HIGH TEMPERATURE PHYSICS EXPERIMENTS USING UO_2 AND SIMULATED IRRADIATED CANDU-TYPE FUEL IN THE ZED-2 REACTOR

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1. INTRODUCTION

Reactor-physics measurements can be performed using a mixed lattice with a central region containing test fuel of interest and an outer region containing reference fuel with known properties. The properties of the test fuel are studied by varying conditions in the test-fuel region and observing the resulting change in critical size of the mixed lattice. For example, the amount of test fuel can be varied and the resulting change in moderator critical height analyzed to determine the material buckling of a pure lattice of the test fuel [1]. If the measurement is repeated without the test-fuel coolant then the buckling change on coolant voiding (BCV) for the test-fuel lattice can also be determined.

A previous paper describes details of the method developed at Chalk River for analysing these "substitution experiments" and the validation of the method [2]. Briefly, the validation exercise involved the comparison of buckling data obtained using the conventional flux-map method and substitution-derived bucklings for a range of different fuel types. Substitution-derived bucklings, and particularly the BCV, can be compared directly to the predictions of computer cell codes.

Previous work described experiments performed in the ZED-2 reactor with channel temperatures up to 300°C to study the lattice properties for CANDU-type assemblies containing 37-element Fresh Natural Uranium (FNU) UO_2 fuel bundles [3]. The experiments have now been extended to include a mixed-oxide (MOX) fuel. The MOX contains plutonium and depleted uranium, and simulates mid burn-up CANDU fuel.

The MOX fuel, along with the FNU fuel, have now been compared in a series of side-by-side experiments in the ZED-2 reactor. This paper presents results comparing:

- room-temperature material buckling data for FNU and MOX fuel bundles in assemblies representing standard CANDU channels at two coolant conditions—D_2O coolant and air (void) coolant,
- high-temperature buckling data for FNU and MOX fuel, also at two coolant conditions, and
- predictions of the lattice-cell code WIMS-AECL to the experimental results.

2. ROOM-TEMPERATURE EXPERIMENTS

2.1 Experiment Description

The effect of fuel burn-up cannot be tested by measurements on irradiated fuel in ZED-2 because systems are not in place to permit the safe handling of highly radioactive bundles. Even if such systems were in place it would be questionable if the fuel composition could be well enough characterized to yield sufficiently high quality reactor-physics data for the purpose of code validation. Therefore, irradiated fuel was simulated by manufacturing a mixed-oxide (MOX) containing plutonium, depleted uranium and an absorber (dysprosium) to simulate the reactivity load due to fission product build-up.

WIMS-AECL burn-up calculations were used to derive the appropriate amounts of uranium and plutonium for the MOX test fuel as well as the amount of dysprosium required to simulate "fission-product" load [3]. Table 1 lists the properties of the MOX fuel bundles. The 37-element MOX bundles were fabricated at CRL specifically for the experimental program.

Figures 1-a and 1-b depict the test assemblies used for the room-temperature study. The seven test assemblies consisted of 35 bundles (five bundles per assembly) in Zr-2.5% Nb pressure tubes and Zircaloy-2 calandria tubes. The test assemblies have bottom openings that allow heavy water to enter the pressure tubes as moderator is pumped into the ZED-2 calandria. Plugs were inserted into the bottom openings of the assemblies for the air-coolant substitution experiments to isolate the test fuel from the moderator.

The substitution method involves setting up a reference lattice with fuel of known properties. The test fuel is then substituted into the lattice and the resulting changes in moderator critical height are used as input in a series of diffusion calculations to derive the material buckling for a uniform lattice of the test fuel [2].

Figure 2 depicts a typical substitution lattice. The seven central sites comprise the substitution region. These are surrounded with reference fuel and, if needed to achieve criticality, an outer ring of booster fuel. Figure 3 shows the standard sequence of substitutions into the lattice.

In all, six different reference fuels were used for the MOX substitution experiments. The various reference-fuel types are listed in Figure 4. Three of these six fuels were also used for the FNU substitution experiments. These three comprised the 28-element UO_2 fuel with D_2O and air coolant, and the low-buckling fuel with D_2O coolant.

2.2 Results

Figure 5 is a plot of critical-height data obtained from substituting MOX and FNU test assemblies into a reference lattice comprising 28-element UO_2 fuel in aluminum channels and cooled by D_2O. The critical height for zero substitution rods corresponds to the reference lattice measurement. Some information concerning the test fuel can be derived

immediately without resorting to a detailed analysis. For example, the substitutions that increase the critical height indicate that the test fuel is less reactive than the reference fuel. The substitutions with air-coolant yield critical heights that are lower than the substitutions with D_2O coolant, indicating a positive void reactivity for both the MOX and FNU. The MOX substitutions yield higher critical heights than the FNU substitutions, consistent with the MOX being less reactive than the FNU.

