia (YSZ) with excellent thermal resistance, is placed between the fuel assembly and the pressure tube to maintain the pressure tube temperature close to the moderator temperature. This fuel channel design is called the high-efficiency channel (HEC). The ceramic insulator is cladded to maintain its integrity and functionality under all conditions (such as crack formation), protect it from interaction with the fuel assembly during operation and refueling, and prevent any loose ceramic particles, if any, from entering the flow stream and transferring to the turbines. Since the physics, thermal hydraulics and mechanical aspects are coupled, the fuel assembly configuration has been optimized (with continuous improvement) for burn-up, enrichment, reactivity coefficients, axial and radial power profiles, fuel and cladding temperatures, linear power rating, reactivity, and stability during the fuel cycle [3], [5]. The current fuel assembly configuration is shown in Figure 3 and the nominal fuel-channel dimensions are listed in Table 1.



(a) Fuel Channel



(b) Fuel Bundle

Figure 3 Canadian SCWR (a) Fuel Channel and (b) Fuel Bundle Cross Section

The outlet plenum is located within the inlet plenum. It is a relatively thin-wall structure as the pressure difference between the inlet and outlet plenums is approximately 0.5 MPa, which is equivalent to the pressure loss of the coolant over the fuel channel. A creep resistant Ni-based alloy has been selected as the candidate material for the outlet plenum, which is insulated to minimize heat loss and thermal stresses.

Table 1: Nominal Fuel-Channel Dimensions for the Canadian SCWR

	Fuel Channel Dimensions
Liner Inside Diameter (mm)	144
Liner Thickness on both sides of the insulator (mm)	0.5
Insulator Thickness (mm)	5.5
Pressure Tube Thickness (mm)	12
Pressure Tube Outside Diameter (mm)	181.0

2.1 Evolution of the Canadian SCWR core concept

The proposed reactor core concept is different from the original concept [1], [2] in that it adopts the outlet plenum (within the inlet plenum) configuration and a two-pass counter-flow fuel channel. These changes were driven by the desire to improve safety and to simplify the concept by eliminating outlet piping at the bottom of the reactor core. Relocation of both inlet and outlet piping above the reactor core allows the use of coolant-based passive core cooling, see Section 3.2, and provides the flexibility of selecting flow direction through fuel elements for improved flow stability. In vertical channel flows with significant density changes along the flow channels, downward flows are known to be inherently less stable than upward flows. Hydraulic instability can cause local reactivity oscillation and can result in a positive feedback between hydraulics and neutronics. The coupled hydraulics-neutronics instability could make it more difficult to control the reactor. Hence, the upward flow is preferable to the downward flow. The newly-proposed reactor concept deals with these problems by positioning all inlet and outlet pipes above the reactor core and by using a two-pass counter-flow type of fuel channel.

With a counter-flow fuel channel, there were two obvious options for the downward flow path where the coolant is not in contact with the fuel: the flow stream could be at the periphery of the fuel channel in a cylindrical annulus (referred to as the re-entrant channel [6]) or at the center of the channel in a flow tube. The latter is selected for its enhanced safety feature and its considerable neutronics advantages [3]. In the peripheral annulus flow option, the annulus could be filled with steam during depressurization and could act as an insulator. This would significantly reduce the heat removal capability of the passive moderator system and possibly invalidate the no-core melt case (see sections 3.2 and 3.3). On the other hand, coolant flowing through the central tube into the fuel channel would have no adverse impact on the enhanced safety characteristics of the HEC. Furthermore, coolant in the central flow tube provides a significant amount of neutron moderation and increases the power produced at the central pins that otherwise produce less power than the peripheral pins. This increased moderation and elimination of the inner fuel ring leads to an almost-uniform radial power profile and an increase in net reactivity, resulting in a significant increase in the maximum achievable exit burnup. As well, it makes it possible to design the fuel with a large negative void coefficient that can be tuned to a desired negative void reactivity at a later stage in the design. The moderation in the central coolant tube does not change with axial position, and so the axial power profile varies much less than in the previous fuel concept [1], thus reducing the axial power peaking factor. A penalty of the new fuel design is the slightly shorter refueling interval (from 455 days to 425 days [3]) as a result of the reduction in fuel mass, but this reduction is nearly off-set by the increase in initial reactivity. The almost-uniform radial power profile leads to a uniform coolant temperature that reduces the peak cladding temperature as much as 300ºC (at the beginning of a fuel cycle) as compared to the previous reference case [5].

Elimination of the outlet piping results in a more compact reactor design leading to a smaller containment and shield buildings. Also, the bottom of the calandria vessel is now available for reactivity control and shutdown devices. The axial insertion of such devices from the bottom of the low-pressure calandria vessel opens the possibility of using larger devices than would be possible with radial insertion only. For example, water displacement tubes inserted axially from the bottom of the calandria vessel can be used for reactivity control and for the shutdown of the reactor. This arrangement would allow the use of gravity to shut down the reactor in an emergency. Because the moderator is at a low pressure of approximately 3 bars, control rod ejection scenario does not pose as much a concern as in pressure-vessel reactors.

Integration of the exit plenum inside the inlet plenum introduces new challenges in the mechanical design. However, these challenges are considered manageable. Being outside the radiation field, a wider selection of high-temperature materials can be employed in manufacturing the components inside the inlet plenum.

3. Advanced safety concepts

Advanced safety concepts are used to ensure improved safety and significantly reduced core damage frequency as compared to existing reactors. Also, an objective is to eliminate the off-site emergency response requirement using automatic reactor shutdown followed by passive and indefinite cooling of the reactor core and reactor buildings.

