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Progression of the Lattice Physics Concept for the Canadian Supercritical Water Reactor

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Abstract

The Canadian Supercritical Water Reactor (SCWR) is a GEN-IV reactor concept with features that support enhanced safety, clean energy, sustainability, economics and non-proliferation. Development of the lattice and core physics concepts for the SCWR has therefore focused on these features, with particular emphasis on safety and sustainability. Recently, a new two-ring fuel concept was adopted in combination with a central flow tube in the fuel channel. The combination of these two features leads to an approximately 40% increase in exit burnup and guarantees negative coolant void reactivity throughout the operating cycle. The progression from earlier concepts to the present physics concept are discussed and reviewed in this paper.

1. Introduction

All GEN-IV reactor concepts must have enhanced safety, improved economics, improved sustainability and enhanced security compared to contemporary reactors [1]. Enhanced safety in the Canadian SCWR is achieved through a negative power coefficient and passive decay heat removal through the moderator. Improvements in both economics and sustainability are achieved with the SCWR through the enhanced thermal efficiency that comes with the use of supercritical water coolant; the SCWR shows an increase in efficiency compared to contemporary HWR from approximately 33% to 48% [2]. The SCWR fuel cycle is driven by fissile Pu, and consequently the SCWR contributes to non-proliferation through the reduction of the fissile Pu inventory generated from uranium-based fuel cycles used in other reactor systems.

During the evolution of the Canadian SCWR concept, a plutonium-thorium based once through fuel cycle was developed [4] and changes were made to the fuel assembly concept to improve burnup and reduce linear element ratings [5]. In addition, refinements were made to the core physics concept, including fuel reload and enrichment distribution options that could be used for channel and axial power peaking reduction [6] [7].

Several recent developments in the SCWR concept have enabled improvements in the efficiency of the fuel utilization. A central flow tube with bi-directional re-entrant coolant flow has replaced the use of outlet feeders [8]. Lattice and core physics modeling have demonstrated that when this flow tube is used in conjunction with a two-ring fuel assembly, it is possible to increase the exit burnup of the fuel by approximately 40% compared to that achieved with the previous 78-element fuel concept [9] [10]. In addition, thermalhydraulic optimization of the concept presented in [9] resulted in significant improvements in peak sheath temperatures compared to prior concepts [10].

In the development of the SCWR concept, currently available tools, e.g. WIMS-AECL 3.1 [11] and RFSP 3.5 [12] have been used for scoping purposes, to obtain relative comparisons of parameters such as exit burnup, linear element ratings and reactivity. No validation of these codes for SCWR applications has been performed to date because of the lack of experimental data for SCWR operating conditions. Modeling accuracy for SCWR is being investigated via code-to-code comparisons, but only preliminary results have been obtained [13]. As such, the values of various lattice and core physics parameters discussed in this paper should be considered estimates, based on current calculation methods.

Ongoing work on the Canadian SCWR concept includes the investigation of strategies for power shaping, reactivity hold-down and control, start-up and shut-down systems, and safety systems. In this paper the recent improvements in the core physics concept of the SCWR are discussed, comparisons are made between the current and previous reference cores.

2. Evolution of the Fuel Assembly Concept

Early Canadian SCWR concepts were extensions of conventional HWR technology and were intended to continue to employ such features as a horizontally oriented core, on-line refueling, and a bidirectional coolant flow [14]. The fuel bundle concepts developed for use with these core concepts were based on the 43-element bundle under development at that time [15], with several options for fuel composition, including: natural uranium (NU), slightly enriched uranium (SEU), mixed-oxide (MOX), direct use of PWR fuel in a CANDU (DUPIC), and thorium-based fuels. As the Canadian SCWR concept has evolved, a series of changes to the fuel concept have been made. The fuel concepts at various stages of SCWR development and evolution to the present fuel concept are described below.

2.1 43-Element Bundle Concept

The initial thorium-based fuel concept for the Canadian SCWR, a 43-element bundle [16], was an extension of an HWR fuel concept already under advanced stages of development [15]. This bundle contained a centre pin with dysprosia, a neutron absorber which acts to lower CVR, and three concentric fuel rings with 7, 14 and 21 elements composed of a mixture of thoria and reactor grade plutonium (RG-Pu) dioxide. A cross-sectional view of the fuel bundle is shown in Figure 1.

