# Coolant Void Reactivity Predictions with Fuel Temperature Effect of 37-Element CANDU 6 Natural Uranium Fuel Lattice Cell Using WIMS-ANL

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## 1. Introduction

In the present paper, the effects of fuel temperature increase on the coolant void reactivity of 37-element CANDU 6 natural uranium fuel lattice cell are studied by using the WIMS-ANL code [1]. It had been known in the past that the fuel temperature reactivity was negative, independent of the burnup range of interest for the design and safety analysis, based upon a model that lumped fuel elements into a single rod. However, with the use of more detailed computational tools, such as, WIMS lattice code, it came to light that the FTR behavior turns from negative to positive with increasing burnup. In order to more realistically understand the effect of positive FTR on coolant voiding in the context of accident analysis, a series of lattice simulations have been conducted, and the results are presented with discussion and some conclusions.

## 2. Conceptual Approach

The neutronic phenomena in the clustered fuel region of 37-element lattice is confronted with the energy and geometry self-shielding effect, and also most importantly in the spectral range of $U^{238}$ resonance absorption with the significant consequences of fuel temperature effect due to Doppler broadening.

The self-shielding effects are pronounced with the result in spatially distributed power density across the rings, and with burnup the ratio of fissile isotopes $Pu^{239}$ to $U^{235}$ is in a tendency of monotonic diversification, with the extreme value for the outer ring elements, and with about 2/3 and 1/2 for the intermediate and the rest elements, respectively, compared to the outer ring $Pu^{239}/U^{235}$ ratio at exit burnup, say ~200 MWh/kgU.

The above-mentioned effects could be more precisely envisaged by relating to the so-called "hot neutron effect" which yields the opposite reactivity change caused by $U^{235}$ and $Pu^{239}$ fission reactions, and could be more realistically modeled by setting up the input data of different fuel temperatures for the ring elements with different power densities.

## 3. Methods, Results and Discussions

The fuel temperature effect is considered to be an "isolated" one, i.e., the coolant temperature increase due to FT increase is excluded based upon the time lag of heat transfer from fuel to coolant. This can also be justified by adopting the assumption that the safety systems are designed to detect the coolant voiding and subsequently shut down the reactor long before the time point where the increased FT would lead to the coolant temperature increase. Furthermore, the temperature of the moderator system remains unchanged due to the physical separation of the system from the fuel region.

The mathematics and physics model used in the WIMS multi-energy group lattice physics methodology has been proven to produce more accurate results compared to the conventional model, such as, the lumping of fuel elements cluster into a single rod and two energy group treatment, when validated against the actual operating history data of CANDU power reactors [2], thus the simulation results generated in the present study using WIMS-ANL could be supported as well.

### 3.1 Input Parameters

The relevant input parameters to WIMS-ANL for full power operating condition are given below.

Fuel Temperature: 687 °C
Coolant Temperature: 288 °C
Moderator Temperature: 69 °C
Coolant Density: 0.807859 g/cc

### 3.2 Coolant Void Reactivity

The coolant void reactivity changes with burnup calculated for 50% and 100% voiding at full power are graphically shown in Figure 1. Note that a flat reference fuel temperature of 687 °C was applied to all the ring elements.

The CVR is 17.78 mk, 18.59 mk (peak value) and 16.26 mk for 0, ~2(SFP) and ~35 MWh/kgU, respectively, in the case of 100% voiding. Passed ~35 MWh/kgU, the CVR starts to level off, and the plateau remains at around ~15.6-15.9 mk. For 50% voiding, the CVR behaves very similarly to 100% voiding, and the ratio is about ~49% for the entire burnup range.

