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VALIDATION OF THE SUBSTITUTION METHOD FOR MEASUREMENT OF VOID REACTIVITY

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1. PURPOSE

The ultimate purpose behind the present work is to enable a cell code to calculate the effect of loss of coolant in a typical CANDU® lattice credibly; i.e. with confirmed validity. This can only follow from comparison of calculation with experiment. To the extent that a pattern appears in the difference, a correction may be derived from it, to enhance the accuracy of the calculation. The remaining difference becomes an error estimate, which is essential for credibility. The right-most column of Figure 1 expresses these purposes.

The central column of Figure 1 shows the validation of the cell code. Section 2 of this paper describes two methods that could in principle provide the necessary data, flux mapping and substitution. Flux mapping is the more direct method, but it is not practicable for most of the data that are needed [1].

Because the substitution method is less direct, it must itself be validated by comparison with flux mapping, and a correction follows. The left-most column of Figure 1 shows this validation. It is the primary topic of this paper.

Section 3 describes the experiments that make up a substitution measurement, and section 4 describes the analysis of them. Section 5 describes how the set of lattices, denoted "Many Lattices" in Figure 1, has been chosen to yield a thorough validation of the substitution method. Section 6 describes the results of that validation. The derivation of the correction and error estimate that follow from the validation is still in progress, but the available results show the form that the correction will take, and an upper bound on the remaining error.

2. FLUX-MAP AND SUBSTITUTION METHODS

The data required are material bucklings for a pure, critical lattice of test fuel with and without water coolant in the fuel. Bucklings are the only data that can pass into the right-most column of Figure 1 meaningfully, because other measures of reactivity have meanings that differ among cell codes, and among the options available in each.

The direct way to measure material buckling is by flux mapping. This can be done with a critical lattice, within which the test lattice occupies a cylindrical space free of other materials. The flux is measured at a number of points, i.e. "mapped", and the results are fitted, as functions of position, to the theoretical result

$$A\ J_0\left(b_r r\right)\cos\left(b_z\left(z - z_0\right)\right), \tag{1}$$

in which r and z are the conventional cylindrical coordinates, and A, b_r, b_z, and z_0 are varied to achieve the fit. b_r^2 and b_z^2 are the radial and axial bucklings.

To yield accurate bucklings, the fitted measurements must be distributed over a sufficiently large region within the test fuel, several lattice pitches in each direction. However, all the fitted measurements must be remote from the boundaries of the lattice of test fuel, where the neutrons' energy distribution is not characteristic of a pure lattice. Thus, a flux map with CANDU-style fuel typically requires 275 bundles (55 fuel rods, 5 bundles/rod).

As indicated in a companion paper at these proceedings [1], the complexity and expense associated with the type of experiments needed for validation preclude the use of such a quantity of fuel. The substitution method reduces the number of fuel rods required to seven (35 bundles). As shown in Figure 2, and explained in the following two sections, the perturbations associated with the replacement of centrally located "reference" fuel rods with "test" fuel rods are measured and analyzed to derive the buckling of a pure lattice of the latter.

3. SUBSTITUTION EXPERIMENTS

3.1 Reactor

A substitution measurement on any one test fuel and coolant involves a number of experiments in the ZED-2 reactor [2], shown schematically in Figure 3. This reactor consists primarily of a cylindrical calandria with a vertical axis. Fuel channels are hung in it by chains from movable beams. Criticality control is by the quantity of moderator in the calandria, or "moderator height". The simplicity makes for accurate measurements. In particular, the absence of in-core reactivity devices makes a pure lattice possible.

3.2 Experiment Types

A "reference lattice" is a lattice that differs from the test lattice that is to be studied with its aid, and that is uniform over a large enough volume that flux mapping of it can yield an accurate measure of its buckling, per equation (1). The reference lattice has the same pitch as the test lattice. The uniform part of the lattice is often surrounded by "booster" fuel, to enable it to go critical when low-buckling lattices are involved. The booster fuel is not necessarily at the same pitch. In Figure 2, the diagram marked "Reference" represents this lattice, with booster fuel not shown. Figure 3 shows a vertical cross section of a reference lattice, *mutatis mutandis*.

A "substitution lattice" is identical to some specific reference lattice with which it is to be analyzed, except that, in some of the lattice positions, the reference fuel and coolant is replaced with the test fuel and coolant. In the procedures that we have validated, every rod contains the same fuel and coolant throughout its length, and consequently the substitution is of whole rods. Figure 2 shows the configurations used. (The configuration "Triple 1 Substitution Lattice" was used in one experiment set only, in which the configuration "1 Substituted" would have made the critical height exceed the top of the substitution fuel.) Figure 3 shows a vertical cross section of a substitution lattice.