Two independent analyses were performed on the data obtained from the MOX and FNU experimental program. The Chalk River Laboratory (CRL) analysis made use of the substitution method validation data [2] to apply a calibration to the results of the MOX and FNU substitutions to correct for a systematic error that varied with the magnitude of buckling mismatch between the test and reference fuels. The uncertainty assessment was then based on the reproducibility error for the repeat MOX and FNU substitutions into the various reference lattices.

The other analysis also made use of the validation data but it employed a more rigorous substitution-data statistical model that combined the validation data, along with the MOX and FNU substitution data, in the same model.

The results of the two analyses are listed in Table 2. Also listed are k-effective values calculated using the lattice code WIMS-AECL. The results of both analyses are found to be in good agreement for the derived buckling values, BCV values, and uncertainty assessments.

The MOX fuel buckling with D_2O coolant is approximately one-quarter the buckling of the FNU. This is due to the reduced gross-fissile content in the MOX and the dysprosium poison.

The MOX has a larger BCV (i.e. coolant void reactivity (CVR)) than the FNU. The major components of CVR are decreased resonance capture in U^{238} when the channels are voided (positive component) and neutron leakage (negative component). The absence of coolant results in a decrease in the resonance flux inside the channels. Both the MOX and the FNU contain about the same amount of U^{238} so this component to CVR is common to both fuel types. However, the smaller MOX buckling (i.e., larger critical-lattice size) relative to FNU results in a smaller negative contribution to CVR for the MOX. The CVR for room-temperature MOX has been calculated to be about 9 mk larger in magnitude than for FNU because of the smaller MOX buckling.

The WIMS-AECL calculations imply an over-prediction of BCV by the code for both fuel types. The Chalk River analysis implies over predictions of about 1.7 and 1.9 mk for the MOX and FNU, respectively. The other analysis implies over-predictions of 1.3 and 1.9 mk for the MOX and FNU, respectively. In all cases the over-predictions are significant relative to the assigned BCV uncertainties.

3. HIGH-TEMPERATURE EXPERIMENTS

The main physics processes that impact lattice reactivity as channel temperatures increase are decreased D_2O coolant density, decreased fissions in U^{235}, and Doppler Broadening of the resonance absorber nuclides within the fuel. In CANDU this broadening involves the U^{238} isotope and the various plutonium nuclides. The rates of neutron absorption in plutonium nuclides and in the U^{235} isotope are also affected by neutron upscattering from oxygen in the fuel as the fuel temperature changes.

3.1 Experiment Description

The heating of the channel contents was achieved using specially designed fuel channels. These channels are capable of operating at power-reactor coolant conditions (300°C, 10 MPa).

Figures 1-c and 1-d depict the test assemblies used for the high-temperature study. The temperature of the channel contents was raised and maintained by the use of small high-power electrical heaters located under the test-fuel strings. Natural convection distributed the heat throughout the channels. A pressurized helium cover gas was used to suppress boiling with D_2O coolant in the channels. Pressurized CO_2 gas was the convective medium for the voided measurements.

The results listed below were obtained using 7-rod substitution lattices with the reference fuel comprising 28-element UO_2 bundles in aluminum channels and with D_2O coolant.

3.2 Results

Figures 6 and 7 are plots of critical height vs. channel temperature obtained for the FNU and MOX fuels, respectively. Again, information concerning the test fuels can be derived immediately without resorting to a detailed substitution analysis. The critical heights obtained with FNU in the channels (Figure 6) increase with temperature for both coolant conditions.

With D_2O coolant the heights increase smoothly with temperature up to about 250°C before flattening out. Above 250°C the water density begins to decrease almost exponentially. The positive CVR is responsible for the critical-height curve beginning to turn around.

With CO_2 coolant there is minimal coolant-density effect and these data are a direct measure of the fuel-temperature reactivity effect. The heights increase approximately linearly with temperature between room temperature and 300°C.

The two FNU critical-height curves imply that the reactivity worth of the fuel decreases with temperature for both coolant conditions. However, the D_2O-coolant curve increases more rapidly than the CO_2-coolant curve, implying that the CVR for FNU increases with channel temperature.

The MOX data (Figure 7) are significantly different.

With D_2O coolant the height rises very slowly initially and then begins decreasing smoothly with temperature up to 300°C. This implies that the reactivity worth of the D_2O-cooled MOX increases with channel temperature.

The CO_2-coolant MOX curve increases linearly with temperature, although not as rapidly as the FNU curve. The implication is that the MOX fuel-temperature reactivity coefficient is also negative, but smaller in magnitude than the FNU coefficient.

The convergence of the two MOX curves as the temperature increases clearly indicates that the MOX CVR decreases with channel temperature.

