Effect of Downgraded Moderator Purity on Lattice Reactivity and Coolant Void Reactivity for a LEU Lattice in the ZED-2 Reactor

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Abstract

ZED-2 measurements have been compiled that were obtained using a lattice comprising Low Enriched Uranium (LEU) fuel assemblies. The data are to determine the effect of downgraded moderator purity on lattice reactivity and Coolant Void Reactivity (CVR). These data span moderator purities ranging from 99.882 to 98.519 weight % D_2O. Since the assemblies contain LEU fuel, the measurements did not require making any changes to the lattice configuration over the range of purities studied. These data therefore provide unique applicability to address the reactor physics phenomenon Moderator-Purity-Change Induced Reactivity (MPCIR) and its impact on Coolant Void Reactivity (CVR).

An analysis was performed using the Monte Carlo code MCNP5 (v1.40) employing nuclear data derived from the ENDF/B-VII.0 evaluation. Reactivity coefficients are determined and compared to code predictions. The comparison indicates that there are suspected errors in the nuclear-data library regarding the cross sections for hydrogen in heavy water.

1. Introduction

In 2005 the Advanced CANDU®* Fuel Development Laboratory (ACFDL) at Chalk River fabricated 316 fuel bundles containing low enriched uranium (LEU) fuel for physics experiments in ZED-2. The majority of these bundles (243) contain uniform-enrichment LEU oxide pellets that are loaded into 43-element CANFLEX®‡ bundles; the LEU enrichment is 0.95 wt% U^{235} in U. These bundles are referred to in this paper as CANFLEX-LEU.

Another 37 bundles were fabricated that contain uniform-enrichment recovered uranium (RU). The RU was derived from spent light water reactor (LWR) fuel. The enrichment of this fuel is 0.96 wt% U^{235} in U. The RU also contains increased U^{234} content and some U^{236}; therefore, it is very similar to the LEU fuel in terms of lattice reactivity. The bundle geometry is the same as the CANFLEX-LEU bundle and these are referred to in this paper as CANFLEX-RU.

Historically, ZED-2 lattices have comprised assemblies containing natural uranium (NU) fuel [1], [2]. Experimental programs to study more advanced fuel cycles (e.g. uranium-thorium [3], plutonium-thorium [4], plutonium-uranium [5], etc.) have employed substitution

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experiments where a limited amount of the NU reference fuel is replaced by the test fuel of interest.

The main physics effect of replacing NU with LEU fuel in a ZED-2 lattice is to increase the reactivity worth of the lattice (i.e., increase k-infinity). The optimum moderator-to-fuel ratio is also affected and it is possible to achieve criticality using a significantly reduced moderator isotopic purity.

The standard ZED-2 reference lattice since 2005 has comprised CANFLEX-LEU assemblies. Multiple measurements have been performed using these assemblies over a range of moderator purities between 99.882 and 98.519 wt% D_2O. Since the assemblies contain LEU fuel, the measurements did not require any changes to the lattice configuration over this range of purities. The data therefore provide unique applicability to address the reactor physics phenomenon Moderator-Purity-Change-Induced Reactivity (MPCIR) and its impact on Coolant Void Reactivity (CVR).

This paper presents the experimental data (moderator critical heights and core conditions) and includes an analysis of these data using the Monte Carlo N-Particle (MCNP) code employing a nuclear data library derived from the ENDF/B-VII.0 evaluation. K-effective values were calculated for a range of moderator conditions and the analysis has yielded experimental data for MPCIR and CVR.

The reactivity data are compared to MCNP predictions. The measurements and analysis provide a good test for the sensitivity of the nuclear data library to reactivity calculations involving small changes in hydrogen isotopics in the moderator.

2. ZED-2 Reactor

The ZED-2 calandria vessel, as shown in Figure 1, is a cylindrical tank with a sidewall thickness of 0.64 cm and a bottom thickness of 2.7 cm. The calandria has a 3.36-m diameter and 3.30-m depth. It is surrounded by graphite blocks arranged with an average thickness of 60 cm radially and 90 cm below the tank. Fuel assemblies are hung vertically from beams located above the calandria.

