

IMPACT OF CORROSION PRODUCT DEPOSITION ON CANDU-SCWR LATTICE PHYSICS

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Abstract

The CANDU[®] supercritical water-cooled reactor (CANDU-SCWR) is a pressure tube reactor intended to operate with a coolant pressure of 25 MPa and temperatures ranging between 350°C (core inlet) and 625°C (core outlet). Along the length of a fuel channel, there is a drastic decrease in the coolant density and dielectric constant, which is expected to result in a rapid decrease in the solubility of corrosion products. Therefore, it is anticipated that corrosion product deposition onto the cladding and liner in an SCWR fuel channel will be much greater than in conventional water-cooled reactors operating below the critical point of water. While optimized materials selection and chemistry control strategies may mitigate corrosion and corrosion product deposition to some degree, it may not be possible to completely eliminate corrosion product deposition within SCWR fuel channels. Corrosion product deposition on fuel cladding will have a negative impact on the neutron economy of the CANDU-SCWR because of parasitic absorption of neutrons within the deposited material. In this paper, lattice physics calculations are used to assess the impact of corrosion product deposition on fuel exit burnup, based on corrosion product deposition rates estimated for prototypical SCWR conditions.

1. Introduction

The CANDU-based pressure-tube (PT) supercritical water-cooled reactor (SCWR) is Canada's primary contribution to the Generation IV International Forum (GIF) [1], the objectives of which are to carry out research and development on potential next generation nuclear energy systems which satisfy four general criteria: safety, sustainability, economics and proliferation resistance [2]. The use of supercritical water coolant enables an increase from 33% thermal efficiency attained in conventional CANDU reactors to between 45 % and 50 % for the CANDU-SCWR. The increased thermal efficiency of the CANDU-SCWR has the potential to yield significant economic gains (via higher power production) and enhanced sustainability (via increased fuel efficiency).

The CANDU-SCWR is intended to operate with a coolant pressure of 25 MPa and temperatures ranging between 350°C (core inlet) and 625°C (core outlet) with a direct steam cycle [3]. The combination of supercritical water coolant and a direct steam cycle maximize the thermodynamic efficiency of the SCWR (~ 50% efficiency) compared to other steam cycles, such as an indirect (~ 33% for CANDU-6 reactors) or a dual steam cycle (~49 % with reheat channels) [4]. The rapid increase in coolant temperature along the length of a fuel channel will result in a drastic decrease in the coolant density and dielectric constant. The low dielectric of supercritical water makes it behave like a nonpolar solvent, which is expected to result in a rapid decrease in the

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solubility of metal oxides such as magnetite [5]; magnetite is expected to be the primary corrosion product in this system, arising from corrosion of out-of-core surfaces [6]. Therefore, it is anticipated that corrosion product deposition onto the cladding and liner in an SCWR fuel channel will be much greater than in conventional water-cooled reactors operating below the critical point of water [6].

While optimized materials selection and chemistry control strategies may mitigate corrosion and corrosion product deposition to some degree, it may not be possible to completely eliminate corrosion product deposition within SCWR fuel channels [7]. Corrosion product deposition on fuel cladding will have a negative impact on the neutron economy of the CANDU-SCWR because of parasitic absorption of neutrons within the deposited material. In this paper, lattice physics calculations are used to assess the impact of corrosion product deposition on fuel exit burnup, based on corrosion product deposition rates estimated for prototypical SCWR conditions.

2. Modelling and Analysis Methods

A 54-element bundle design was used for these studies, as described in [8] and shown in Figure 1, below. The bundle has three concentric fuel rings, with 12, 18 and 24 elements composed of 4% low enriched uranium (LEU) fuel. The bundle also has a large centre element which can be filled with air, solid material (e.g. stainless steel or zirconia) or coolant. The fuel channel is a re-entrant type fuel channel (REC) as described in [9]. The outermost component of this channel is a calandria tube, which is separated from a pressure tube by a gas annulus. Inside the pressure tube is an outer annulus of coolant, which surrounds a solid liner tube. The coolant flows past the liner tube and, at the end of the channel re-enters and passes through the channel centre, along the fuel bundles. Detailed bundle specifications can be found in [8].