Two major principles are being followed: ensure passive natural circulation heat removal and radiative cooling of the fuel in any postulated accidents; and provide assured ultimate heat sinks (UHS) for indefinite time intervals. The following design features are incorporated for these purposes.

3.1 Negative reactivity coefficients

The Canadian SCWR fuel is specifically designed by choice of enrichment, burnable poison and fuel to moderator ratio to exhibit a negative coolant void reactivity coefficient and negative overall power coefficient throughout the residence time in the core [3]. Therefore, a reduction in coolant density resulting from unanticipated power rise would automatically reduce the reactivity and subsequently reduce the peak power. The improved fuel bundle design described in reference [3] features large negative void reactivity coefficients. The current fuel design includes some margin for further optimisation: the size of the large diameter central flow tube can be reduced to fine-tune the negative void reactivity coefficient (towards a smaller magnitude), which currently has a large negative value.

3.2 Two Independent and Diverse Passive Safety Systems

As in most other pressure-tube type nuclear reactors, the Canadian SCWR has a low-pressure heavy water moderator that surrounds the high-pressure fuel channels. This configuration provides a unique safety enhancement in that unwanted excess heat (i.e., decay heat at accident conditions) can be independently removed by the surrounding moderator as well as by the circulation of the primary fluid. Hence, the Canadian SCWR is equipped with two independent safety systems. The first safety system is the primary-coolant system (PCS), which is similar to the safety systems proposed for advanced boiling water reactors. The two-pass counter-flow fuel channel makes it possible to passively remove decay heat through natural circulation of the light water coolant. In case of any LOCA, reactor is automatically shutdown, depressurized and flooded with emergency coolant.

The second (diverse and independent) safety system is the moderator cooling system (MCS) that provides a new passive layer of safety for the defense-in-depth approach. In all accident scenarios, the PCS activates first and prevents the fuel from overheating. For the extremely unlikely scenario of the total loss of coolant combined with the loss of PCS function, the moderator-based MCS is activated. Both the coolant-based and moderator-based cooling systems are designed to remove 100% decay heat independently and passively. The passive MCS represents a significant improvement in the defence-in-depth such that a one to two orders of magnitude improvement in core damage frequencies are achieved for events caused by station blackout, large break LOCA, and complete loss of emergency core cooling function [8].

3.3 No-Core melt concept

One key safety goal is to avoid core (i.e., fuel and fuel cladding) melting using moderator passive heat removal, even assuming complete loss of all primary coolant flow, emergency cooling systems, and station power supplies. This is possible in the Canadian SCWR because the unique feature of the distributed channel core is that the decay heat can be removed by passive radiative cooling of the fuel bundle to the insulator, and then thermally conducted out to the pressure tube and moderator which are still at low temperatures. Analyses show that close to 2% of decay heat power can be removed without exceeding clad and fuel melting temperatures in the hottest (inner ring) of fuel pins [7]. The safety limit is then placed on both channel power and peak pin rating to attain this goal. Hence, as long as pressure tubes and moderator are intact, fuel and fuel cladding will not reach melting temperatures. In the Canadian SCWR, this is called the "no-core melt concept".

3.4 Passive and very long-term heat removal

The goal is to provide passive UHS for an indefinite time. The long-term heat removal strategy of the Canadian SCWR is to use a combination of a large water reservoir and air coolers as heat sinks in the event of a complete station blackout and loss of all emergency power supplies. This is achieved by maintaining sufficient water in the containment as a heat sink until the decay power is reduced to 0.5% of full power (24 hours after blackout) at which point air cooling itself becomes sufficient to remove decay heat indefinitely. Long-term cooling systems are being developed to achieve this objective.

3.5 Leak-before-break and severe accident management

Accident prevention is the ultimate goal in the concept development. To prevent the worst-case scenario of a complete pressure-tube rupture, two independent and diverse leak/crack detection systems must be engaged to ensure pressure tube leaks will be detected before they lead to a large break. Candidate techniques for leak detection are through monitoring of noise produced by the leak (acoustics), local perturbations of the neutron flux (due to H_2O mixing with D_2O in the moderator) and the increased H_2O concentration in the D_2O moderator. Also, on-line crack detection systems are considered to detect cracks before they grow through pressure tube wall. Upon detecting a pressure tube leak, the reactor will be shut down and depressurized to prevent pressure tube rupture. If a pressure tube were to rupture, its effects would be mitigated by the calandria vessel design, such that the calandria vessel would remain intact even when multiple pressure tubes are ruptured.

4. Conclusions

An improved Canadian SCWR concept is presented. The reactor core concept has been simplified and adopts a two-pass counter-flow fuel channel. As compared to the previous single-pass fuel channel [2], it offers the following advantages:

1. Passive and enhanced safety with the natural-convection driven primary-coolant safety system

2. Improved fuel performance: higher burnup, negative void coefficient, flatter radial and axial power profiles
3. Reduced peak cladding temperature because of flatter radial power profile
4. Smaller reactor building with the reduction of outlet pipes

The design efforts and various analyses of reactor core are ongoing at a more detailed level. Integration of the exit plenum inside the inlet plenum introduces new challenges in the mechanical design. However, these challenges are considered manageable. Although the basic concepts presented in this paper will remain, minor modification of the presented concept is anticipated as the behavior of the reactor core will be better understood by analysis.

5. Acknowledgments

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