The Version of Record of this manuscript has been published and is available in :
Nuclear Technology (2020) https://www.tandfonline.com/doi/full/10.1080/00295450.2020.1827884

ON THE AMOUNT OF MODERATION IN THE CANDU LATTICE

B. Rouben[1] and E. Nichita[2]
[1] 12 & 1 Consulting, Toronto, Ontario, Canada, also Adjunct Professor at McMaster University and Ontario Tech University
[2] Ontario Tech University, Oshawa, Ontario, Canada
roubenb@alum.mit.edu, eleodor.nichita@ontariotechu.ca

Abstract

Throughout the years, various reports and training manuals on CANDU reactors have mentioned that the CANDU lattice is *over-moderated*. *Over-moderation* is not always defined in such documents, but often appears associated with the positive void reactivity of the CANDU lattice. Some documents refer, logically, to *over-moderation* as meaning that the lattice pitch is larger than the pitch that maximizes the infinite-lattice multiplication constant, but do not demonstrate this is the case for CANDU. We demonstrate that, in fact, the CANDU lattice is *under-moderated*, that is, the current 28.575-cm lattice pitch is smaller than the pitch for which the infinite-lattice multiplication constant reaches its maximum. We hypothesize that the misconception of CANDU *over-moderation* may have originated from attributing the CANDU positive void reactivity to "too much moderator", by incorrectly equating the effect of losing heavy-water coolant with the effect of losing heavy-water moderator.

Keywords: CANDU; Reactivity; Under-moderation

I Introduction

A number of reports and training manuals[1-4] assert that CANDU reactors are *over-moderated*. For example, Ref. 3 contains the statement "Furthermore, the CANDU lattice is over-moderated to preserve neutron economy which leads to a positive coolant voiding reactivity coefficient", and Ref. 4 includes the statement "CANDU reactors are over-moderated, and for this reason have a positive void coefficient of reactivity". The objective of the current paper is to investigate whether CANDU reactors, more specifically the CANDU lattice, are indeed *over-moderated*.

To examine the issue, first the meanings of over-moderation and under-moderation need to be defined.

A moderator is used to thermalize neutrons, i.e., slow them down to an energy range (small fraction of an eV) in which they have a much higher probability to induce fission in fissile nuclides, such as ^{235}U, ^{239}Pu or ^{241}Pu. Considering an infinite lattice of repeating identical cells, if there is no moderator or very little moderator in every lattice cell, fissions will not be sustainable in reactor lattices that rely on thermal neutrons: the infinite-lattice multiplication constant, k_∞, will have a value smaller than unity (which is required to make the chain reaction self-sustainable). As the amount of moderator in each cell is increased (measured, say, by the ratio of moderator volume to fuel volume), k_∞ will increase, and, at some point, will reach the value 1, i.e., the infinite lattice will be critical.

The infinite-lattice multiplication constant can be raised further by adding more moderator, up to a point beyond which the number of additional neutrons being slowed down is exceeded by the number of additional neutrons being absorbed in the moderator and hence k_∞ will start to decrease. Thus, there is an **optimum** amount of moderator, the one that will give the largest value of k_∞. Consequently, the logical and reasonable meanings of *over-moderation* and *under-moderation* refer to the situation in which the moderator-to-fuel volume ratio is *greater* or *smaller* than the value corresponding to the maximum k_∞ as shown in Figure 1.