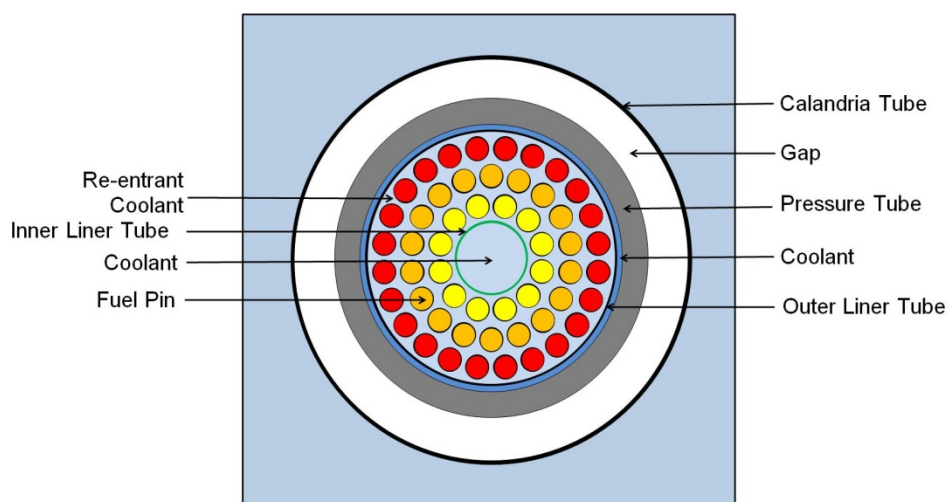


Figure 1 SCWR 54-Element Bundle Design and Re-entrant channel (REC) lattice cell

Lattice physics calculations were performed using WIMS-AECL 3.1, which is a two-dimensional multi-group deterministic lattice physics code that solves the integral neutron transport equation using collision probabilities [11]. For this study, WIMS-AECL was used in conjunction with an 89-group nuclear data library based on ENDF/B-VI. For the results

presented here, WIMS-AECL was used to evaluate lattice reactivity as a function of fuel burnup. Fuel channel models in WIMS-AECL consisted of two-dimensional slices through the channels, perpendicular to the channel axis as illustrated in Figure 1. Calculations were performed at the axial position corresponding to the midpoint of the channel, corresponding to a coolant temperature and density of 402 °C and 0.19 g/cm³, respectively, based on the coolant temperature and density profile provided in [10]. This position was chosen for convenience, since the deposition rate profile is not known for the channel conditions under consideration here. Deposition is likely to occur where there is a significant drop in coolant density and concomitant rise in temperature [6]. Both of these conditions will be satisfied at the channel midpoint but corrosion product deposition may also occur at positions closer to the channel inlet. All other parameters are as specified in [8].

The impact of corrosion product deposition is assessed here by evaluating changes to the neutron multiplication factor (k-infinity) and exit burnup. It was assumed that the exit burnup was reached when the integrated k-infinity reached a value of 1.040, where core leakage and absorption were assumed to have a worth of approximately 40 mk (40 mk corresponds to $dk/k = 0.040$, 4% or 4000 pcm). A more detailed description of the evaluation of exit burnup is provided in [12]. Note that the values for exit burnup presented in this paper are based on online refuelling.

The actual composition of corrosion products will depend on the selection of in-core and out of core components, and the corrosion and the solubility of the core component materials in the coolant cycle. Deposited corrosion products are modelled here using magnetite (Fe₃O₄), since this will likely be the primary corrosion product in the SCWR [6]. The time dependent change in amount of deposited corrosion product was modelled in WIMS by updating that value at each burnup step.

3. Results and Conclusions

A summary of corrosion product deposit data for a variety of water chemistry and operating conditions is provided in [6]. Based on these results, corrosion product deposit rates are estimated to be as low as 7×10^{-7} mg/cm²/h (X-3 in-reactor loop in NRX [13]) and as high as 0.003 mg/cm²/h (Russian fossil plant [14]). The peak deposition rate for the SCWR was estimated by Burrill [6] to be approximately 0.01 mg/cm²/h, based on the assumption that the inlet coolant was saturated in dissolved iron.

In this study three deposition rates were examined, 5×10^{-4} mg/cm²/h, 0.005 mg/cm²/h and 0.01 mg/cm²/h. WIMS-AECL results for k-infinity as a function of burnup are plotted in Figure 2. Note that as time increases, both burnup and the amount of deposited corrosion product increase. The net effect of corrosion product deposition over time is to reduce k-infinity, thereby reducing the exit burnup, as summarized in Table 1. Table 1 also shows the mean thickness of corrosion product deposit when exit burnup is reached.