The reactor is made critical by pumping heavy water moderator into the calandria and power is controlled by adjusting the moderator level. Typical moderator critical levels range between 120 and 250 cm above the reactor floor. The maximum power is 200 watts (nominal), corresponding to an average neutron flux of about 10^9 n cm^{-2} s^{-1}.

3. Experimental Lattice

3.1 CANFLEX-LEU Assemblies

Figure 2 shows a plan view of a CANFLEX-LEU bundle inside a test assembly and Figure 3 shows an assembly side view. LEU pellets are sheathed in Zircaloy-4 to form elements that are assembled into 43-element bundles. Note that the bundle has no appendages (i.e., buttons, bearing pads or spacers) attached to the fuel elements.

3.2 Lattice Configuration

The lattice used for the measurements is shown in Figure 4. It comprises 52 fuel assemblies, each containing 5 CANFLEX-LEU bundles. The assemblies are arranged in an open-centred square array at a 24.0-cm spacing. Four of the fuel assemblies contain CANFLEX-RU bundles and these assemblies occupy corner positions in the outermost region of the lattice.

4. Results

4.1 Experimental data

Moderator critical levels and core conditions are listed in Table 1. As discussed in the introduction, the large reactivity worth of the LEU lattice (relative to NU lattices) allows for the ability to achieve criticality without having to change the lattice configuration over the large range of moderator purities and two coolant conditions listed in the table.

Figure 5 is a plot of the moderator critical levels against moderator purity.

4.2 MCNP Calculations

Calculated k-effective values are also listed in Table 1. The calculations employed MCNP [6] using a multi-temperature, continuous energy neutron cross-section library of nuclear data created at CRL [7] and derived from the ENDF/B VII.0 evaluation [8]. The moderator critical levels plus core conditions (listed in Table 1), and the reactor description in sections 2 and 3 define the input for the calculations.

The model used for the analysis is similar to that described in reference [9] and this model is routinely used for the safety analyses required for preparing the ZED-2 proposals for reactor operation. K-effective calculations (using the MCNP KCODE option) were conducted with each simulation set to run with 100 000 neutrons per cycle (i.e., per neutron generation) for a total of 1200 cycles. The first 200 cycles were used for source convergence, giving rise to 100 million neutron histories per run. The above k-code parameters produced a statistical uncertainty in k-effective of ± 0.00005 (i.e., ± 50 micro-k).

Reproducibility for repeat measurements on the same lattice is estimated to be ± 0.0003 (i.e., ± 300 micro-k). This estimate incorporates the uncertainties of the moderator hydrogen isotopics (± 0.005 weight % D_2O) and the moderator levels (± 2 mm absolute).

Additional calculations were performed to determine the MCNP prediction of changes in k-infinity with moderator purity. Calculations were performed using 0.4 weight % D_2O increments in the range between 98.4 and 100 wt% D_2O. The k-infinity values are listed in Table 2 and Table 3.

4.3 Analysis

4.3.1 Preliminary Comments

Reactivity, ρ, is defined as follows:

$$\rho = k_{initial}^{-1} - k_{final}^{-1}, \tag{1}$$

where k_{inital} and k_{final} refer to the k-effective (or k-infinity) values associated with the initial and final states of the system, respectively. For a reactivity calculation where the system is initially critical:

$$\rho = 1 - k_{final}^{-1}. \tag{2}$$

Ideally a reactor calculation for a critical system will yield a k-effective value equal to unity; in practice the calculation yields a k-effective value that differs from unity. This difference is referred to as the calculation bias. The bias may be due to errors in the reactor model, (e.g., errors in materials, geometry, experimental conditions, etc.), errors in the neutron distribution used for the calculation (e.g., leakage error), or errors in the nuclear data library used for the calculation.