An optimization study on this fuel concept demonstrated that it was possible to achieve an exit burnup of approximately 40 MWd/kg and CVR close to zero with an average fissile enrichment in the fuel of 5 wt% of heavy elements. At that time, online refueling was still considered feasible for the SCWR. The exit burnup based on a cycle with online refueling is approximately 30% higher than would be expected for an equivalent reactor fuelled in a 3-batch fuel cycle. Therefore, the exit burnup of 40 MWd/kg given in [16] that is achievable with online refueling corresponds to an exit burnup of only 30 MWd/kg based on the current concept with a 3-batch fuel cycle. In addition, the relatively high exit burnup and low CVR were only possible through significant grading of the fissile enrichment (with approximately 10 wt% RG-Pu in the outermost fuel ring and only 3.5 wt% in the inner two), which lead to unacceptably high (based on the criteria of [5]) linear element ratings (LER) in the fuel of the outermost fuel ring. Reduction in the outer ring LER with the same or greater exit burnup were only possible if the CVR were allowed to become positive. The average fissile enrichment, exit burnup, fissile utilization, LER and CVR for the 43-element fuel concept are summarized in Table 1.

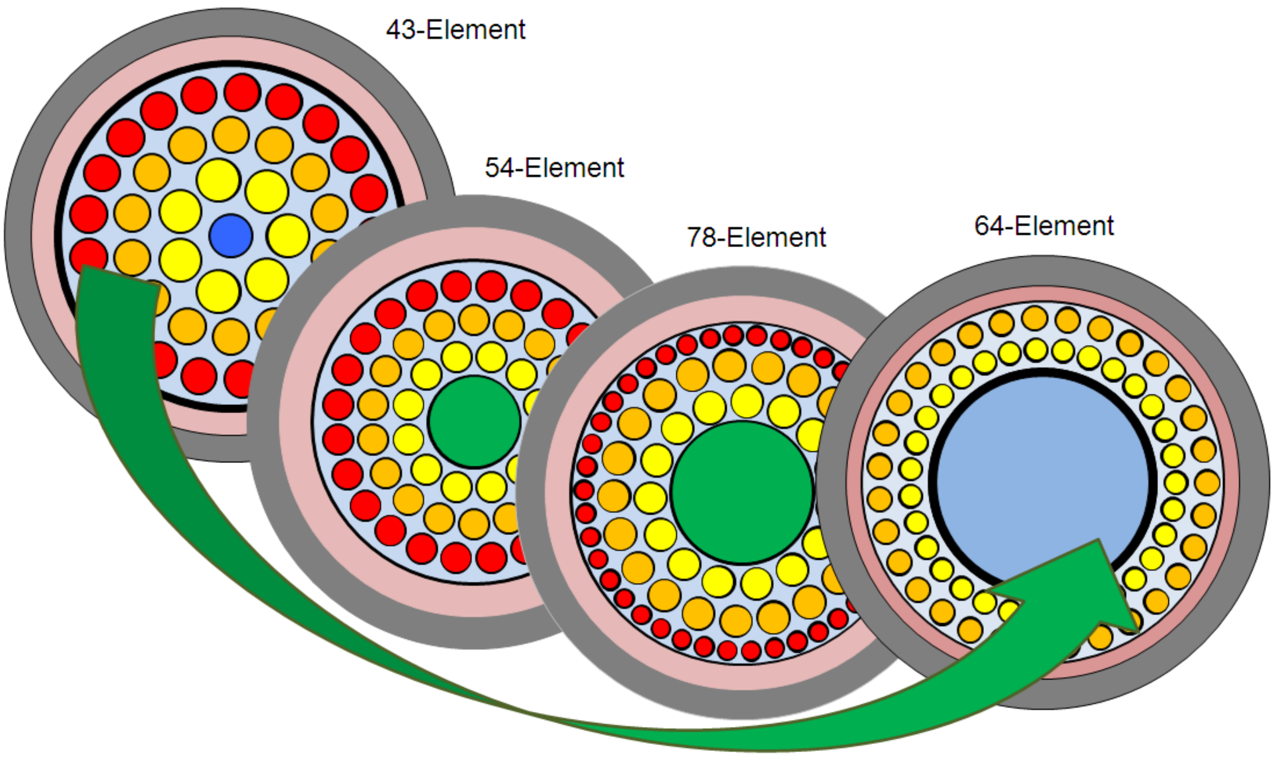

Figure 1 Evolution of the Canadian SCWR Fuel Assembly Concept: Shown left to right are cross-sectional views of the 43-element, 54-element, 78-element and current two-ring 64-element fuel assembly concepts

Table 1 Comparison of estimates for fuel utilization and other parameters in early and current fuel assembly concepts

Concept	Average Fissile Enrichment (wt% HE)	Exit Burnup (MWd/kg)	Fissile Utilization (MWd/kg initial fissile)	Maximum LER (kW/m)	Burnup Averaged CVR (mk)
43-Element [16]	5	30*	600	68	0.0
54-Element [4]	8	42	525	77	-2.4
78-Element [6]	9	42	467	37	<-4
64-Element [10]	9	58	644	38	< -25

*The exit burnup from [16] has been adjusted to correspond to a 3-batch refuelling scheme

2.2 54-Element Bundle Concept

The 54-element fuel concept was introduced in order to increase the exit burnup and avoid the use of a centre poison pin or graded fuel enrichment, while maintaining a negative CVR [4]. This fuel assembly has 12, 18 and 24 fuel elements in the inner, middle and outer rings, respectively, and a large zirconia centre pin. A cross sectional view of the 54-element fuel concept is shown in