For comparing WIMS-AECL predictions of lattice reactivity and the change in BCV to the experimental values it is useful to look at the change in these parameters with channel temperature from the start of the experiment (25°C) to the end of the experiment (300°C).

The buckling results derived from the substitution analysis are plotted in Figure 8. In terms of changes from the room-temperature value WIMS-AECL predictions are also included. Figure 9 compares the change in BCV with temperature for the two fuel types to WIMS-AECL predictions.

These comparisons show that there is good general agreement on trends between calculation and experiment. The assessment of the experimental uncertainties is the subject of an ongoing study.

4. ACKNOWLEDGMENT

This work was funded by the CANDU Owners Group (COG).

5. REFERENCES

[1] M.B. Zeller, A. Celli, G.P. McPhee, and R.S. Davis, "Void-Reactivity Measurements in the ZED-2 Reactor using the Substitution Method", 15th Annual CNS Conference, Montreal PQ, 1994.

[2] R.S. Davis, A. Celli, S.R. Douglas, R.T. Jones, D.C. McElroy, and M.B. Zeller, "Validation of the Substitution Method for Measurement of Void Reactivity", 21st Annual CNS Conference, Toronto ON, 2000.

[3] A. Celli, R.S. Davis, S.R. Douglas, R.T. Jones, G.P. McPhee, and M.B. Zeller, "The Coolant Void Reactivity Program in ZED-2", 21st Annual CNS Conference, Toronto ON, 2000.

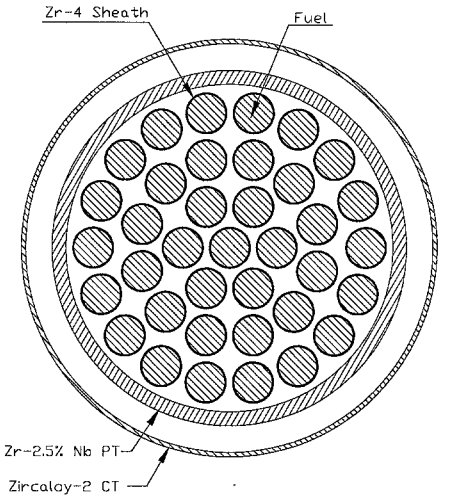
Table 1 - Properties of the MOX fuel

MOX Fuel

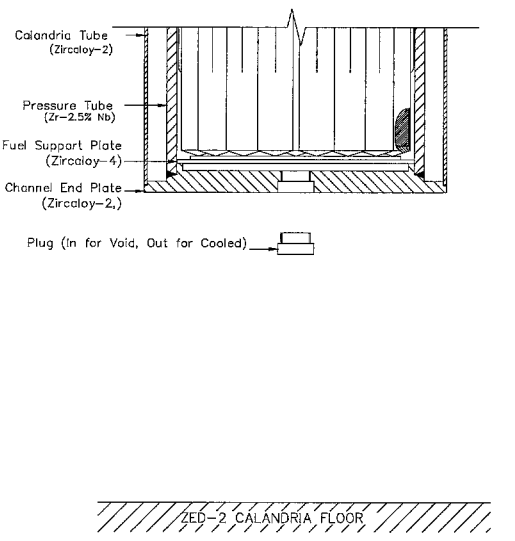
- 37-Element Bundle Geometry
- 0.37 wt% U-235 in U
- 0.3 wt% Pu in Heavy Element (75% Fissile)
- 0.05 wt% Dy in Heavy Element

Table 2 - BCV room-temperature results for MOX and FNU in CANDU-type channels

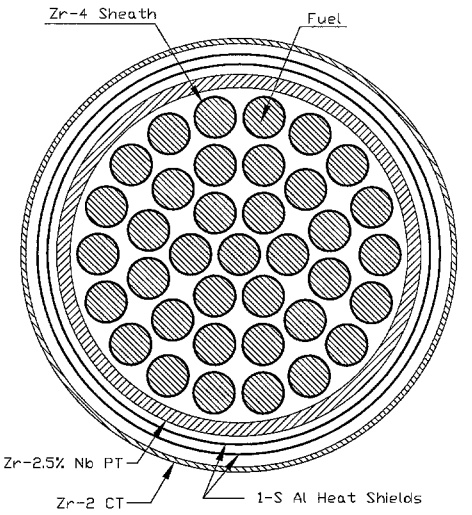
Fuel	**MOX**		**FNU**	
Condition	**Buckling (m^{-2})**	**WIMS-AECL k-effective**	**Buckling (m^{-2})**	**WIMS-AECL k-effective**
Voided (CRL Analysis)	1.483 ± 0.053	0.99262 ± 0.00172	4.074 ± 0.120	0.99866 ± 0.00387
Voided (Other Analysis)	1.470 ± 0.053	0.99305 ± 0.00172	4.083 ± 0.036	0.99835 ± 0.00116
Cooled (CRL Analysis)	0.933 ± 0.046	0.99094 ± 0.00149	3.778 ± 0.102	0.99677 ± 0.00329
Cooled (Other Analysis)	0.907 ± 0.053	0.99176 ± 0.00172	3.788 ± 0.036	0.99645 ± 0.00116
Difference (CRL Analysis)	0.550 ± 0.023	0.00168 ± 0.00075	0.296 ± 0.020	0.00189 ± 0.00064
Difference (Other Analysis)	0.563 ± 0.024	0.00129 ± 0.00078	0.295 ± 0.014	0.00190 ± 0.00045