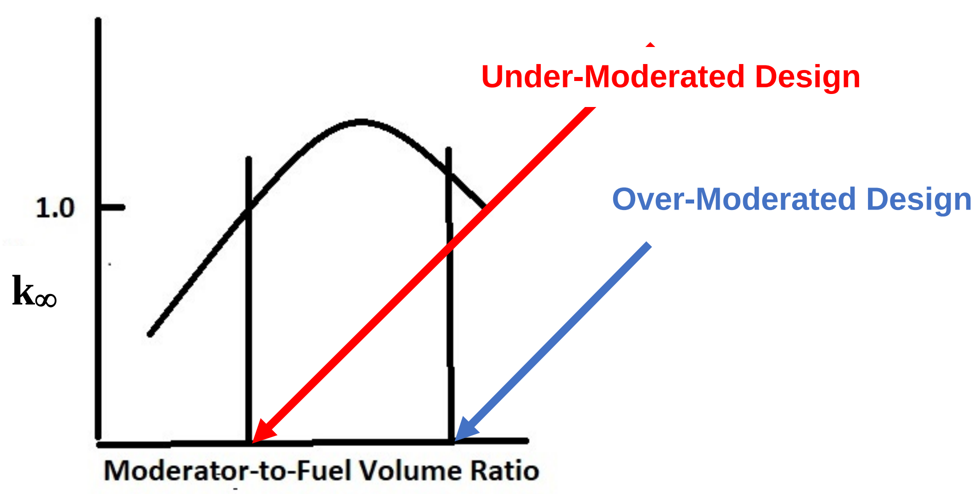

Figure 1. Moderator-to-Fuel Volume Ratio for Under-Moderation and Over-Moderation

This sets the basis for the way to determine whether a reactor lattice is over-moderated or under-moderated by comparing its moderator-to-fuel volume ratio to the one for which the infinite-lattice multiplication constant reaches its maximum. Since the moderator-to-fuel volume ratio increases with the lattice pitch, an equivalent comparison can be made between the selected lattice pitch and the pitch for which the infinite-lattice multiplication constant reaches its maximum.

II Analysis

CANDU reactors are pressure-tube reactors. The main reactor vessel is the non-pressurized calandria, shown in Figure 2.