Figure 1. In this concept, negative CVR is achieved using a method first proposed in [17], where it was shown that CVR reduction could be achieved by the use of a large non-fissile and low absorption cross section centre pin that displaces coolant and fuel. An open centre version of the 54-element bundle concept was first introduced in [17] and the version presented here is based on that initial concept. Unlike the 43-element fuel concept, the 54-element fuel concept does not have fuel with graded enrichment. This uniform fuel composition simplifies, and reduces the costs associated with, fuel manufacturing, which will impact the economic performance of the SCWR. The increase in exit burnup and negative CVR were achieved with this concept at the cost of a reduction in fissile utilization and unacceptably high LER in the fuel of the outermost fuel ring. Significant increases in exit burnup and fissile utilization could be achieved with this concept with higher fissile enrichment in the outer fuel ring, but would be accompanied by even higher LER in the outer ring of fuel. The average fissile enrichment, exit burnup, fissile utilization, LER and CVR for the 54-element fuel concept are summarized in Table 1.

2.3 78-Element Bundle Concept

The 78-element fuel concept, see Figure 1, was introduced in order to reduce the high outer ring LER of the 54-element fuel concept [5]. The 78-element fuel concept has 15, 21, and 42 elements in the inner, middle and outer rings. The reduction in LER was achieved by subdividing the fuel in the outer ring into a larger number of smaller elements. Some additional changes were made, including an increase in the diameter of the zirconia centre pin, changes to the size and number of pins in the inner rings and a small increase in the fissile content of the fuel. With this concept, the 40 MWd/kg exit burnup was maintained, while reducing the maximum LER to an acceptable level (less than 40 kW/m). However, there was also a further reduction in fissile utilization and a small positive increase in CVR. As with the 54-element concept, the fuel composition was the same in each fuel ring. Increased fissile utilization would be possible with this concept with increased fissile content in the outer ring, but would result in increased LER in the outer fuel ring. The average fissile enrichment, exit burnup, fissile utilization, LER and CVR for the 78-element fuel concept are summarized in Table 1.