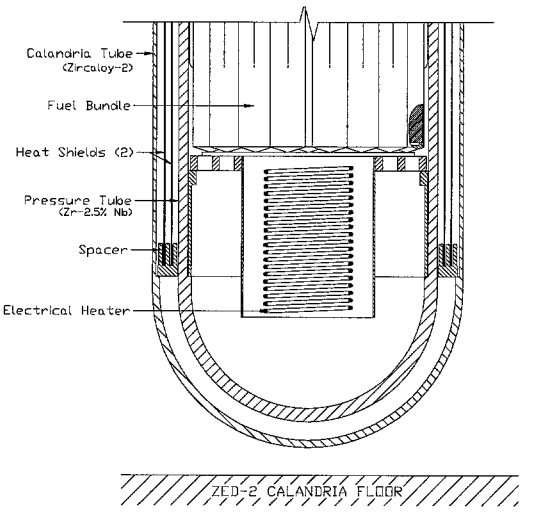
1-a
CANDU-Type Channel – Plan View



1-b
CANDU-Type Channel – Bottom Section



1-c
Hot Channel – Plan View



1-d
Hot Channel – Bottom Section

Figure 1 – Description of the test assemblies used for the room-temperature measurements (top) and high-temperature measurements (bottom)

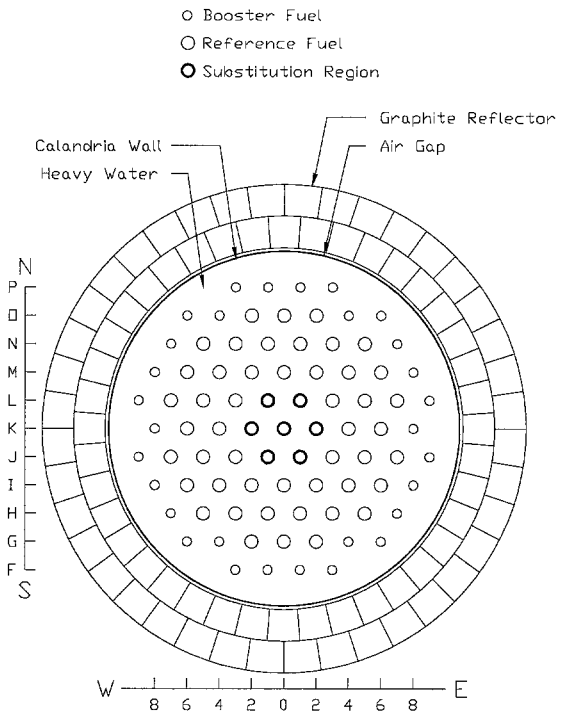


Figure 2 – Typical set-up for a substitution experiment in ZED-2

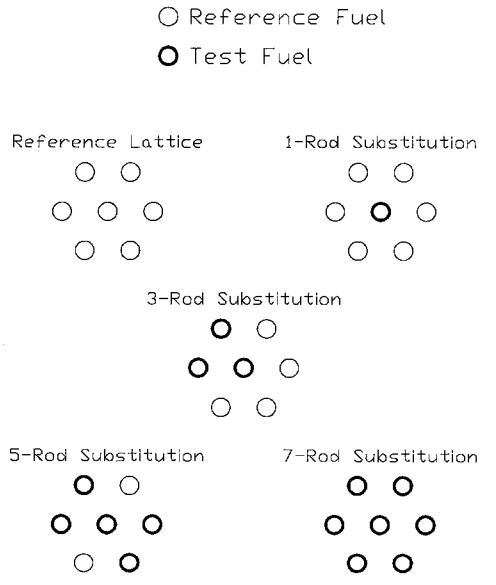


Figure 3 – Arrangement of fuel in the substitution region

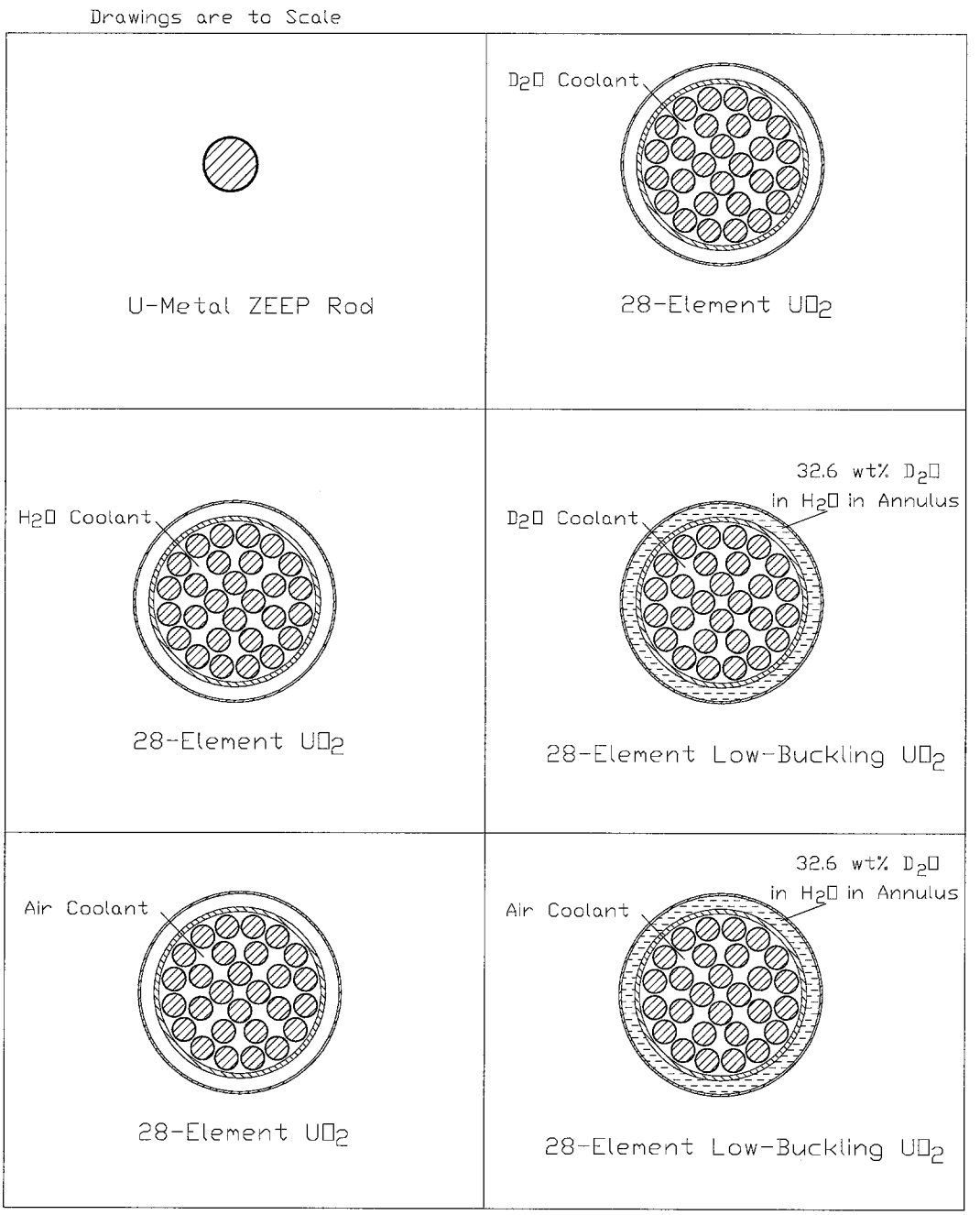


Figure 4 – Reference fuel types used for the
room-temperature substitution measurements