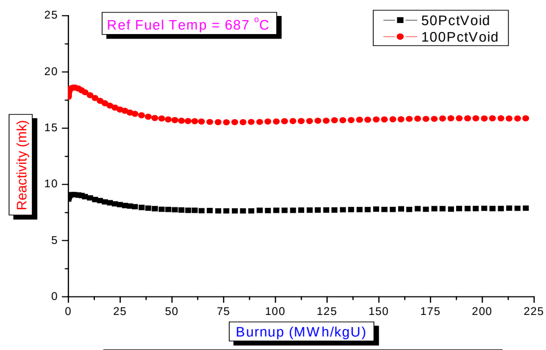


Figure 1 Coolant Void Reactivity of 37-Element CANDU 6 Natural Uranium Fuel Lattice Using WIMS-ANL

### 3.3 CVR with Distributed Fuel Temperature

As discussed in Section 2, the effect of fuel temperature is studied by applying distributed $FT_i$ across the rings. For a given FT being applicable to the entire fuel elements, the individual $FT_i$ to be used for the elements of the ring $i$ is approximated at each burnup point according to the following relationship.

$$FT_i = (FT-CT)*PD_i + CT \quad (1)$$

In Eq. (1), CT stands for coolant temperature and $PD_i$ for fractional power density of the ring $i$, respectively.

In order to obtain the final value $FT_i$ with coolant voiding, the initial $FT_i$ values calculated with FT = 687 °C and $PD_i$ ($FT_i$ = 687 °C ) are used, and then the recalculated $PD_i$ with coolant voiding is used to determine the final CVR with the distributed $FT_i$ across the rings. The CVR changes from the CVR values obtained with the flat FT of 687 °C applied for the entire rings to the CVR predictions with the distributed $FT_i$ across the ring *i* are displayed in Figure 2 for the FT range 800-1800 °C with 200 °C increment for 100% voiding.

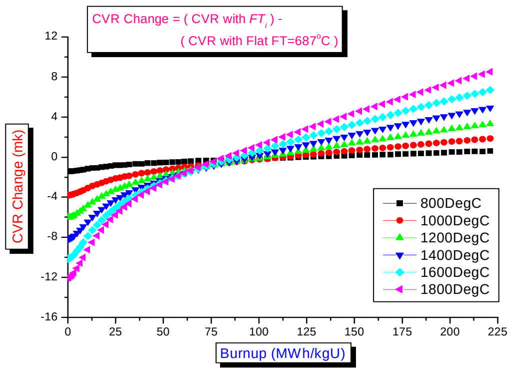


Figure 2 CVR Change with Distributed Fuel Temperature Compared to CVR with Flat FT=687 °C for 100% Voiding

For 50% voiding, the CVR changes are almost comparable to the case of 100% voiding, with the differences showing all positive values, i.e., [ $(\text{CVR Change})_{100\%\text{Void}}$ - $(\text{CVR Change})_{50\%\text{Void}}$ ] > 0, and the difference increases slightly with FT and burnup and it becomes about ~+1 mk at FT = 1800 °C for burnup greater than ~220 MWh/kgU.

From Figure 2, it can be seen that the sign of CVR changes becomes opposite between ~90-~125 MWh/kgU, and the turning points occur at lower burnup for higher FT. The slope of curves is much sharper in the range of negative CVR changes, while on the opposite side the slopes show almost linearity. The absolute value of the slopes become larger with FT increase and also vary with burnup, which explain the combined results of Doppler broadening and "hot neutron effect" as well as the ratio of $Pu^{239}/U^{235}$.

For the accident analysis with coolant voiding, the uncertainty of CVR predictions would usually be allowed, and taking this allowance to be about ~2.5 mk, the burnup points where the CVR change with FT effect reaching the uncertainty allowance ~+2.5 mk are about ~190, 155~, ~135 and ~120 as well as ~205, ~170, ~150 and ~130 MWh/kgU for the FT values of 1200, 1400, 1600 and 1800 °C, and for 100% and 50% voiding, respectively. For the FT values less than 1200 °C the CVR change remains below ~+2 mk for the entire burnup range both for 100% and 50% voiding cases.