In some experiments, foils are suspended at cell boundaries of the lattice at the flux-map positions shown in Figure 3. They are activated by the flux, and counting of their activations yields the flux distribution. In the following, experiments are referred to as "mapped" or "unmapped" according to the presence of these foils. An unmapped experiment yields only a critical height. Flux-map foils add greatly to the information from an experiment, but they affect the buckling of a lattice.

3.3 Sequence of Experiments

Unmapped experiments are performed with the sequence of configurations shown in Figure 2, from "Reference" to "7 Substituted". They are then performed again in reverse order. The average critical height of the two experiments with each configuration is used in the analysis. This procedure leads to the cancellation of any source of error that is linear with sequence number. The prime example is the gradual downgrading of the heavy water.

For precise measurement of change of buckling upon voiding, the above sequence is run with air coolant and then with water coolant in the substituted channels. The two sequences are executed consecutively, and the critical heights are corrected to common conditions in accordance with all four reference experiments.

In some sets of experiments, the water coolant is pumped into and out of the test channels without removing them from the reactor. Thus the sequence of reference and substitution configurations, forward and reverse, is followed only once, but for each substitution configuration the critical height is measured with air and with water coolant substituted. This procedure further reduces the effect of gradual changes on the measured coolant void effect.

A mapped reference experiment is also part of the set, as is a mapped substitution experiment with each coolant with 7 channels substituted. The mapped experiments are done outside the above sequence of unmapped experiments, but within a short time of them.

The above corrections for gradual changes of conditions are made before the analysis described in the following section. Consequently, in the following procedure, only one experiment of each type is represented.

4. ANALYSIS PROCEDURE

4.1 Software Used

Since the essence of the analysis procedure is adjustment of a model, every experiment is analyzed in an iterative process. The adjustments and iterations are performed by a set of programs collectively known as "FitExpts".

The methods of the many experiments and of their analyses lead to many commonalities among them. Consequently, their database structure is built on a fairly deep file directory structure. Each directory represents an object, and contains a database file about that object. Subdirectories represent subobjects, and inherit this information. When any operation is performed, the object of the operation is the object represented by the current working directory.

Some of the objects are individual experiments. The directory that represents an experiment initially contains only the properties that distinguish it from other, similar experiments. When FitExpts analyzes that experiment, it places the results (such as those described in sections 4.2 and 4.3 below) in that directory. An experiment, in turn, is a subobject of a set of experiments with some common properties. For example, the set of substitution experiments that are based on a particular reference experiment is an object, with a directory of its own. When FitExpts analyzes that reference experiment, and places the results of that analysis in the set's directory, those results become properties of the set.

Other occurrences of common properties lead to additional levels of grouping of experiments. In particular, all the experiments discussed in this paper were performed in ZED-2. This reactor is an object in the database, and its directory contains the only description of ZED-2. All experiments in ZED-2 belong in subdirectories of that directory, so that they inherit this description from it.

This database structure takes its name from the routine used to retrieve information, "FillForm", so named because its queries are templates of whatever files are necessary. The actual form of the information in each directory is any combination of:

- macros, which specify that certain text shall be replaced with other text in the ultimate data file;
- functions, which enable arithmetic and decisions on the basis thereof; and
- template files, which may be included selectively, according to the results of other operations.

The reactor model is calculated by a set of subroutines collectively known as "Conifers", which have the geometrical flexibility necessary to represent a small reactor, such as ZED-2, with the necessary accuracy, and the flexibility to accommodate the many adjustments to the mathematical model. The subroutines are driven by a program named "Con4Z2". It can work with any number of energy groups. For the present work, four

energy groups are used. Thus, the downscatter cross sections of heavy water do not depend strongly on the energy spectrum, as they do in two groups. For the work reported here, Conifers was used with the finite-difference, homogenized-cell option.

Cell data for Conifers are calculated by a version of WIMS-AECL that dates from 1996. It uses the Winfrith data library, which is similarly dated. Thus, the cell code is different from any that will be validated with the results, so that the validation is more than just a consistency check. (When a few cases were analyzed using the ENDFB-V library, intermediate results were considerably different, but the final results were not significantly affected, as explained in section 4.4 below.)

The program ConPack organizes the data for Con4Z2 and WIMS-AECL.

4.2 Basis of the Procedure

The basis of the analysis procedure is to set up a mathematical model of each experiment, and adjust it until it agrees with the experiment. Since many ways exist by which to adjust each model, the accuracy of the substitution method depends on the choice of adjustments. The main criterion is that they do not contradict anything that is known about the experiment, but rather compensate for known inaccuracies in the model.

