21st Conference of the Canadian Nuclear Society
Toronto, Ontario, Canada / June 11-14, 2000

THE COOLANT VOID REACTIVITY PROGRAM IN ZED-2

A. Celli, R.S. Davis, S.R. Douglas, R.T. Jones, G.P. McPhee, and M.B. Zeller

Reactor and Radiation Physics Branch
Atomic Energy of Canada Limited
Chalk River Laboratories
Chalk River, Ontario, Canada
K0J 1J0

1. Introduction

The coolant void reactivity program at Chalk River produces reactor physics data for validating cell codes, in particular WIMS-AECL. One type of data provides detailed spectrum information within the various regions of a lattice cell. Most often however, the experiments are designed to provide the material buckling of a specific fuel type in a specific cell environment.

Experiments are performed in the ZED-2 reactor. Fuel rod assemblies are positioned vertically, and the reactor is brought to criticality by reducing the neutron leakage from its top surface. This is done by raising the level of the heavy water moderator. The moderator height at the critical condition represents a key measurement in most experiments. The challenge is to covert this measurement, along with other supporting information such as foil activation data and moderator temperature, into the desired nuclear property of the test fuel - usually its material buckling.

Since it's inception, the program has attempted to make measurements at conditions that are as close as possible to those in a power reactor. Most of the previous data available was for natural uranium at room temperature, the so called 'cold-clean' condition, and for the extreme ends of the coolant density range. Extending these conditions necessitated including effects of fuel burnup and the temperature of the fuel and coolant. A major component of the program has been to develop techniques for acquiring as much of that information as possible while operating within the constraints of a limited budget and the capabilities of a zero-energy critical facility.

In the following sections, the progress made in developing some of the techniques necessary for generating data at power reactor conditions will be reviewed. A limited comparison with WIMS-AECL calculated values will also be made where appropriate.

2. Validation of the Substitution Method

A companion paper [1] at these proceedings describes details of the substitution method for measuring bucklings, including the method used to analyze the experiments. Its development, and the experiments performed to test its capabilities, represent a major component of the coolant void reactivity program. Without the substitution method, the acquisition of data at conditions close to those in a power reactor would have been too expensive by conventional lattice measurements.

The conventional method of determining the material buckling of a fuel is to measure the geometric buckling of a full core of the fuel at the critical condition - the so-called flux map method. In ZED-2, this is done by placing activation foils at about a hundred cell boundary locations and fitting the resulting activities to a cosine and Bessel function. A full core of fuel would require about 55 rods, each containing five fuel bundles.

The effect of fuel burnup cannot be tested on irradiated fuel in ZED-2 because systems are not in place to handle highly radioactive bundles. Even if such systems could be put in place, it would be questionable if the fuel composition could be well enough characterized to provide good validation data. Therefore, irradiated fuel was simulated by manufacturing a mixed oxide containing plutonium, depleted uranium and an absorber to simulate the fission product load. Fifty-five rods of such fuel would be expensive, and in any event would be insufficient to achieve a critical core in ZED-2 without being driven by another more reactive fuel. The impracticality of the flux-map method extends to other tests, such as those relating to the effect of high channel temperature on void reactivity. The substitution method reduces the required number of fuel assemblies to seven. This small quantity of test fuel reduces the cost and complexity of the tests and ensures that achieving criticality is not a problem.

The substitution method requires that test fuel bucklings be derived from the critical height changes resulting from the replacement of a reference fuel with test fuel. The standard sequence of substitutions is: one, then three, then five, then seven rods in the central region of the core. An analysis involving a calculational model of the core is used to produce an estimate of the test fuel buckling at each stage, and extrapolation to a full core of test fuel produces the best estimate. The final error associated with a substitution analysis is expected to be a function of how much the test fuel properties differ from those of the reference fuel and, to a first approximation, this error is likely to be proportional to the buckling difference between the two fuels.

Testing the capabilities of the substitution method means comparing the results it produces with those from flux mapping. In a validation exercise extending over several years, measurements were made on 23 combinations of test and reference fuels in substitution experiments. Figure 1 shows the fuels used. They varied from uranium metal fuel, to oxide fuel containing elements with plutonium. The fuel geometries varied from a single metal slug (used as reference fuel because it cannot be voided) to common production fuel. Coolants varied from air to heavy and light water, which has about an order of magnitude greater void effect than heavy water. A particularly relevant fuel was a low buckling variant of the 28-element bundle because it had a buckling very similar to that of the simulated irradiated fuel (Section 6).

All the fuels that had their bucklings measured by the substitution method were also tested by flux mapping. A detailed statistical analysis of the differences between the two measurements is currently being undertaken, but it is already evident that for the buckling change on voiding, the method has associated uncertainties which are comparable to those of flux mapping.