In Table 1, the coolant void reactivity with distributed fuel temperature is given for 100% voiding. The minimum and maximum values occur at FT = 1800 °C for zero and exit burnup, respectively. For fresh fuel the CVR value at 1800 °C is dropped to nearly ~1/3 of the value at 687 °C whereas for the exit burnup state the CVR value is increased by about 48% for the same FT rise. It is interesting to observe for this particular example that the CVR values are almost equal (~16.50 mk) for zero and exit burnup states after FT is increased from 687 to 800 °C. It is further to note that as FT increases higher the gradual increase of CVR for exit burnup is overwhelmed by the larger decrease of CVR for zero burnup at the same FT level.

This opposite effect of CVR change between zero and exit burnup lattice cells suggests that the pattern of fuel burnup distribution of lower and higher burnup fuels between alternating neighboring channels in the core might lead to the overall net effect of negative fuel temperature reactivity contribution in the case of coolant voiding. Further in-depth scrutinizing allows envisaging that when the coolant voiding occurs, initially the flux in lower burnup lattice cells will rise faster due to the larger CVR, which in turn lead to higher FT rise followed by stronger insertion of the FT negative reactivity. This physical phenomena would be supported to a certain extent of the burnup regions where the lower and higher burnup distribution alternates across the channels.

For mid(~100 MWh/kgU) burnup case the FT reactivity is initially negative and becomes positive from 1200 °C. For tav(~145 MWh/kgU) core average burnup it is positive for the entire FT range. The reactivity increases by about 1.47 and 4.34 mk for mid and tav burnup, respectively, from 687 °C to 1800 °C.

In the case of tav burnup, the realistic application of reactivity increase would be about 4.34-2.5 = 1.84 mk at 1800 °C if the CVR prediction uncertainty is discounted. However, until before FT reaches 1800 °C, the shutdown system would have been long before activated and the sufficient amount of negative reactivity would have been inserted into the tav equivalent burnup region of the core, so that such additional slight increase of FT positive reactivity, say ~1.8 mk, would have been overwhelmed by the shut down system and as a result would not pose any safety concern.

Table 1 Coolant void reactivity with distributed fuel temperature for 100% voiding (Ref FT = 687 °C)

| | Burnup (MWh/kgU) | | | | | |
|---|---|---|---|---|---|---|
| FT (°C) | 0 | ~2(SFP) | ~35 | ~100 | ~145 | ~200 |
| 687 | 17.91 | 18.75 | 16.26 | 15.72 | 15.87 | 15.98 |
| 800 | 16.50 | 17.35 | 15.49 | 15.58 | 16.04 | 16.49 |
| 1000 | 14.15 | 15.05 | 14.54 | 15.56 | 16.53 | 17.57 |
| 1200 | 11.92 | 12.88 | 13.77 | 15.74 | 17.25 | 18.87 |
| 1400 | 9.81 | 10.87 | 13.17 | 16.11 | 18.11 | 20.32 |
| 1600 | 7.78 | 8.97 | 12.68 | 16.60 | 19.10 | 21.93 |
| 1800 | 5.84 | 7.17 | 12.37 | 17.19 | 20.21 | 23.59 |

## 4. Conclusions

The present study has shown that the coolant void reactivity with fuel temperature effect during power excursion of 37-element natural uranium fuel loaded CANDU 6 system would have additional slight increase of void reactivity in the burnup region where all the bundle burnup would be represented by, e.g., time-average based core average burnup. However, the amount of void reactivity increase due to fuel temperature rise would be within the range such that it could be safely coped with by the inherent capability of the shutdown systems.

For the burnup regions where lower and higher burnup fuel bundles are positioned in the neighboring channels alternatively due to the opposite direction refueling scheme of neighboring channels, the FT reactivity would be negative to a certain extent of the low and high burnup combinations.

It could be concluded that the fuel temperature reactivity in the case of coolant voiding would not pose any additional concern to safety problems.

## 5. Acknowledgements

The author, D.H. Chung, wishes to express his appreciation to the authors of WIMS-ANL, and also to IAEA/NEA Data Bank for the use of WIMS-ANL.

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