Figure 3 shows seven regions of a model of a substitution experiment, in each of which FitExpts performs a distinct adjustment. (The periphery overlaps the reference top and bottom regions. Cells in the overlaps undergo two adjustments.)

In the two top regions, the adjustments are the extrapolation lengths. FitExpts represents the space above the moderator surface as vacuum, because Conifers uses diffusion theory. The adjusted extrapolation length takes account of the material that is there.

In each of the other regions, FitExpts manages a correction factor that is divided into the rate of neutron production, hereafter called the "n.p.c.f.", for "neutron production correction factor". This factor, if applied to an entire reactor, would fit the conventional definition of k-effective. However, a k-effective greater/ less than 1.000 is a prediction that a reactor that fits the description will have increasing/ decreasing power. Since the analysis is of a reactor that is known to have been critical, any difference of n.p.c.f. from 1.000 is an indication of inaccuracy in the mathematical model; hence the term "correction factor" is used. Also, the fact that FitExpts applies distinct values of n.p.c.f. to different regions of the reactor is inconsistent with the definition of k-effective.

Since WIMS-AECL represents a cell's environment as a pure lattice of the same cell type, the value of k-effective that it quotes is consistent with n.p.c.f. (and would be more accurately referred to by that name, since the reactor is known to have been critical). FitExpts performs iterations (additional to those described below), so that the bucklings input to WIMS-AECL for each region are consistent with the n.p.c.f., as well as with whatever can be inferred from the calculated fluxes with equation (1). Distinct

adjustments are necessary near the interfaces between lattice and reflector, because WIMS-AECL's representation of the surroundings is inaccurate there.

4.3 Sequence of Reactor Models

FitExpts builds up the set of model adjustments by analysis of each type of experiment in turn. The first step is the analysis of a mapped reference experiment. That yields the adjustments in the reference top region, reference bottom region, and periphery. FitExpts iterates on these adjustments so that the fit to equation (1) yields the same result for calculated and measured fluxes. FitExpts uses these adjustments in the analyses of all other experiments in the set. This analysis also yields bucklings to be input to WIMS-AECL for those regions.

The above analysis also yields an n.p.c.f. and bucklings for the reference body region but, because these quantities are affected by the flux-mapping foils, FitExpts applies them only to mapped substitution experiments. To obtain these quantities for unmapped experiments, FitExpts analyzes the unmapped reference experiment.

FitExpts finds that the necessary n.p.c.f. in the periphery region varies over the relatively wide range 1.000 ± 0.025, because of the inaccuracy of WIMS-AECL's model of the environment of a cell there. The n.p.c.f. in the reference body region, in contrast, lies in the range 1.000 ± 0.005, because WIMS-AECL models more accurately a cell's environment there.

From a mapped substitution experiment, FitExpts finds the adjustments and bucklings for the substitution top and bottom regions. It seeks agreement in fits similar to those to equation (1), except that, since the region of uniform lattice has insufficient radial extent, FitExpts derives only axial spacial dependence. Since FitExpts does no adjustment to bring about agreement between theory and experiment in the radial dependence in a mapped substitution experiment, FitExpts prepares a graph of the disagreement in this direction, as a check on the accuracy of the model.

The culmination of the reactor calculations is the analysis of an unmapped substitution experiment. In it, all the above adjustments are used. The only adjustments in the model of this experiment are of the n.p.c.f. in the substitution body, and the corresponding buckling input to WIMS-AECL. The n.p.c.f. in the substitution body is the quantity that goes into the analyses described in the rest of this paper.

4.4 Derivation of the Result for a Pure Lattice

The n.p.c.f. that FitExpts derives for any one test fuel varies among the unmapped substitution configurations in a set. Primarily, this is because of the varying degree to which the reference lattice affects the neutron energy spectrum in the substitution lattice, and the substitution lattice similarly affects the reference lattice. FitExpts uses the supposition that this effect, hereafter called the "contamination", in each reference and substitution channel is proportional to the number of nearest neighbors it has of the other

type. FitExpts extrapolates to an n.p.c.f. at zero contamination, characteristic of a pure lattice, with weighting according to the supposition that the error of each measurement is inversely proportional to the number of substitution channels. Figure 4 shows typical extrapolations.

(Since contamination affects the n.p.c.f. of the test fuel, the possibility exists that contamination may also affect the model adjustments derived from mapped substitution experiments. A set of mapped experiments with a full set of substitution configurations showed that the dependence is barely perceptible, so that the use of only seven-channel mapped substitution experiments is a good approximation.)