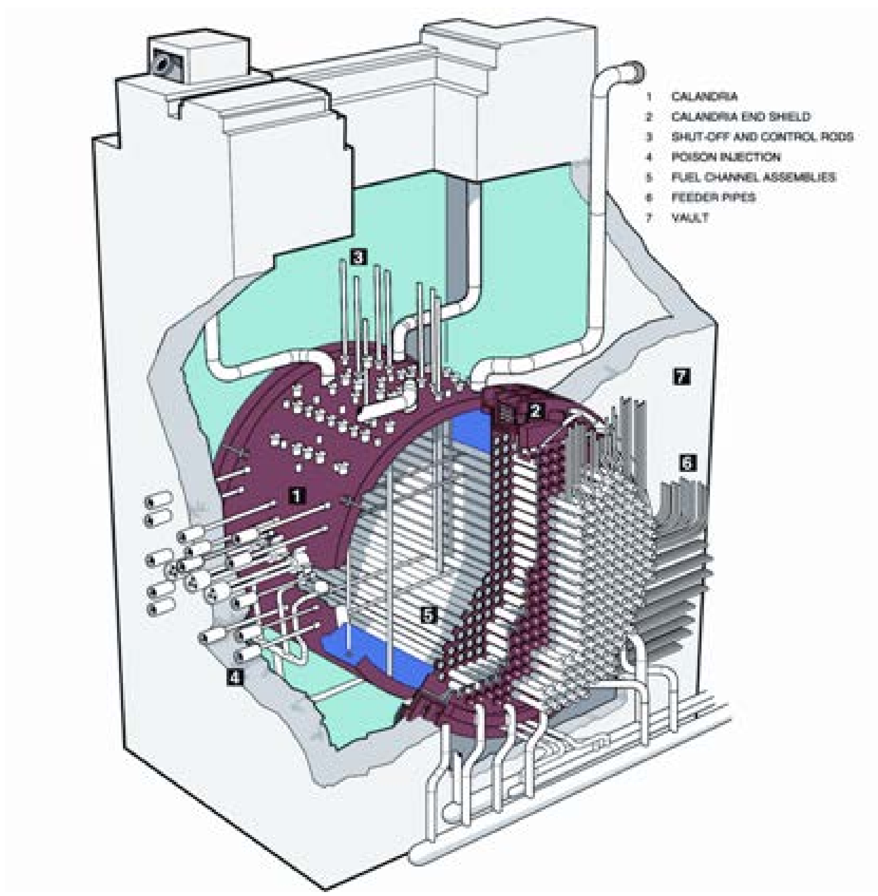

Figure 2. CANDU Reactor

Fuel and primary coolant are contained in pressure tubes in horizontal channels surrounded by moderator. The CANDU channels are set on a square lattice; the distance between channels is the lattice pitch, which is 28.575 cm in the CANDU design. Figure 3 is the face view of a unit or basic cell in a CANDU reactor, showing the fuel and coolant in the pressure tube, surrounded by the moderator outside the calandria tube. The dimensions of the basic cell are 28.575 cm horizontally and vertically. In the depth direction, not shown in Figure 3, the axial dimension is 49.53 cm, the length of a fuel bundle. The moderator and coolant are both heavy water, but they are totally separate and not in contact with one another. This is an important difference from pressure-vessel reactors where the coolant serves also as moderator, and vice versa.

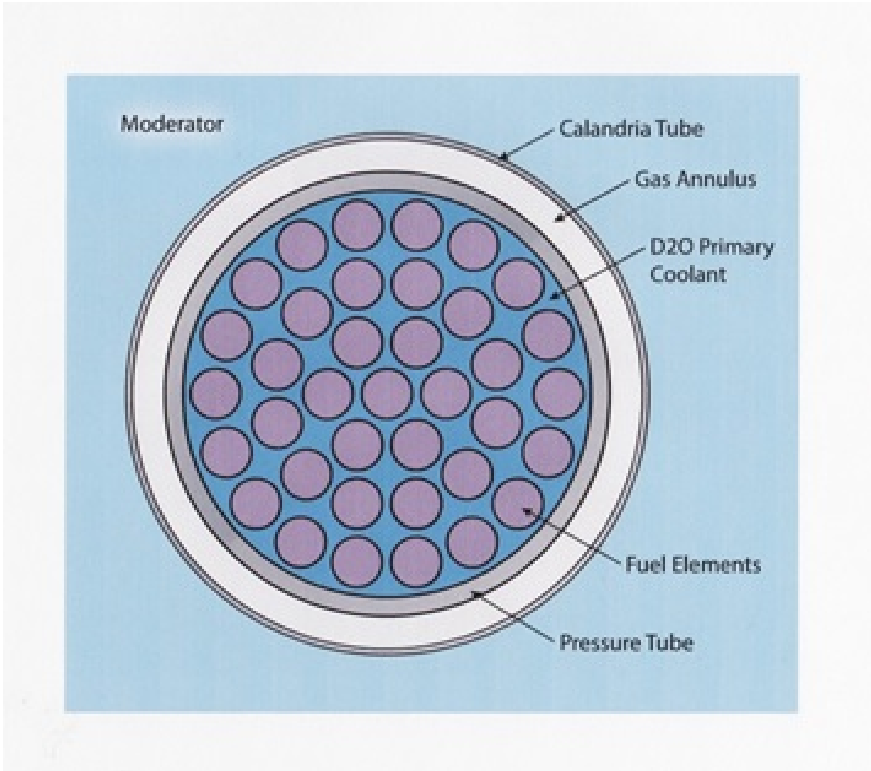

Figure 3. Face View of CANDU Basic Lattice Cell

Lattice codes, such as, for example, POWDERPUFS-V[5] or DRAGON[6] , can be used to calculate the multiplication constant of the infinite lattice, k_∞, by using a single basic cell imagined mirrored in all directions. This quantity excludes the effects of leakage (since it is for the infinite lattice). We have calculated k_∞ as a function of lattice pitch, to examine where the multiplication constant is at its maximum. Moderator and coolant purities were 99.750 a/% and 99.222 a/%, respectively.