A standard method [10], [11] used to correct for calculation bias is to renormalize k-infinity using the k-effective value obtained by modelling the critical system. With this renormalization, the bias-corrected calculation is forced to achieve neutron balance.

4.3.2 MPCIR Analysis

The k-effective values listed in Table 1 are plotted against moderator purity in Figure 6. The data are fitted assuming (flat-weighting) linear fitting functions. The expressions describing the fitted curves are included in the figure.

These fitted curves are used to derive k-effective values that, in turn, are used to renormalize the k-infinity values listed in Table 2 and Table 3. The renormalized k-infinity values are labelled as “k-infinity (with bias correction)” in the tables.

The k-infinity values are used to derive the MPCIR values and these are also listed in Table 2 and Table 3. The MPCIR values are plotted against moderator purity in Figure 7. The curves indicate that the MCNP calculations (without bias correction) over predict the reactivity effect of downgrading the moderator to 98.5 wt % D_2O by just under 1 milli-k for both coolants.

4.3.3 CVR Analysis

MCNP was used to calculate CVR versus moderator purity for the lattice. The calculations assumed the core conditions listed in Table 1 for the light-water coolant measurements (i.e., moderator purities and critical levels). K-effective values were calculated for air-cooled assemblies assuming these same conditions.

The CVR values are listed in Table 4. K-effective values listed under the heading "$k_{initial}$" correspond to light-water coolant and values under the heading "k_{final}" correspond to air coolant. For the values listed under the heading "no bias correction" Equation (1) was used to derive the CVR values. For the values listed under the heading "with bias correction" the $k_{initial}$ values are all unity (because the reactor is known to be critical). The k_{final} values are renormalized using the top fitted curve in Figure 6 to calculate k-effective values to make the bias corrections. Equation (2) is then used to derive the CVR values.

The CVR values, with and without bias correction, are plotted against moderator purity in Figure 8. The two curves indicate that there is a systematic CVR bias of about 3 milli-k over the moderator purity range shown in the figure.

5. Discussion

As discussed in Section 4.3.1 calculation bias can be due to the following:

- Errors in the reactor model (e.g. materials, geometry, experimental conditions, etc.),
- Error in the neutron distribution assumed for the calculation (e.g., leakage error),
- Errors in the nuclear data library used for the calculation.

One concludes that the first two possibilities listed above do not explain MPCIR analysis results from this study. The argument for this conclusion is as follows.

The reactor components and lattice configuration are common to all measurements in this paper. The only things that varied were the moderator condition (i.e., isotopic purity and temperature), coolant (light water and air coolant) and the moderator critical level. While there were small variations in the moderator temperature, the temperature variation was random and was accounted for in the analysis. One concludes that the observed change in MPCIR bias with moderator purity is not due to errors in the reactor model.

However, model error could account for most of the 3 milli-k CVR bias. For the light-water coolant analysis, the absolute k-effective calculations are sensitive to the volume of light water assumed in the model. The air-coolant k-effective values are insensitive to the coolant volume. Sensitivity calculations indicate that a small reduction in the coolant-tube inner diameter assumed in the model would significantly decrease the CVR bias.

Numerous analyses [10], [11], [12], have been performed that compare MCNP calculations to foil activation measurements in ZED-2. These studies have concluded that as long as a sufficient number of cycles are used to define the initial neutron distribution for the reactor calculation, the MCNP model successfully calculates neutron distributions in ZED-2.

Measurements have been performed [13] to determine the ability of MCNP to calculate reactivity changes due to changes in neutron leakage in ZED-2. This was achieved by operating the reactor at constant power and then varying the moderator level to make the reactor subcritical or super-critical. The resulting transients were analysed using inverse point kinetics to determine reactivity values for the non-critical states. MCNP calculations were then compared to the measured reactivity values. The conclusion of that study was that there are no serious errors in the MCNP model regarding calculation of neutron leakage in ZED-2.