As section 2 above explains, the ultimate product is to be a buckling for a pure lattice, to be compared with a flux-map value. For this purpose, FitExpts finds a buckling under standard conditions (temperature, moderator purity, and ratio radial/ axial buckling), at which WIMS-AECL yields k-effective equal to the extrapolated n.p.c.f..

As section 2 implies, the n.p.c.f. depends on the cell code and data library, while the buckling is supposedly determined entirely by the experiment. To test this important point, a few cases were analyzed using the ENDFB-V library in place of the Winfrith library, as mentioned in section 4.1. The resulting values of n.p.c.f. were different by as much as 0.011. However, the bucklings changed by no more than 0.003 metres^{-2}. An increase of buckling by this much in cell-code input would change k-effective by only about -0.0001.

This finding shows that FitExpts finds a buckling determined by the experiments, not by the software. However, the conversion to standard conditions, and even the extrapolation to a pure lattice, depends on the supposition that the appropriate n.p.c.f. (i.e. any inaccuracy in WIMS-AECL's model) is constant over the range of conditions involved. This supposition has been proven valid by analysis of flux-map experiments of various lattices under ranges of conditions. The reason for its validity is that variation of conditions over the ranges involved has much less effect than coolant voiding has.

5. CHOICE OF LATTICES

Since the validation is based on comparison of results for each test lattice by flux mapping and by substitution, the test lattices were restricted to ones for which flux maps were obtainable. (This restriction made possible the test described in the preceding paragraph for most test lattices.)

A substitution experiment in which the reference and substitution lattices are identical will yield the same result as a flux map experiment. Therefore, if the substitution method yields results that disagree with flux mapping, the disagreement depends on the difference between the reference and substitution lattices. For this reason, the validation database includes a variety of reference and substitution lattices in varying combinations, with emphasis on large differences between reference and substitution lattices. The one strong dependence found is on differences in buckling between reference and substitution lattices.

The bucklings of the reference lattices in the validation database range from 0.999 metres^{-2} to 4.404 metres^{-2}. For the substitution lattices, the ranges are 0.432 metres^{-2} to 5.366 metres^{-2} with water coolant, 1.180 metres^{-2} to 5.709 metres^{-2} with air coolant. Low bucklings were obtained by use of light-water coolant, and by introduction of 32.6% pure heavy water into the annuli between pressure and calandria tubes.

For additional variety, fuel from the former lattice test reactor ZEEP was used as reference fuel, making a highly overmoderated lattice. Most lattices had pitches of 31 centimetres (hexagonal), but pitches of 30 and 24.5 centimetres were also used. Also, four of the fuel elements in each of a set of 28-element fuel bundles were replaced with elements with relatively high plutonium content, to serve as both test fuel and reference fuel. This was used because plutonium is important in irradiated fuel.

6. RESULTS

Figures 4 and 5 show typical extrapolations to a pure lattice. These slopes show that contamination markedly affects the result for each substitution experiment. The slopes vary considerably with choice of reference and substitution lattice. The error bars in Figure 4 only represent the scatter of points about the fitted line, and are not estimates of the overall accuracy of the substitution method. The scatter of points about the fitted line is much less in Figure 5 than in Figure 4. (The error bar in Figure 5 is the sum in quadrature of the error bars in Figure 4.) This indicates that much of the experimental error is common to the measurements with both coolants, and consequently does not affect the accuracy of the derived void reactivity.

Statistical analysis of the set of results for all experiments is still in progress. One complication is that the basic measure of error is the disagreement between results by substitution and by flux mapping. However, the bucklings obtained by flux mapping also contain uncertainties, which are comparable to those of substitution. These uncertainties contribute to the set of disagreements, but not in a simple way, because all the substitution experiments with each test fuel are compared with the one flux-map result for that test fuel.

Some idea of the correction that will result can be seen by the summary of the disagreements between substitution and flux mapping, shown in Figure 6. (The exceptionally long line shows an experiment with light-water coolant, which is of questionable relevance to a study of voiding of heavy-water coolant.) The fitted line is an unweighted fit to all the disagreements, for illustration only. Table 1 shows statistical summaries of the disagreements, without and with that fitted dependence subtracted from the substitution results as a crude correction.

For the uncorrected results, the negative means for water and air coolant only reflect a preponderance of experiments with low-buckling substitution fuel, but the positive mean for the void effect shows a strong tendency for substitution to overestimate the void effect. With the illustrative correction, the mean disagreement for all the substitution measurements becomes zero, of course, but there is a residual bias in the void effect,

which indicates a further tendency for the substitution method to overestimate void reactivity. (In Figure 6, the line segments representing void effects have on average higher slope than the fitted line.) With separate corrections for water and air coolant, the summarized disagreement in void effect becomes 0.000 ± 0.026 metres^{-2}.