II.A POWDERPUFS-V Results for Lattice Multiplication Constant

POWDERPUFS-V is a very early Canadian lattice (or cell) code, developed in the 1960s and 1970s at AECL for heavy-water, natural-fuel lattices. While not strongly founded on the neutron-transport equation, this largely empirical code was based on quantitative results gleaned from early research on heavy-water lattices at Chalk River Laboratories. As opposed to more modern codes, POWDERPUFS-V does not use an international library of microscopic cross sections. Rather it has an internal set of data. POWDERPUFS-V was used extensively and very successfully for several decades in the analysis and design of CANDU reactors, and even as the lattice code in the software dedicated to many decades of core-follow calculations. POWDERPUFS-V calculates the parameters in the *four-factor formula* (ε, p, f, η), lattice two-energy-group properties and the infinite-lattice k_∞ as functions of fuel irradiation (burnup). Despite POWDERPUFS-V's lack of "sophistication", the longevity of its use supports its application in our current query. We have used POWDERPUFS-V to calculate the infinite-lattice multiplication as a function of the lattice pitch, from 24 cm to 40 cm, both for a fresh core (zero irradiation) and for the equilibrium core (average fuel discharge irradiation of 1.7 n/kb, equivalent to an average discharge burnup of 7,100 MW.d/Mg(U) for the as-built CANDU-6 reactor). (In the equilibrium-core model, the lattice properties are averaged over fuel burnup from 0 to the average exit burnup.) The results are displayed in Figures 4 and 5 respectively .

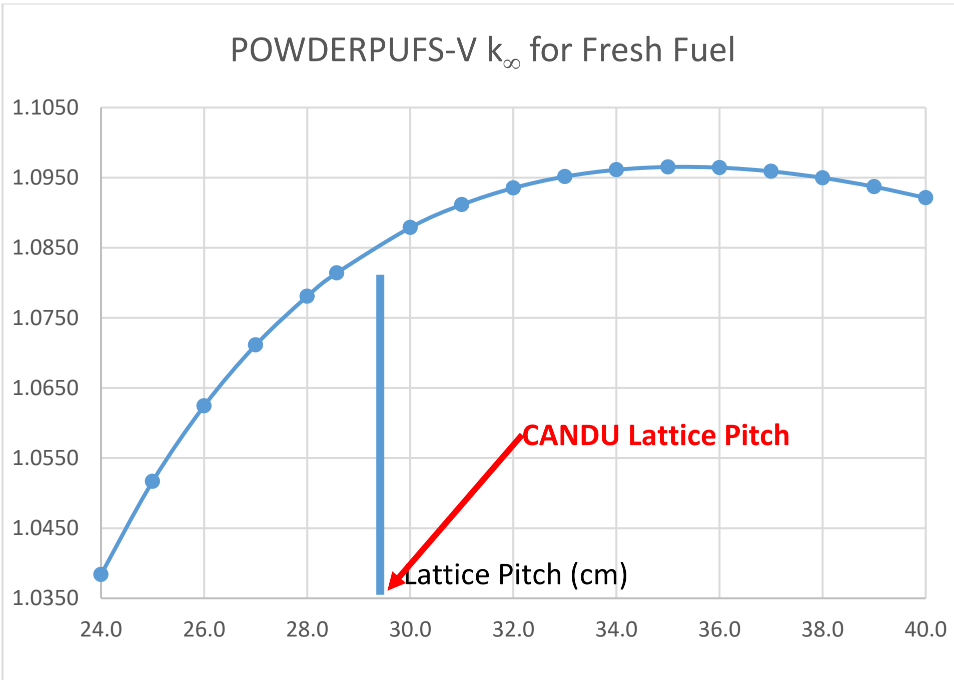

Figure 4. k_∞ as a Function of Lattice Pitch for Fresh Core - POWDERPUFS-V Result