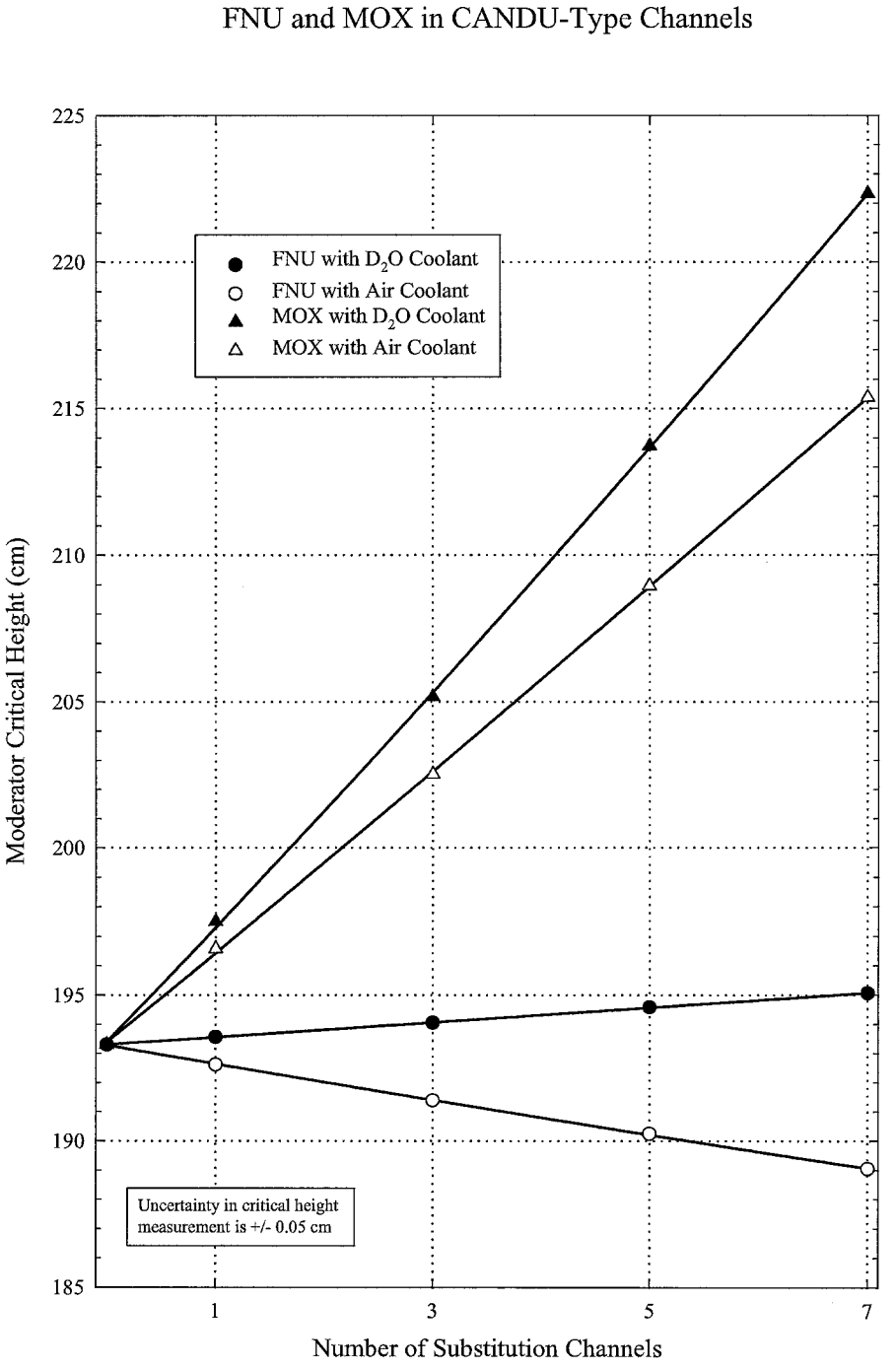


Figure 5 – Comparison of critical-height data obtained from FNU and MOX substitutions