The flux-map void effects have estimated errors in the range 0.013-0.047 metres^{-2}. When the proper allowance is made for their contribution to the disagreement, the estimated inaccuracy of the substitution method with correction will become considerably less than 0.025 metres^{-2}.

7. ACKNOWLEDGEMENT

This work was funded by the CANDU Owners Group through the Safety and Licensing Technical Committee.

8. REFERENCES

1. 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, 2000 June

2. Anonymous, *ZED-2*, AECL-2132,1964

	Water Coolant	Air Coolant	Void Effect
Not Corrected	-0.105 ± 0.207	-0.031 ± 0.166	0.073 ± 0.085
Crudely Corrected	-0.011 ± 0.091	0.011 ± 0.086	0.022 ± 0.026

Table 1: Means and Standard Deviations of Disagreements between Substitution and Flux Mapping Bucklings in Metres^{-2}, Without and With Simplest Correction

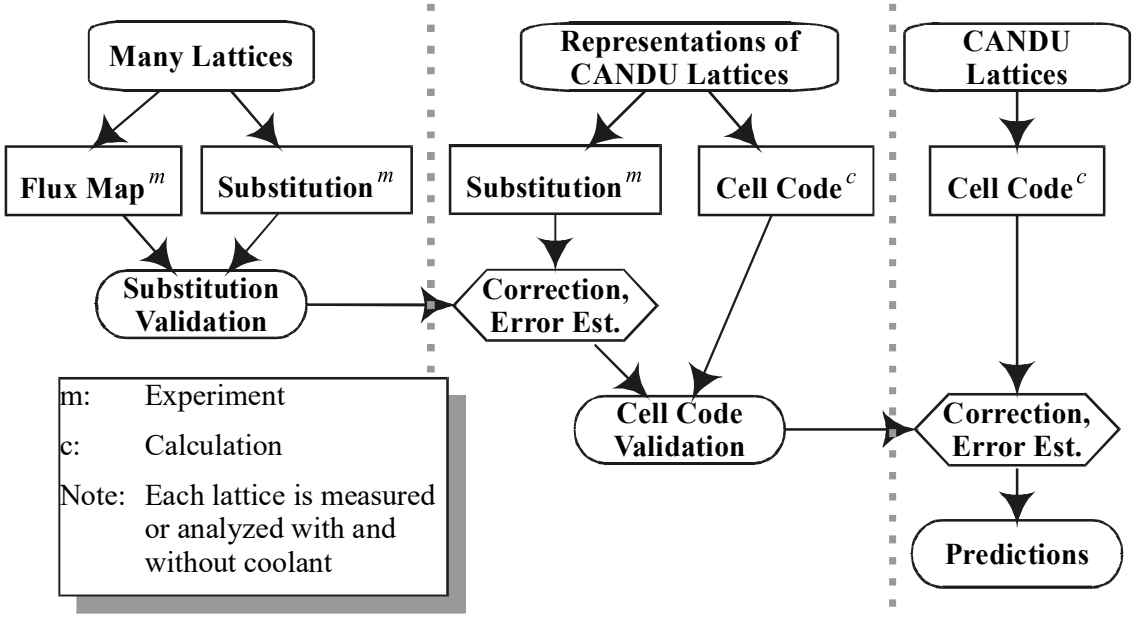