The MPCIR analysis and the CVR analysis in this study are both consistent with there being errors in the hydrogen cross-section data used in the analysis. When the moderator downgrades, the major change in core conditions is the increase in hydrogen abundance in the moderator. Similarly, when light water replaces air coolant in the channels there is a significant increase in the hydrogen content in the channel coolant.

Additional analyses should be performed on these data using nuclear data libraries derived from other evaluations to determine if the suspected errors in the hydrogen absorption and/or scattering cross sections can be identified.

6. References

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Table 1 Reactor core conditions and MCNP k-effective calculations

Moderator Purity (weight % D_2O)	Moderator Temperature (^oC)	Coolant	Moderator Critical Level (cm)	MCNP k-effective value
98.519	23.4	Air	135.859	0.99492
98.610	25.9		135.229	0.99530
98.668	25.8		134.460	0.99510
98.772	22.9		133.320	0.99556
99.054	20.9		129.973	0.99524
99.477	25.0		126.174	0.99560
99.882	22.8		122.485	0.99584
98.531	23.9	H_2O	208.938	0.99228
98.610	25.9		204.876	0.99264
98.668	25.9		200.942	0.99240
98.868	24.3		191.852	0.99291
99.476	24.0		168.727	0.99312
99.873	22.2		156.896	0.99303

Note: Uncertainties on k-effective are estimated to be ± 0.3 milli-k

Table 2 - MCNP MPCIR calculations with and without bias correction—light water coolant

Moderator Purity (weight % D_2O)	Moderator Temperature (°C)	MCNP k-infinity (no bias correction)			MCNP k-infinity (with bias correction)		
		$k_{initial}$	k_{final}	MPCIR (milli-k)	$k_{initial}$	k_{final}	MPCIR (milli-k)
100.00	25.0	1.13261	1.13261	0.0	1.14031	1.14031	0.0
99.60			1.12333	-7.3		1.13120	-7.1
99.20			1.11401	-14.7		1.12205	-14.3
98.80			1.10472	-22.3		1.11293	-21.6
98.40			1.09549	-29.9		1.10386	-29.0

Note: MPCIR calculations are relative to 100 wt% D_2O

Table 3 - MCNP MPCIR calculations with and without bias correction—air coolant

Moderator Purity (weight % D_2O)	Moderator Temperature (°C)	MCNP k-infinity (no bias correction)			MCNP k-infinity (with bias correction)		
		$k_{initial}$	k_{final}	MPCIR (milli-k)	$k_{initial}$	k_{final}	MPCIR (milli-k)
100.00	25.0	1.23064	1.23064	0.0	1.23572	1.23572	0.0
99.60			1.22275	-5.2		1.22806	-5.1
99.20			1.21490	-10.5		1.22043	-10.1
98.80			1.20672	-16.1		1.21246	-15.5
98.40			1.19846	-21.8		1.20442	-21.0

Note: MPCIR calculations are relative to 100 wt% D_2O

Table 4 - MCNP CVR calculations with and without bias correction

Moderator Purity (weight % D_2O)	Moderator Level (cm)	MCNP k-effective (no bias correction)			MCNP k-effective (with bias correction)		
		$k_{initial}$	k_{final}	CVR (milli-k)	$k_{initial}$	k_{final}	CVR (milli-k)
98.531	208.938	0.99228	1.05839	62.9	1.00000	1.06365	59.8
98.610	204.876	0.99264	1.05794	62.2		1.06316	59.4
98.668	200.942	0.99240	1.05697	61.5		1.06215	58.5
98.868	191.852	0.99291	1.05580	60.1		1.06085	57.4
99.476	168.727	0.99312	1.05163	56.0		1.05631	53.3
99.873	156.896	0.99303	1.04852	53.3		1.05296	50.3

Note: $k_{initial}$ corresponds to light water coolant and k_{fina1} corresponds to air coolant