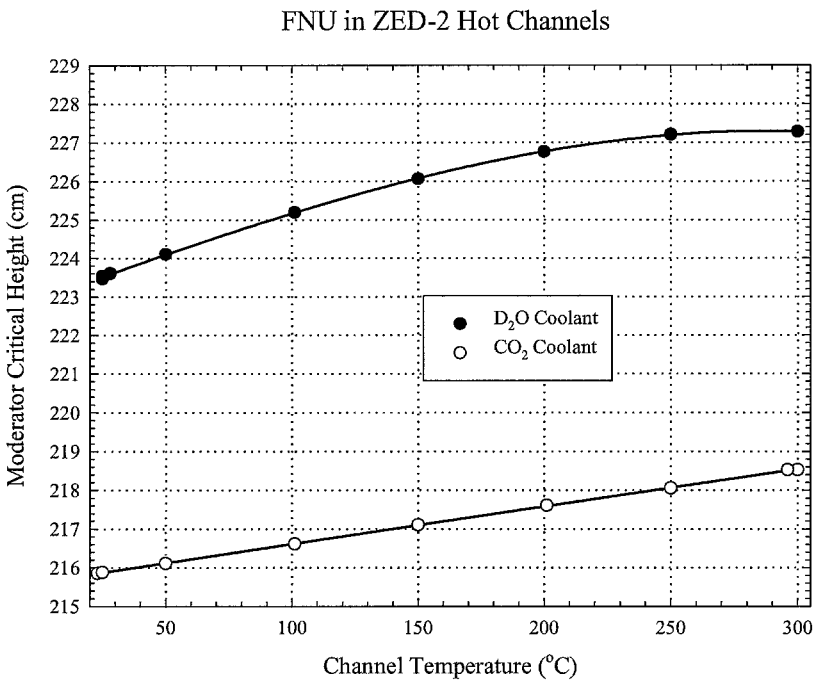


Figure 6 – Critical height data from high-temperature experiments using FNU

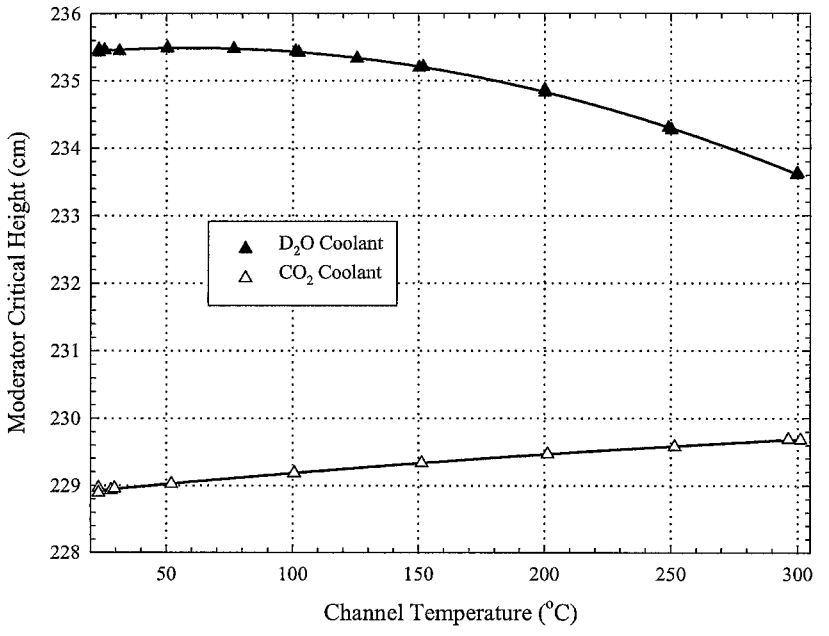


Figure 7 - Critical height data from high-temperature experiments using MOX