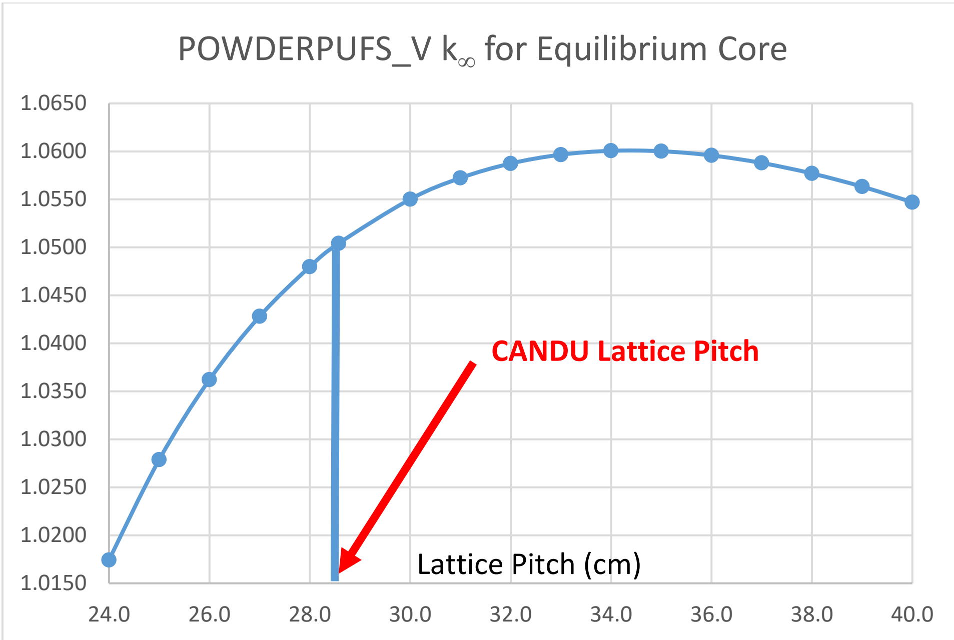

Figure 5. k_∞ as a Function of Lattice Pitch for Equilibrium Core - POWDERPUFS-V Result

Figure 4 shows the fresh-core infinite multiplication constant to reach a maximum at ~35.5 cm, while Fig. 5 shows the equilibrium-core infinite multiplication constant to peak an ~34.5 cm. Both figures clearly show that the multiplication constant as reported by POWDERPUFS-V reaches a maximum at a lattice pitch 6-7 cm greater than the CANDU lattice pitch.

II.B DRAGON Results for Lattice Multiplication Constant

The analysis was repeated using the collision-probabilities method in the lattice code DRAGON version 3.06 L [6]. The 69-group IAEA WIMS-D Library Update Project microscopic cross section library [7] was employed. Results for a fresh core are shown in Figure 6 and results for an equilibrium core are shown in Figure 7.