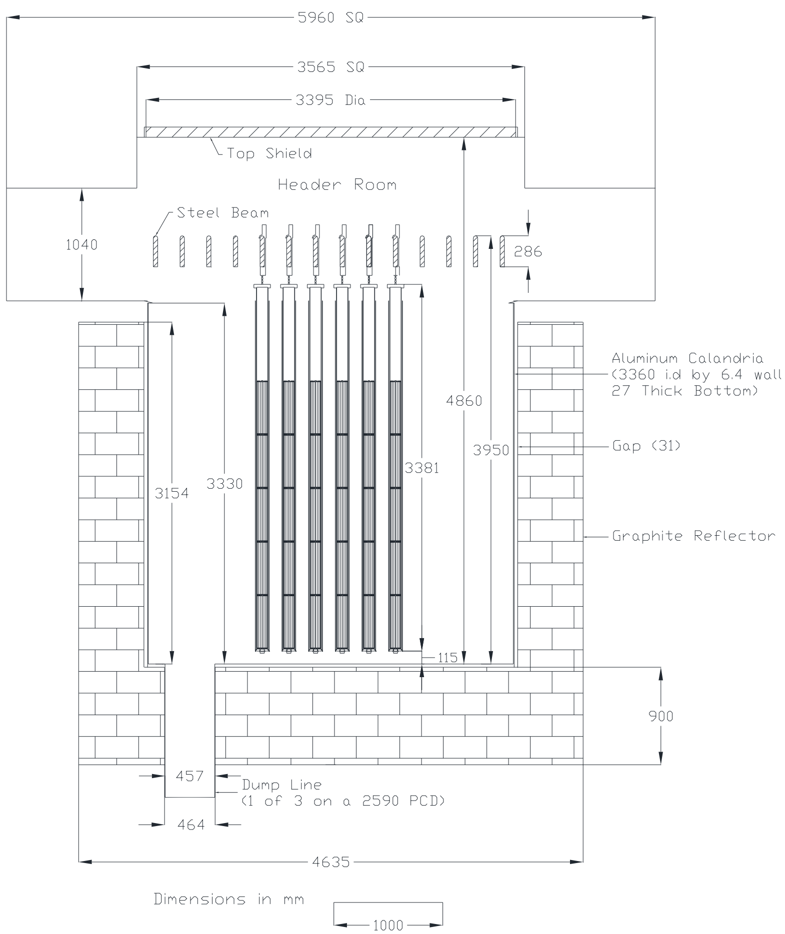

Figure 1 ZED-2 cross section

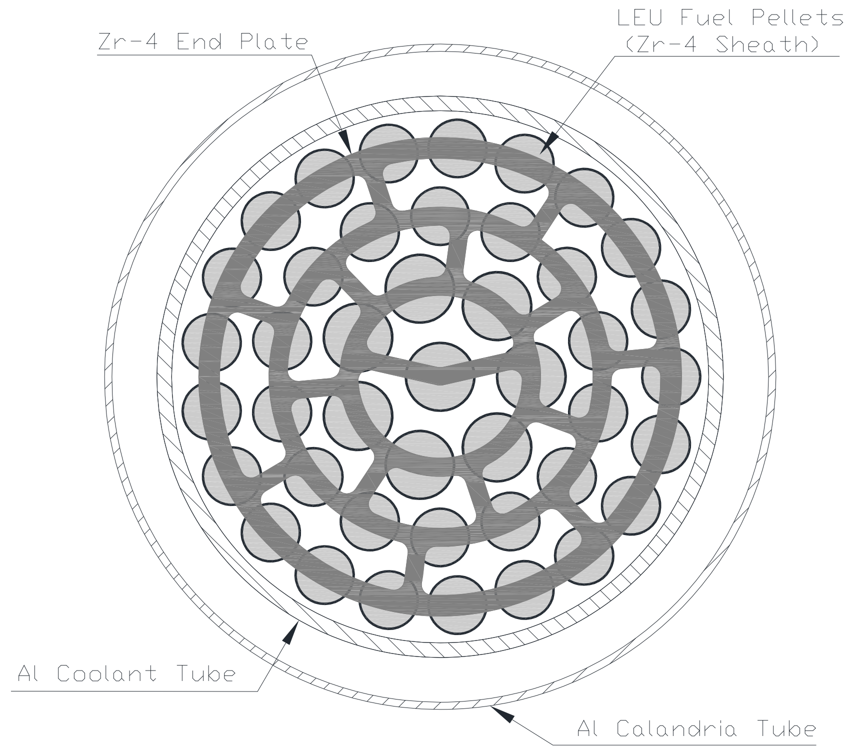

Figure 2 Channel plan view with CANFLEX-LEU bundle