2.4 Two Fuel Ring, 64-Element, Bundle Concept

The two-ring fuel concept introduced in [9] is a significant departure from the previous SCWR fuel concepts and was introduced to take advantage of other recent changes in the Canadian SCWR concept. A cross-sectional view of this concept is shown in Figure 1. A recent development in the

Canadian SCWR concept is the elimination of outlet feeders; the solid centre pin used previously has been replaced by a coolant flow tube and the channel now utilizes a bi-directional re-entrant coolant flow. In each fuel channel coolant flows from the inlet plenum at the top of the core, through the central coolant flow tubes, is redirected upwards at the bottom of the fuel channel through the fuelled region of the channel and flows into an outlet plenum which is located inside the inlet plenum. A schematic illustrating the coolant flow is provided in Figure 2, and a more detailed description and illustration of the core is provided in [8]. The two-ring fuel concept was initially introduced in [9] with 62 fuel elements. Further refinement and optimization of the two-ring concept resulted in a 64-element concept, with 32 elements in each ring as reported in [10]. The two-ring concept shows improvements in exit burnup, fissile utilization, and LER, with a large negative CVR. The reason for the improvements is the increase in thermal fissions in the fuel in inner fuel ring due to the neutron moderation in central tube. This moderation is also the reason why the CVR has such a large negative value. The large negative CVR may be a concern due to its potential impact on reactor control and the possibility of transients that result in an increase in coolant density. However, as discussed in [9] the magnitude of the CVR can be reduced by reducing the volume of coolant in the central tube. The average fissile enrichment, exit burnup, fissile utilization, LER and CVR for the 64-element fuel version of the two-ring fuel concept are summarized in Table 1.

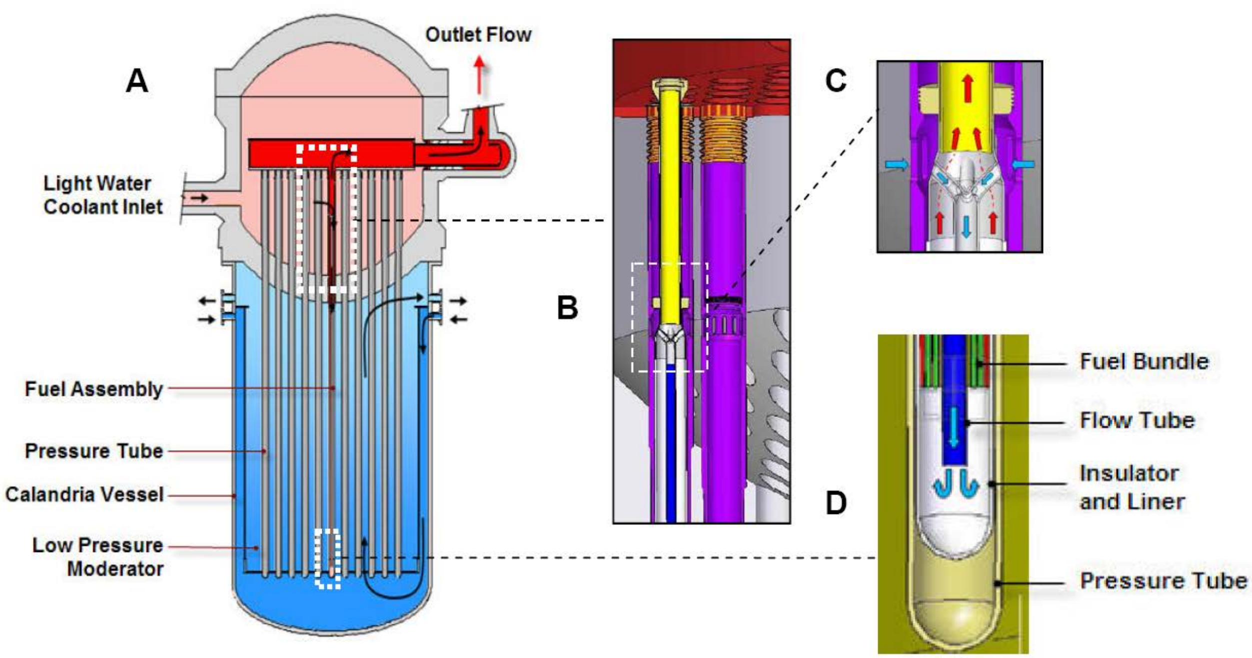

Figure 2 Cross-sectional side views of SCWR core and flow streams. A. Core layout, B. Pressure tube connection to tube sheet, C. Coolant flow from inlet plenum (blue arrows) and flow to outlet (red arrows), D. Redirection of coolant flow (blue arrows). Adapted from [8]

A square double row fuel arrangement with a central flow tube has recently been introduced for the light water moderated pressure vessel-type SCWR [19]. Although both the double row and two-ring fuel assembly concepts share some common features and advantages, the use of two-ring fuel concept discussed here depends on the presence of the heavy water moderator, which is a unique feature of the Canadian SCWR.