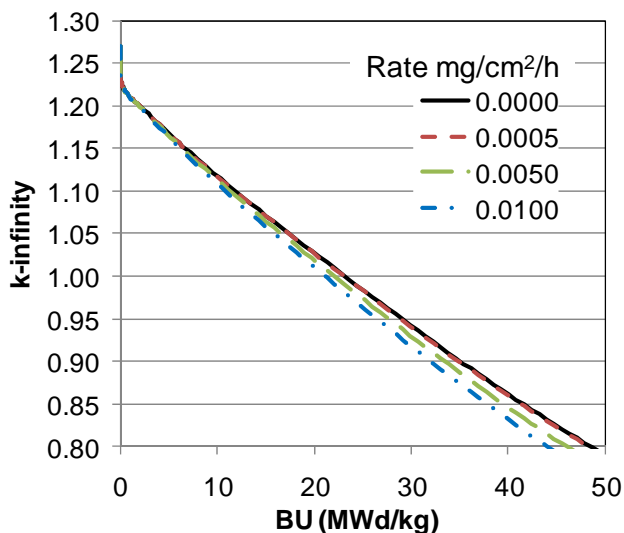


Figure 2 k-infinity versus Burnup (MWd/kg) for Lattice Cells with Various Values for Corrosion Product Deposition Rate

Table 1
Corrosion Product Deposit Thickness and Exit Burnup versus Deposition Rate

Deposition rate (mg/cm ² /h)	Final layer thickness (cm)	Exit BU (MWd/kg)	ΔExit BU (MWd/kg)
0.0000	0.000	36.82	0.00
0.0005	0.002	36.65	-0.16
0.0050	0.022	35.13	-1.69
0.0100	0.041	33.63	-3.19

Figure 3 shows the change in exit burnup (relative to no deposition) as a function of deposition rate of corrosion product. A correlation is also plotted in Figure 3, which shows that the change to exit burnup is essentially linear with deposition rate. The linear correlation provided in the inset to Figure 3 can be used to obtain an estimate of the change to exit burnup based on deposition rate of corrosion products. Note that the linear relationship may not hold for rates higher than 0.01 mg/cm²/h.

Based on the maximum corrosion product deposition rate obtain by Burrill [6], WIMS-AECL lattice physics calculations have shown that corrosion product deposition can lead to a substantial, up to 10%, reduction in fuel exit burnup, due to parasitic absorption of neutrons in the deposited magnetite layer. The actual reduction in channel average exit burnup is likely to be less than 10%, assuming lower deposition rates elsewhere along the channel.

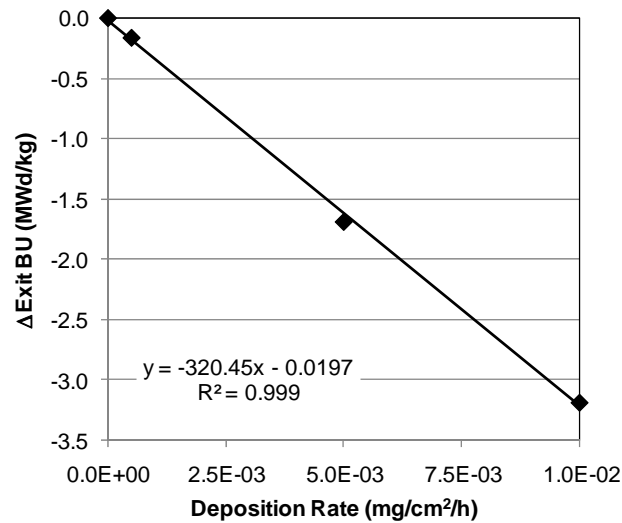


Figure 3 Change in Exit Burnup versus Deposition Rate of Corrosion Product

However, it is important to note that the deposition rate profile calculated by Burrill [6] was based on a much smaller temperature gradient with an inlet temperature of 350 °C and outlet temperature of 384 °C. A calculation of the deposition rate profile for the system examined here requires a heat transfer correlation for SCW, and solubility data for magnetite over the range of conditions in the channel, neither of which are presently known. As discussed above, it is likely that maximum deposition will occur before or near the channel midpoint. However, it is not obvious how the much higher temperature gradient considered here would affect the magnitude of deposition rate or its profile along the channel.

It should also be noted that, although not examined here, the deposition of corrosion products will have significant adverse affects on cladding heat transfer properties, eventually leading to cladding failure (for a review see, e.g., [15]). For high deposition rates, i.e. approaching 0.01 mg/cm²h, the issue of cladding failure will likely be much more significant than the loss of neutron efficiency.

4. References

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