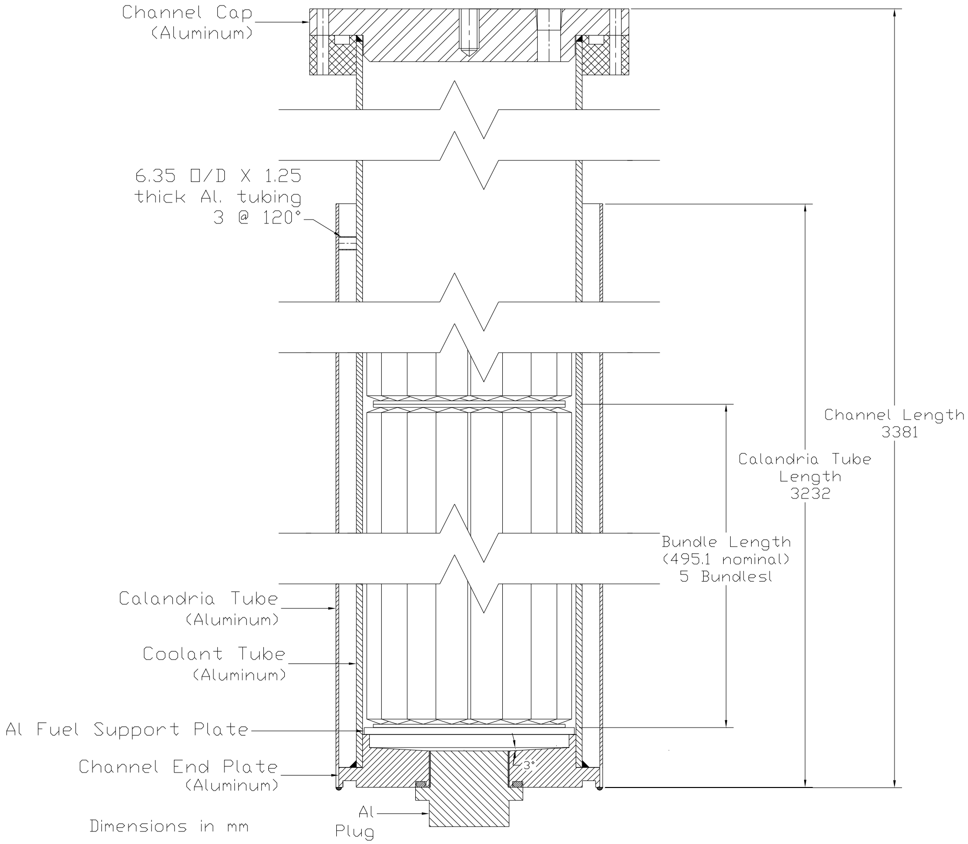

Figure 3 Channel cross section

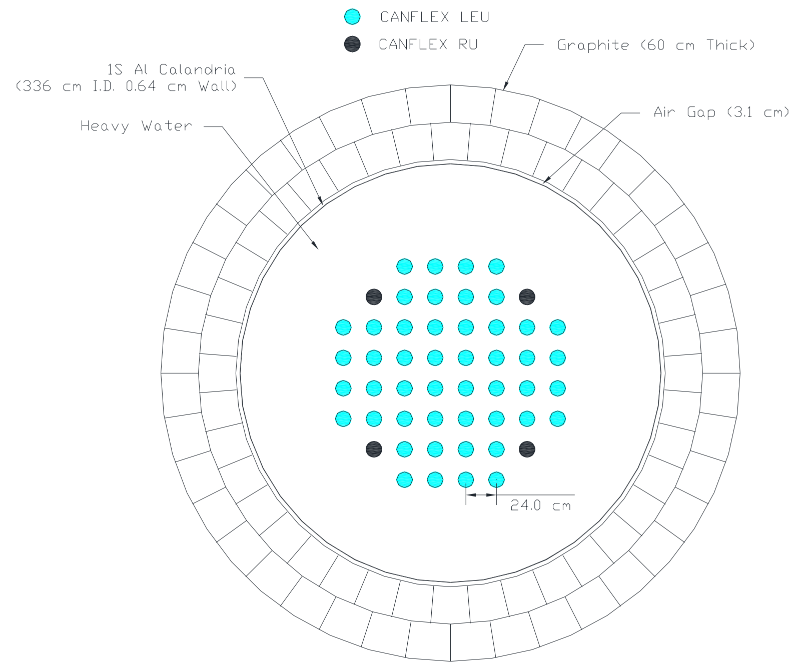

Figure 4 ZED-2 lattice

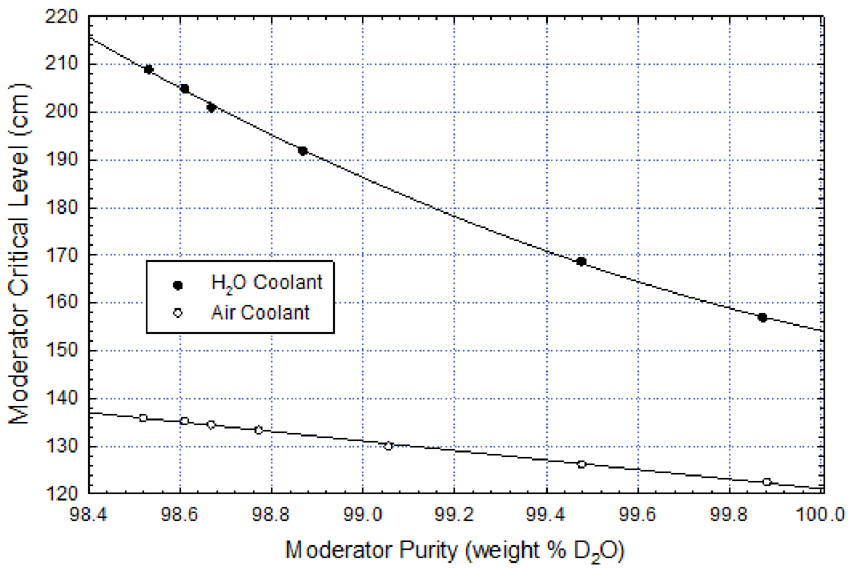