2.5 Integral Fuel Burnable Absorbers for Reactivity Hold Down

As part of the development of the SCWR fuel concept, incorporation of a burnable neutron absorber into the fuel was considered as a means of reactivity control. Integral fuel burnable absorbers (IFBA) are an attractive option for reactivity hold-down because they circumvent the problem of positive moderator temperature coefficient resulting from addition of soluble poisons to the moderator. Potential IFBA include ZrB_2 [20] and the rare earth oxides, Gd_2O_3, Sm_2O_3, Dy_2O_3 and Er_2O_3 [21]. As discussed in [20], ZrB_2 cannot be mixed directly with fuel, but instead is incorporated with fuel as a coating on the fuel pellet surface. ZrB_2 has the advantage that its rate of depletion is well suited for typical cycle lengths (i.e. can be completely depleted by the end of one cycle), but disadvantages include reduction of heat transfer from the fuel to the fuel sheath and increase in internal pressure from the production of helium. Of the potential rare earth IFBA, Gd_2O_3 and Er_2O_3 were found, based on the calculation results presented in [21], to be the best options for reactivity control in PWR. For the Canadian SCWR, Gd_2O_3 and Er_2O_3 were chosen as potential IFBA because of prior experience in their use with PWR and BWR fuel. ZrB_2 is not under consideration because of its negative impact on heat transfer and the internal pressurization associated with helium production.

Methods of incorporation of IFBA in PWR or BWR fuel assemblies can vary depending on the application. Because PWR and BWR fuel assemblies are square, the fuel pin compositions within the assembly can be very heterogeneous, e.g. with all burnable absorber lumped into the fuel pins located at the corners of the square fuel assemblies. With an annular fuel cluster arrangement (such as in the Canadian SCWR and more conventional HWRs), the pin power distribution is cylindrically symmetric, and there is therefore much less flexibility in the distribution of neutron absorber material in the fuel. Lumping of burnable absorber into specific fuel pins would disrupt the cylindrical symmetry in the pin power distribution, and also result in a similar disruption in the temperature distribution. The only feasible way to achieve any heterogeneity in absorber distribution in an annular fuel pin arrangement is through relative differences in the compositions between fuel rings.

Preliminary calculations were performed to assess the potential use of Gd_2O_3 or Er_2O_3 as IFBA in the SCWR. For fuel loaded with Er_2O_3, the reduction in initial excess reactivity is as high as 150 mk, thus confirming the potential use of this fuel for reactivity hold-down. However, the depletion of erbium with burnup is very slow, and, as a result, the reduction in reactivity with the addition of Er_2O_3 persists throughout the entire cycle, negatively impacting the exit burnup and fissile utilization of the cycle. The use of Er_2O_3 alone as an IFBA for the SCWR is therefore not considered feasible.

For fuel loaded with Gd_2O_3, the reduction in initial excess reactivity is also large, but the gadolinium is depleted relatively quickly. For 0.5 wt% Gd_2O_3 in the fuel the initial excess reactivity is suppressed by over 300 mk, and once the gadolinium is depleted the reactivity rises again to over 100 mk (still within the first cycle). Higher concentrations of Gd_2O_3 also show large swings in reactivity although over a longer period. The use of Gd_2O_3 alone as an IFBA is therefore also not considered feasible.