Figure 1: Generation and Purpose of the Substitution Validation

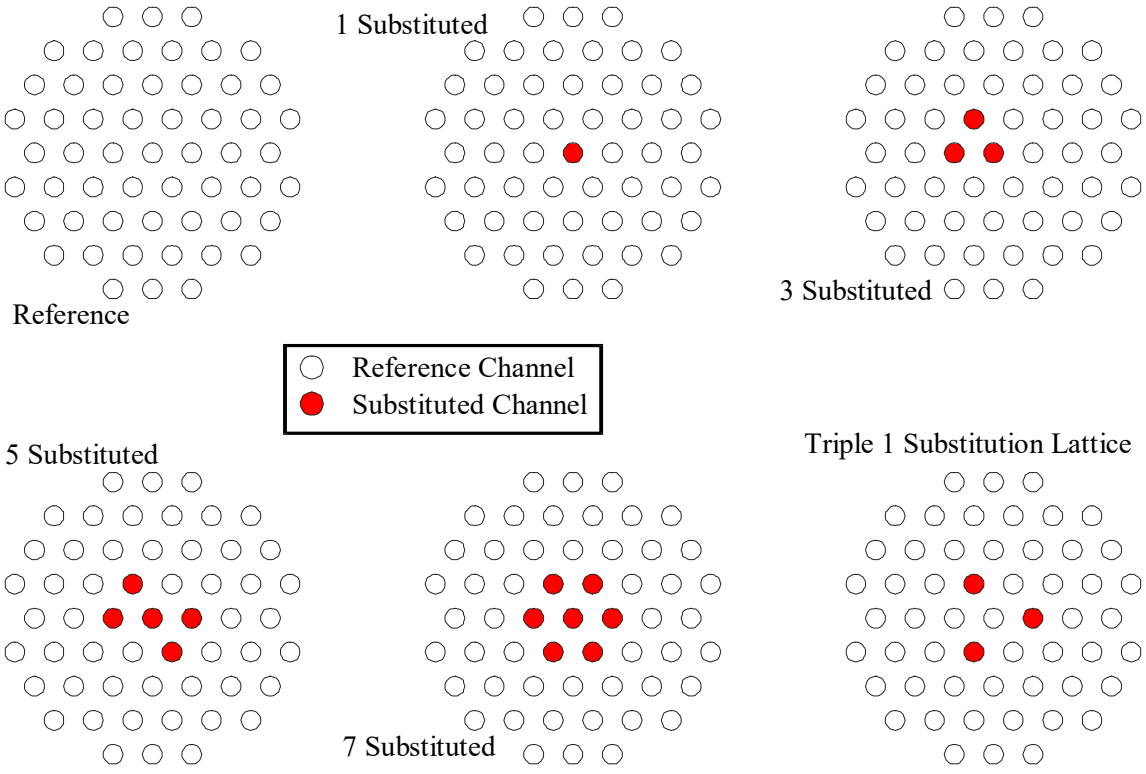

Figure 2: Reference and Substitution Lattices Used, Top Views

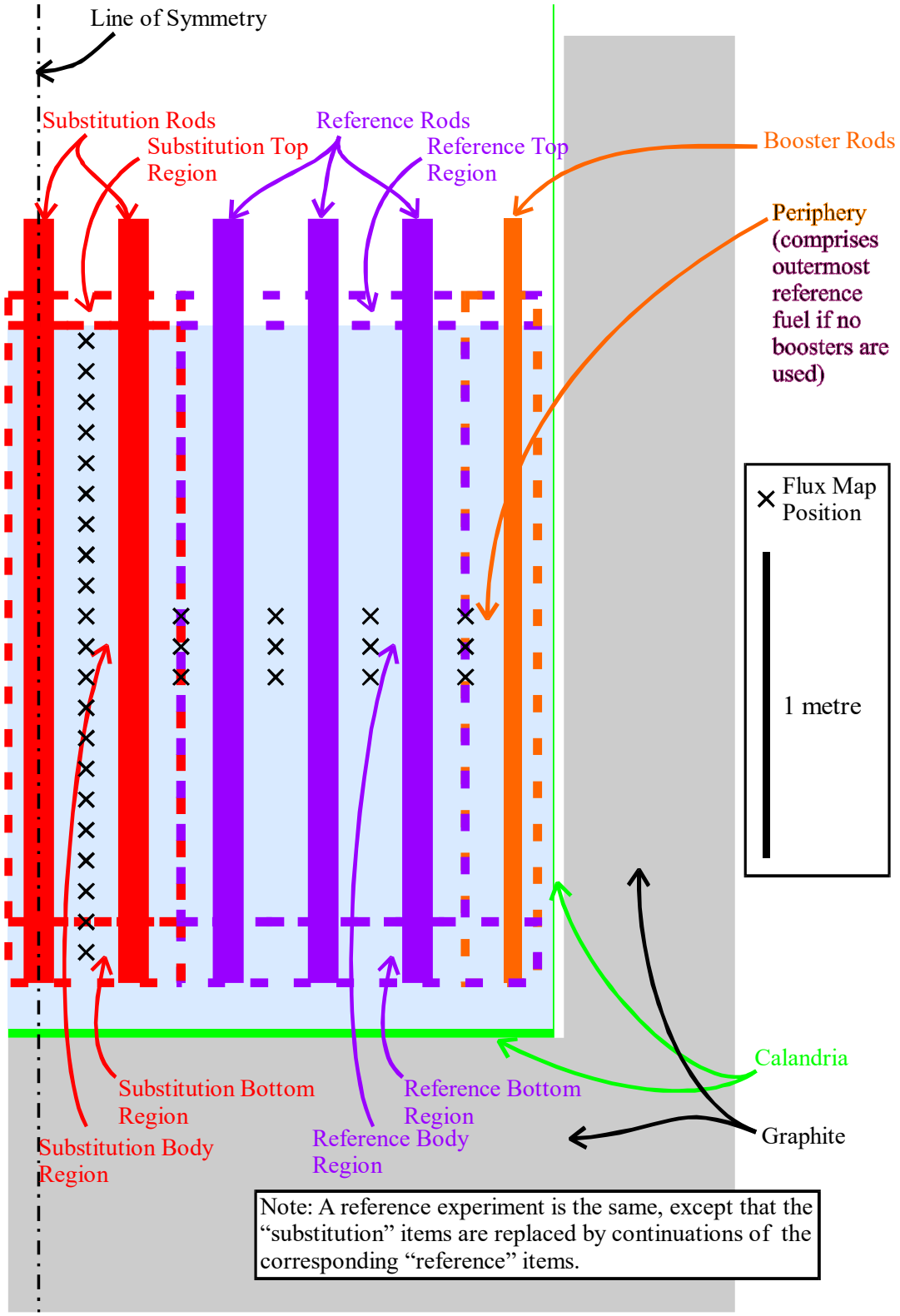

Figure 3: Cross Section of ZED-2 Reactor, with Regions of Adjustments of the Mathematical Model

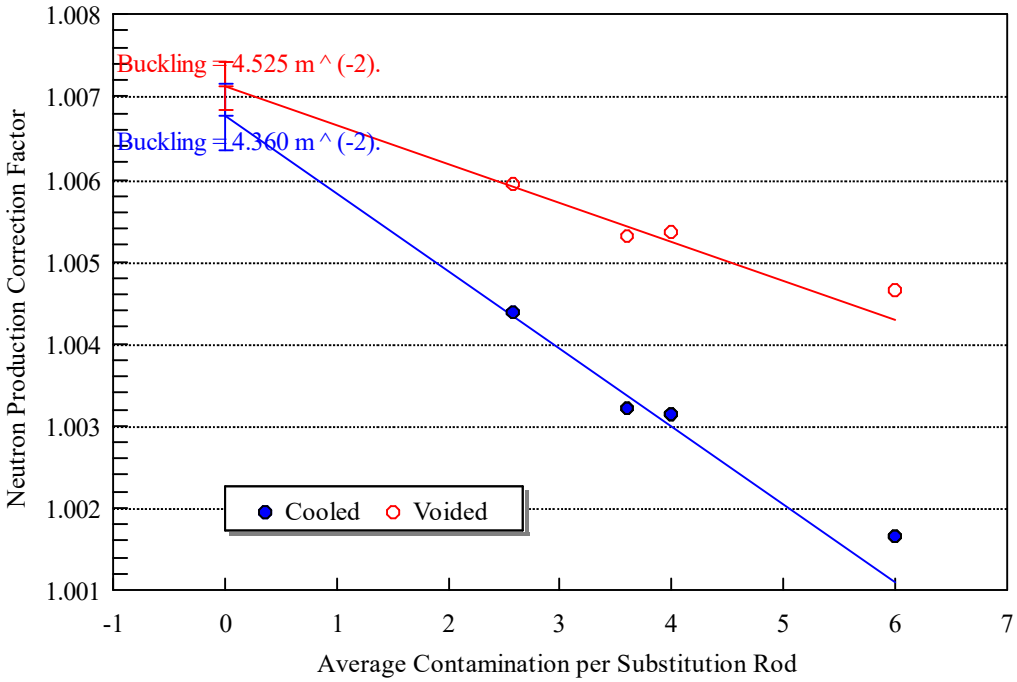

Figure 4: Extrapolation of Neutron Production Correction Factor to a Pure Lattice