Figure 5 Moderator critical level versus moderator purity

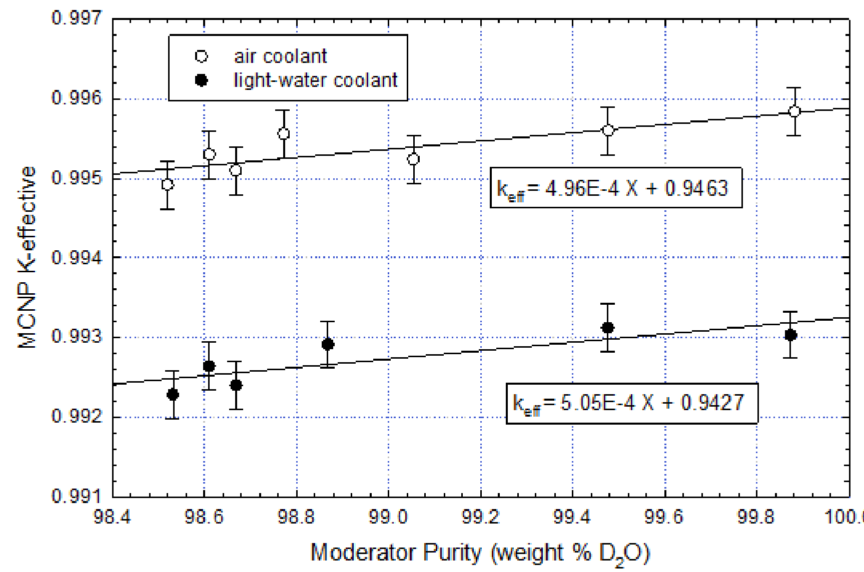

Figure 6 MCNP calculated k-effective values