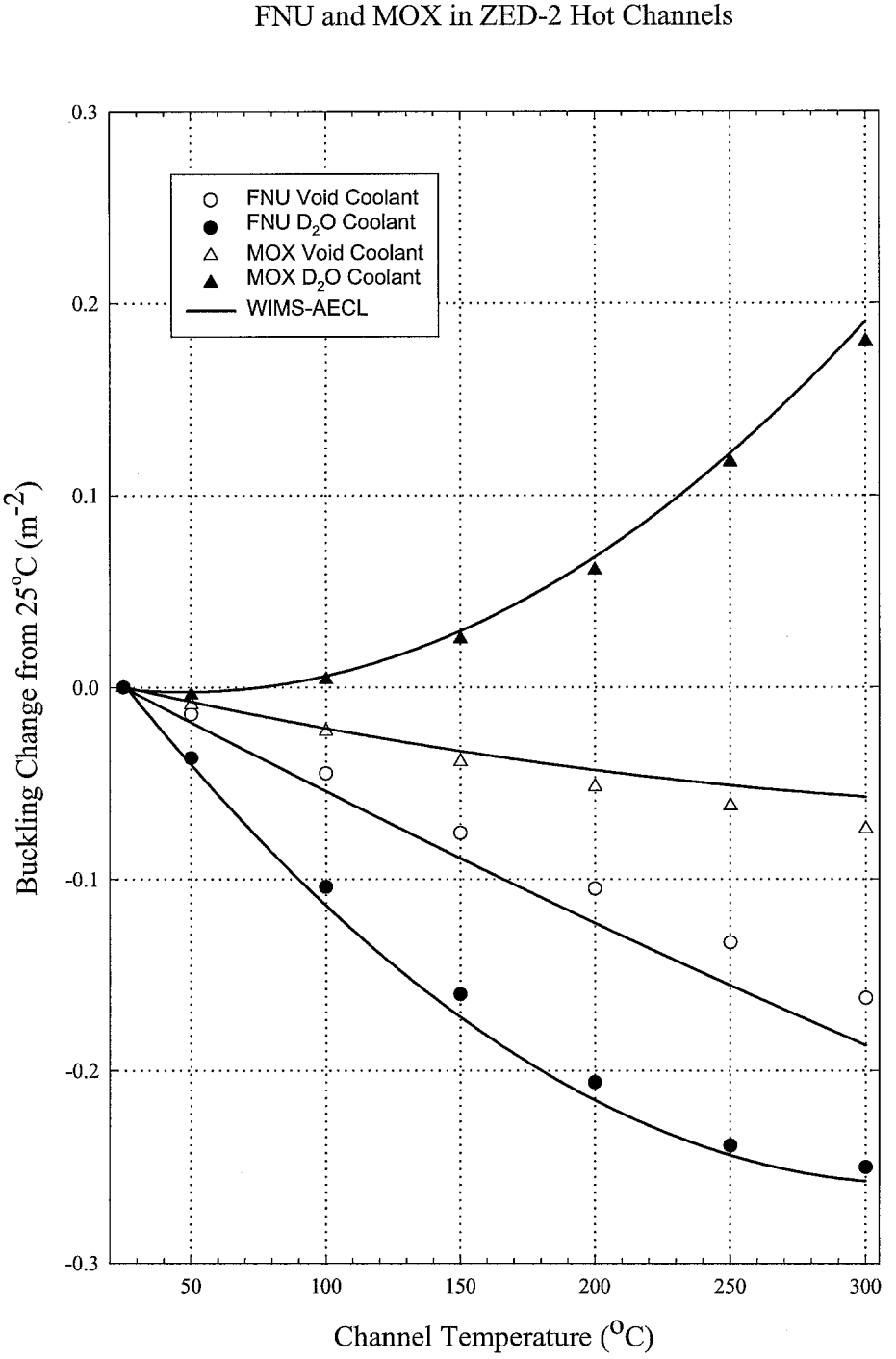


Figure 8 - Comparison of WIMS-AECL predictions to channel-temperature reactivity results

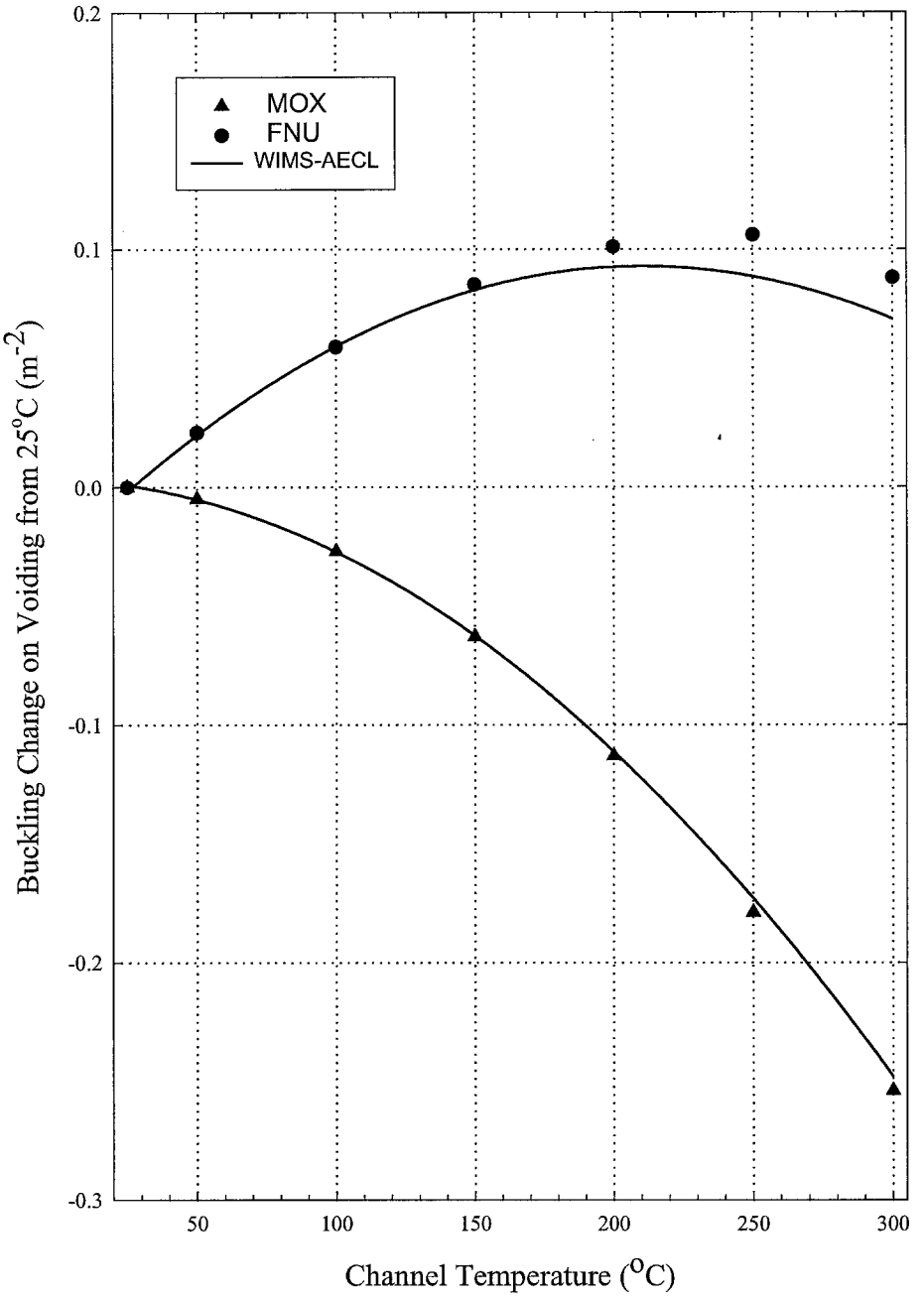


Figure 9 – Comparison of WIMS-AECL predictions to high-temperature BCV results