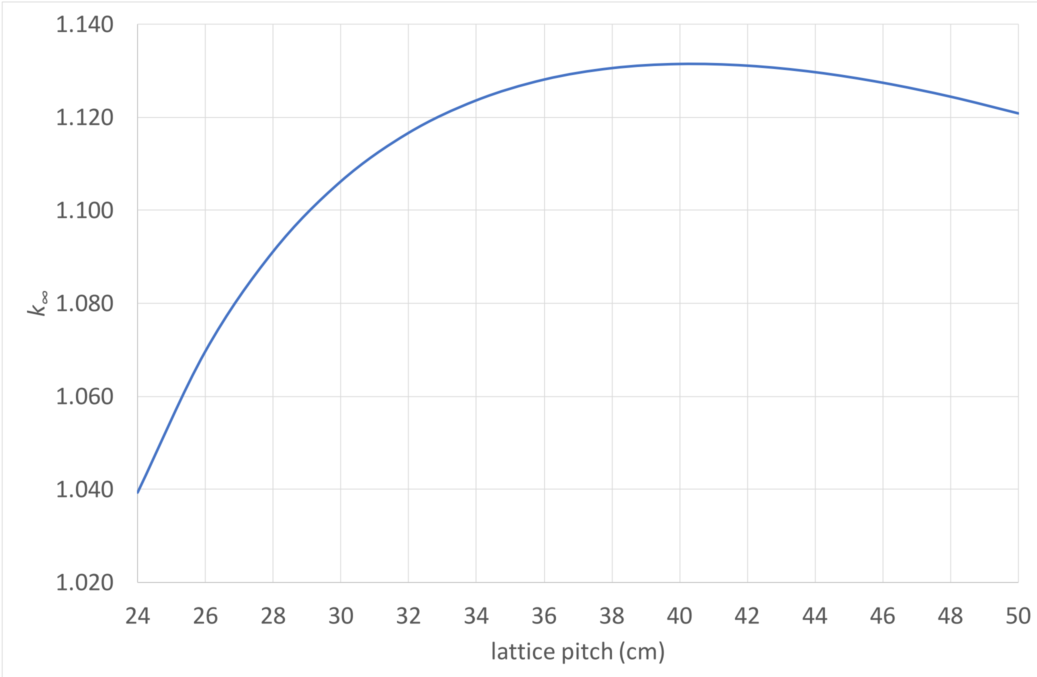

Figure 6. k_∞ as a Function of Lattice Pitch for a Fresh Core- DRAGON Result

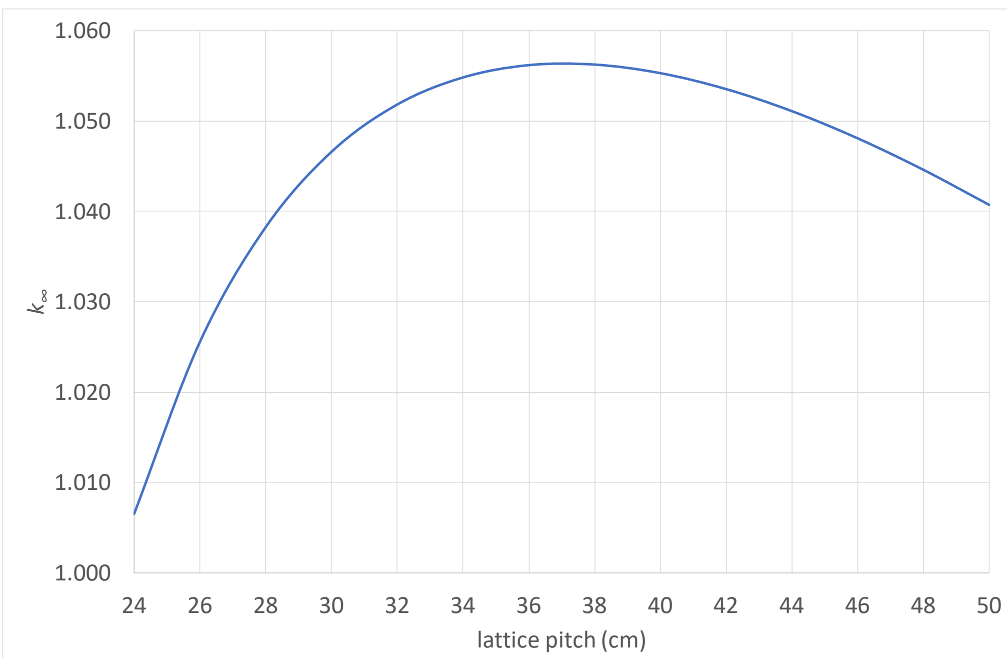

Figure 7. k_∞ as a Function of Lattice Pitch for an Equilibrium Core- DRAGON Result

Figure 6 shows the maximum k_∞ for a fresh core to occur for a lattice pitch of 40 cm, while Fig. 7 shows the maximum k_∞ for an equilibrium core to occur for a lattice pitch of 37 cm. These results are ~4cm larger than those predicted by POWDERPUFS-V, but they are consistent with those results in the sense that the pitch for which the infinite multiplication constant is maximized is slightly shorter for the equilibrium core than for the fresh core, and far larger than the 28.575 cm CANDU lattice pitch. The differences between DRAGON results and POWDERPUFS-V results are very likely due to the more sophisticated computational model used by DRAGON.

III SUMMARY, CONCLUSION AND FUTURE WORK

Results from both POWDERPUFS-V and DRAGON clearly show that the CANDU lattice is significantly under-moderated. In fact, the more modern code, DRAGON, with a firmer mathematical foundation on neutron transport theory, indicates an even greater degree of under-moderation than POWDERPUFS-V.