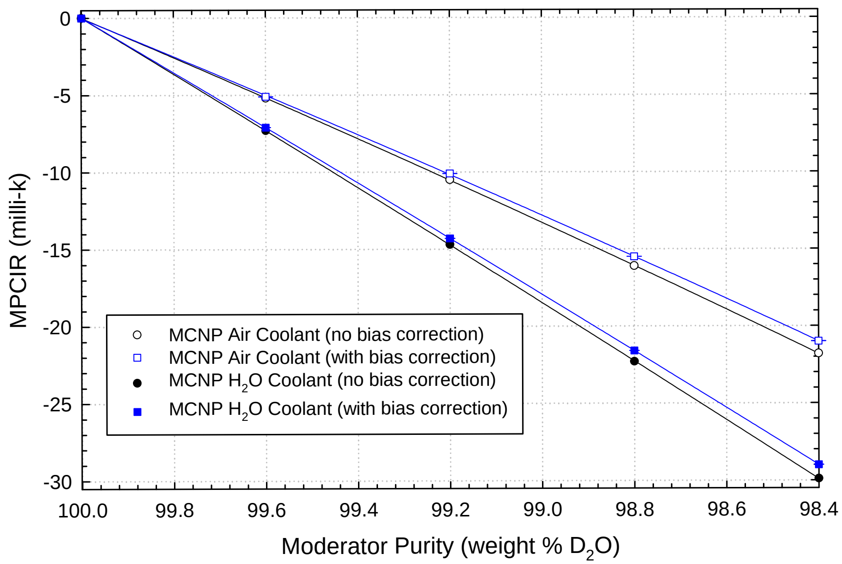

Figure 7 Moderator purity change induced reactivity

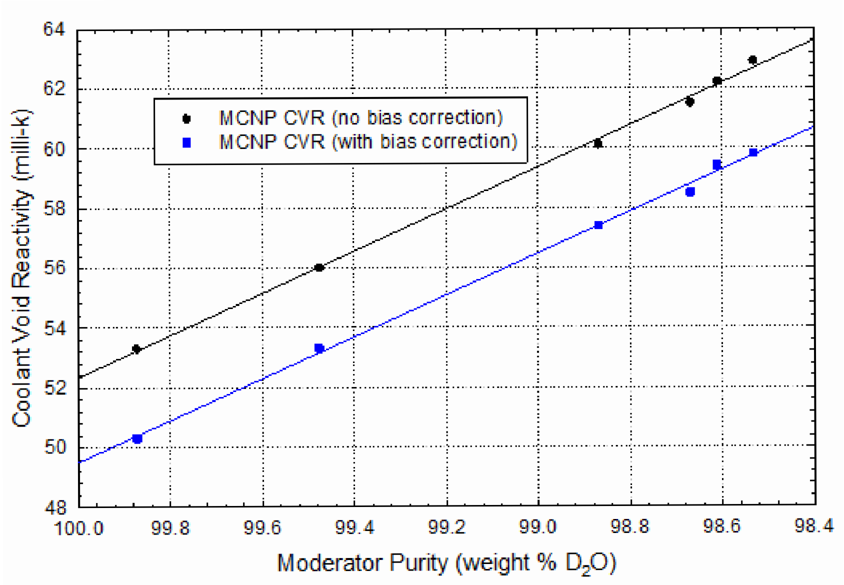

Figure 8 CVR versus moderator purity