3. Core Physics Performance Comparison: Present and Prior Concepts

As discussed above, the two-ring fuel concept used in combination with a central flow tube provides significant advantages over the 78-element fuel concept considered previously. A detailed comparison of core physics aspects of the two concepts was presented in [9]. Values for the integral core parameters for both concepts are provided in Table 2. The current two-ring fuel concept shows several performance enhancements over the previous reference option. There is an approximately 40% increase in exit burnup. The higher burnup of the present concept also results in a significantly lower (1/3 less) remainder of fissile Pu at the end of the cycle, thus enhancing the non-proliferation benefits of the SCWR via reduction in the Pu inventory that has accumulated from other reactor systems. There is a 15% decrease in the beginning of cycle (BOC) axial peaking factor and a similar decrease at the end of cycle (EOC). These gains are slightly offset by the reduction in cycle length by about 10% (which reduces the capacity factor) and increase in radial power peaking factor by about 2%. There is also a significant decrease in the core average CVR.

Table 2 Estimated Integral Core Parameters for the 78-element and two-ring fuel concepts

Parameter	78-element concept [6]	64-element, two-ring concept [10]
Average initial wt% PuO_2	13%	13%
Average initial fissile wt% heavy element	8.7%	8.7%
Average Exit Burnup (MWd/kg)	41.5	58.1
Cycle Length (EFPD)	455	410
Excess Reactivity BOC / EOC (mk)	95.3 / 9.7	110.4 / 12.3
Coolant Void Reactivity BOC / EOC (mk)	<-4 mk	<-25 mk
Channel Power Peaking Factor BOC / EOC	1.28 / 1.19	1.31 / 1.22
Axial Power Peaking Factor BOC / EOC	1.39 / 1.19	1.19 / 1.05
Maximum LER (kW/m)	37.4	38.4
Exit [fissile Pu] (wt% HM)	4.5	2.7
Exit [U-233 + Pa-233] (wt% HM)	1.1	1.1

The improvements seen with the two-ring fuel concept are due to the combined use of the central coolant flow tube and two, rather than three, fuel rings. The coolant in the central flow tube contributes to neutron moderation, thereby increasing the thermalization of the local neutron flux, and increasing rate of thermal fissions in the inner fuel ring. This increase in thermal fissions in the inner ring, combined with the use of only two fuel rings makes it possible to balance the fission power between the inner and outer rings. The largest difference in power densities between the inner and outer fuel ring, at the beginning of the fuel cycle, is approximately 7%, compared to a difference of approximately 140% between the innermost and outermost rings of the 78-element fuel concept.

The balanced fission power between the inner and outer fuel rings leads to better fissile utilization than the previous 78-element concept where the fissile material in the inner fuel rings was previously underutilized. The improved fissile utilization in the two ring concept leads to a higher achievable exit burnup than with the 78-element concept using the same fissile enrichment. The moderation in the central coolant tube does not change with axial position, and so variation of the axial power profile is less than in the previous reference case. This reduction in variation in turn reduces the axial power peaking factor. The reduction in cycle length is a result of the decrease in fuel mass related to the change in the assembly geometry, but this decrease is nearly off-set by the increase in initial reactivity. The small (~3%) increase in channel power peaking factor is due to the larger initial reactivity of fresh fuel and resultant increase in reactivity difference between fresh and partially irradiated fuel.

4. Summary

Improvements have been introduced in the Canadian SCWR concept [9], including the introduction of a central flow tube filled with coolant (replacing the large zirconia centre pin of earlier concepts) combined with the use of a two-ring fuel assembly. Performance improvements achieved with the two ring concept include a reduction in coolant void reactivity (CVR) by more than 10 mk, and an approximately 40% increase in fuel exit burnup, which is achieved via balanced power distribution between the fuel pins in the fuel assembly. Thermalhydraulic optimization of the concept presented in [9] resulted in significant improvements in peak sheath temperatures compared to prior concepts [10]. The performance improvements achieved in the present SCWR concept translate directly to improvements in the GIF metrics of enhanced safety (via CVR reduction), improved sustainability and economics (via the increase in exit burnup for the same average enrichment fuel as earlier concepts), and improved proliferation resistance (via a decrease in the inventory of plutonium).

The two-ring fuel concept introduced here shares some similarity to the double row square fuel assembly concept introduced elsewhere [19]. The two-ring fuel concept differs from the double row concept in that it achieves a uniform radial power and burnup distribution through a balance in neutron moderation between the light water region in the central flow tube and the heavy water moderator, which is unique to the Canadian SCWR.

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