The differences in the results produced by the two codes likely have many sources, including different microscopic cross-section libraries, different computational models and, for the equilibrium core, likely different fuel compositions for the discharge burnup. Because the codes are so different in their philosophies and coding implementation, it is difficult to isolate differences due to specific elements. That, in both cases, the optimum lattice pitch, in terms of reactivity, is so much greater (by several cm) than the design value (28.575 cm) gives high confidence in the assertion that the current lattice is under-moderated. The large difference between the optimum lattice pitch and the design lattice pitch is unlikely to be eliminated by the use of a different cross-section library or by considering slightly different fuel compositions at specific burnups. We contend that future references to the over- or under-moderated character of the CANDU must reflect this conclusion.

While calculations have been performed for an infinite lattice, it is clear that a finite reactor is also under-moderated. Comparing a CANDU core having the design lattice pitch (28.575 cm) with a hypothetical CANDU core with the same number of channels but with a larger lattice pitch, it is clear that the positive reactivity difference between the larger core (with its lower leakage) and the smaller core (with its higher leakage) will be even larger than the reactivity difference between the corresponding infinite lattices. Therefore, in reactivity terms, the larger-pitch finite core is even more under-moderated than indicated by the infinite-lattice calculations

We surmise that the statements on over-moderation in the literature originate from consideration of the positive void reactivity of CANDU, interpreted as being due to the loss of the moderating effect of the coolant. However, this may only be true for a reactor with no separation of coolant from moderator, but not for CANDU, where the coolant provides little moderation compared to the much larger volume of moderator. The CANDU void reactivity is in large measure due to an increase in fast fissions and in resonance escape at both the high end and the low end of the resonance region, while the fission resonance of ^{239}Pu at 0.3-eV neutron energy contributes to reducing the void reactivity when plutonium is present[8]. It is important to clearly note, therefore, that correcting the label of the lattice to under-moderated does not change the sign of the coolant void reactivity.

Finally, it is important to note that considering the effect brought about by a change in *coolant density* should ***not*** have been used to make an argument about over-moderation or under-moderation. Such an argument about over- or under-moderation can be made using the more apt effect, that of a change in moderator density. This effect - a drop in reactivity upon a decrease in moderator density – can correctly be used to indicate that the CANDU lattice is under-moderated, in agreement with our calculations presented here.

To confirm the lattice pitch at which reactivity peaks, additional calculations using other modern transport codes, including Monte Carlo, would be useful.

1. References

[1] "Rolphton Training Centre, Course 227", in CANTEACH Document Library, https://canteach.candu.org/Content%20Library/20053701.pdf.

[2] "Nuclear Theory, Course 127", in CANTEACH Document Library, https://canteach.candu.org/Content%20Library/20050309.pdf.

[3] J.C. Luxat and G.M. Frescura, "Space-Time Neutronic Analysis of Postulated LOCA's in CANDU Reactors", ; 1978; 12 p; ENS/ANS International Topical Meeting on Nuclear Power Reactor Safety; Brussels, Belgium.

[4] J.G. Waddington and T.J. Molloy (AECB), "Lessons for PHWRs Learned from the Chernobyl Accident", IAEA - INIS.

[5] B. Rouben, "Description of the Lattice Code POWDERPUFS-V", AECL-11357, 1995 October.

[6] Marleau, G., Hébert, A., Roy, R., 2013. A User Guide for DRAGON 3.05L. Ecole Polytechnique de Montreal, Montreal, Canada.

[7] International Atomic Energy Agency, 2007. WIMS-D Library Update, STI/PUB/1264, Vienna, Austria

[8] J.J. Whitlock, W.J. Garland and M.S. Milgram, "Effects Contributing to Positive Coolant Void Reactivity in CANDU", in Proceedings of American Nuclear Society Annual Meeting, Philadelphia, PA, USA, 1995 June 25-29.