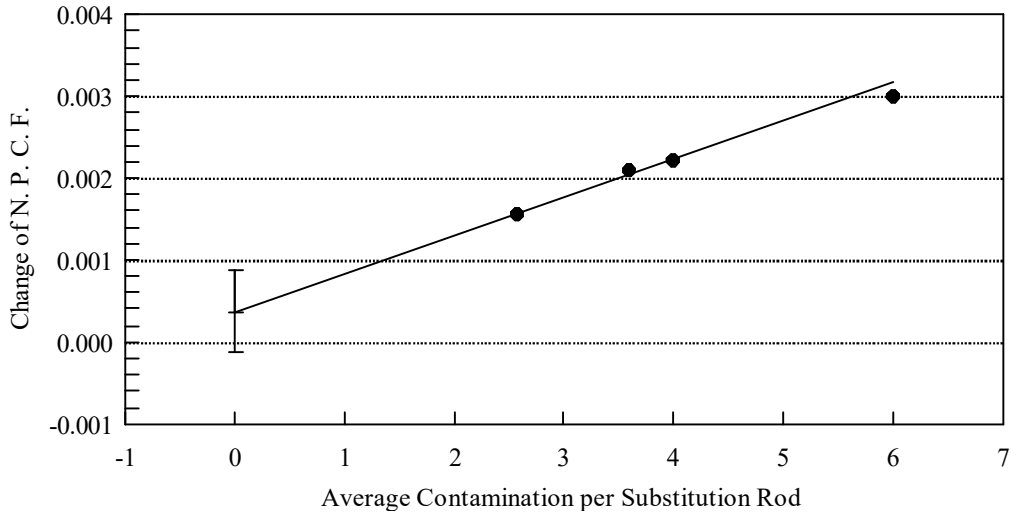

Figure 5: Void Effect on Neutron Production Correction Factor from Figure 4

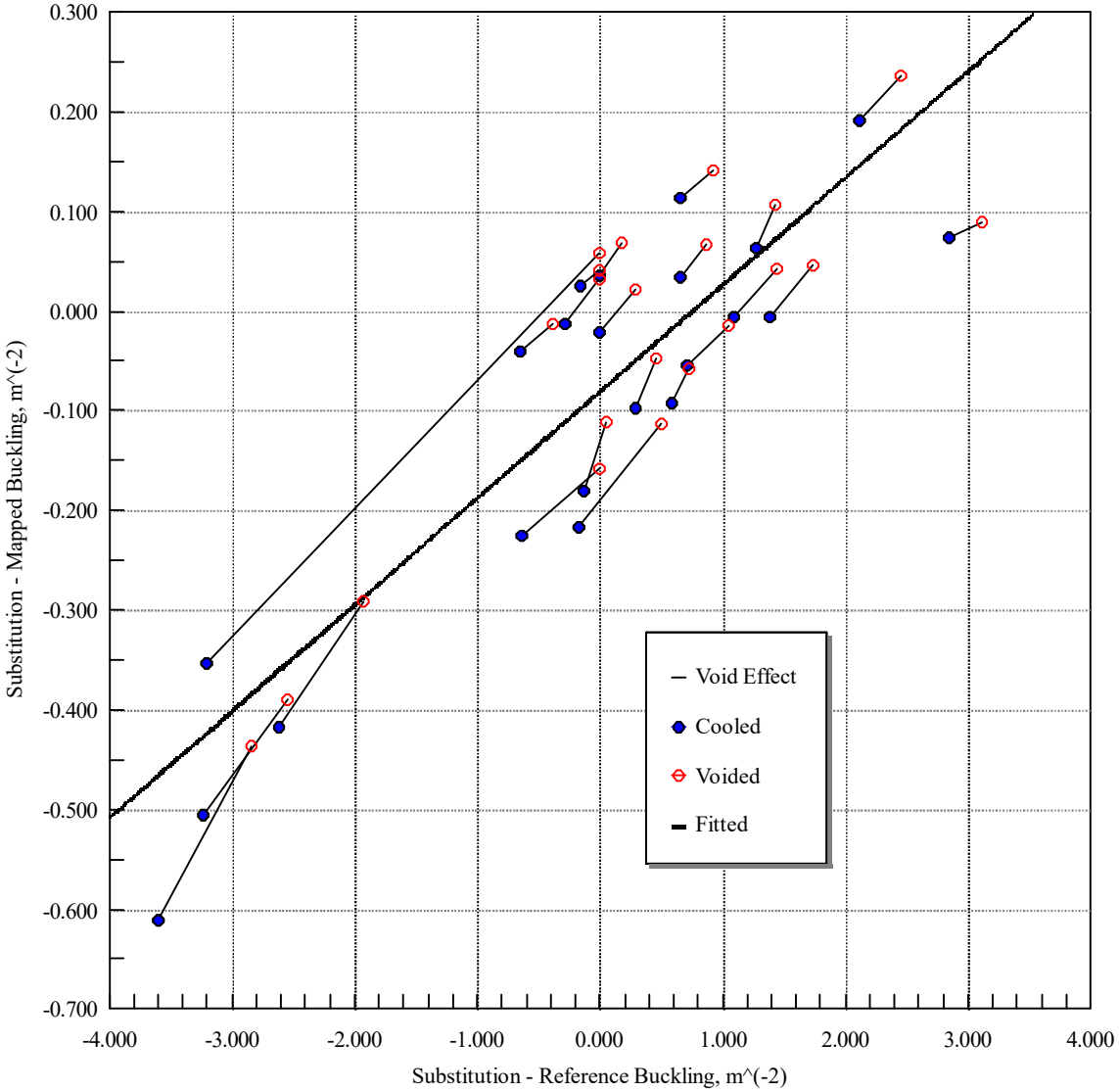

Figure 6: Buckling Difference Substitution - Flux Map, versus Buckling Difference Substitution - Reference, metres^{-2}