In the current program, all the experimental data generated for cell code validation has been obtained by the substitution method. The following sections give examples of the type of experiments performed and the data generated.

3. Partial Voiding Experiments

These experiments were designed to generate critical bucklings as a function of coolant density. The coolant density was varied by forcing air through a porous medium located at the bottom of each of the seven substituted channels. To achieve a particular average void fraction, say 30%, water was added into the channel to 70% of the fuelled height and then 'foamed' to the full height of the fuel by the introduction of air.

The technique was developed out-reactor using an unfuelled glass column and an acrylic pressure tube filled with fuel. The former allowed for quantitative measurements of void fraction variation with height, and the latter was for visualization purposes and for developing the void measurement technique that would be used in-reactor. Void fractions approaching 70% were achieved. The coolant was completely removed for the measurement at 100% void.

Figure 2 shows the raw data collected for 28-element UO_2 fuel. It is a plot of reactor critical height as a function of void fraction for the one, three, five, and seven rod substitutions. The positive void reactivity is clearly evident (a decreasing height is indicative of an increasing buckling). As expected, the effect increases with the number of substituted rods.

The substitution analysis produced a critical buckling at each void fraction. A critical buckling at each void fraction was also calculated by WIMS-AECL. Figure 3 shows a graph which is intended to compare trends between experiment and calculation as a function of void fraction. For the calculation, the buckling change on partial voiding is indicated as a fraction of the change resulting from complete voiding. It is evident that the trends are similar and approximately linear.

4. Temperature Effects

The effect of channel temperature on void reactivity was measured using specially designed fuel channels. These channels were capable of operating at power reactor coolant conditions (300 °C, 10 MPa).

Figure 4 shows some of the structural details at the bottom region of the channels. The temperature of the channel contents is raised and maintained by the use of a small but high power electrical heater. Natural convection distributes the heat throughout the fuel channel. With water coolant, the axial variation in temperature in the central section of the fuel bundle is about ± 1 °C.

A particularly difficult problem was to heat the channel contents in the voided condition. Several methods were tried. One of the best methods also relied on natural convection, but with the use of a dense, low neutron absorbing gas. CO_2 satisfied the requirements well, although temperature variations were slightly higher than with water (± 5 °C).

Figure 5 shows results for 37-element UO_2. Here the critical buckling derived from a substitution experiment is plotted against the fuel/coolant temperature for both the voided and flooded cases.

In the voided case the variation in buckling is a result of the fuel temperature only. The buckling decreases with temperature in a linear fashion due mainly to resonance broadening in U-238.

With D_2O in the channel, the initial rate of change of buckling with temperature is also negative, but of a greater magnitude than in the voided case. Here also the dominant effect is increased resonance absorption in U-238, but the magnitude is larger because the epithermal flux is higher. With increasing temperature however, the coolant density decreases, initially slowly, but quite rapidly in the high temperature regions. This density reduction causes an increase in buckling due to reducing epithermal flux such that the values for the cooled and voided situations begin to approach each other.

The buckling change on voiding is a measure of the void reactivity and it can be seen that the separation between the voided and cooled buckling curves initially increases. At some point the two curves have an equal slope and the change in buckling peaks. Thereafter it decreases.

Figure 6 shows the measured buckling change on voiding with the peak occurring at about 240 °C. The WIMS-AECL prediction of the variation of void reactivity with channel temperature shows a very similar behavior.

5. Effect of Fuel Burnup

To simulate the effect of burnup, a $(U,Pu)O_2$ mixed oxide fuel (MOX) was manufactured at CRL. It had a U-235 and Pu composition which approximately simulated equilibrium burnup fuel. The effect of fission products was simulated with the addition of 0.05 wt.% dysprosium. The Dy was added to reduce the buckling to that of a power reactor. The effect of Dy addition on buckling is shown in Figure 7.

The substitution method was used to measure the bucklings of this fuel at room temperature in six reference lattices. As indicated in Section 2, the error in the substitution method depends on the buckling difference between the test and reference fuel. In one experiment this difference was reduced to almost zero by making a special low buckling fuel (Figure 1). Cooled and voided buckling measurements were also made up to a channel temperature of 300 °C.

Results are preliminary but some general comments can be made concerning the behavior of the MOX fuel. These are:

- the room temperature measurements with the six reference lattices gave consistent results for the buckling change on voiding,
- the buckling change on voiding at room temperature was much higher than for natural uranium (due mainly to a much lower negative effect of leakage on voiding because a low buckling core represents a large core) and,
- unlike natural uranium, the buckling change on voiding continuously decreases with temperature.

6. Acknowledgment

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

7. References

1. 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, 2000 June.

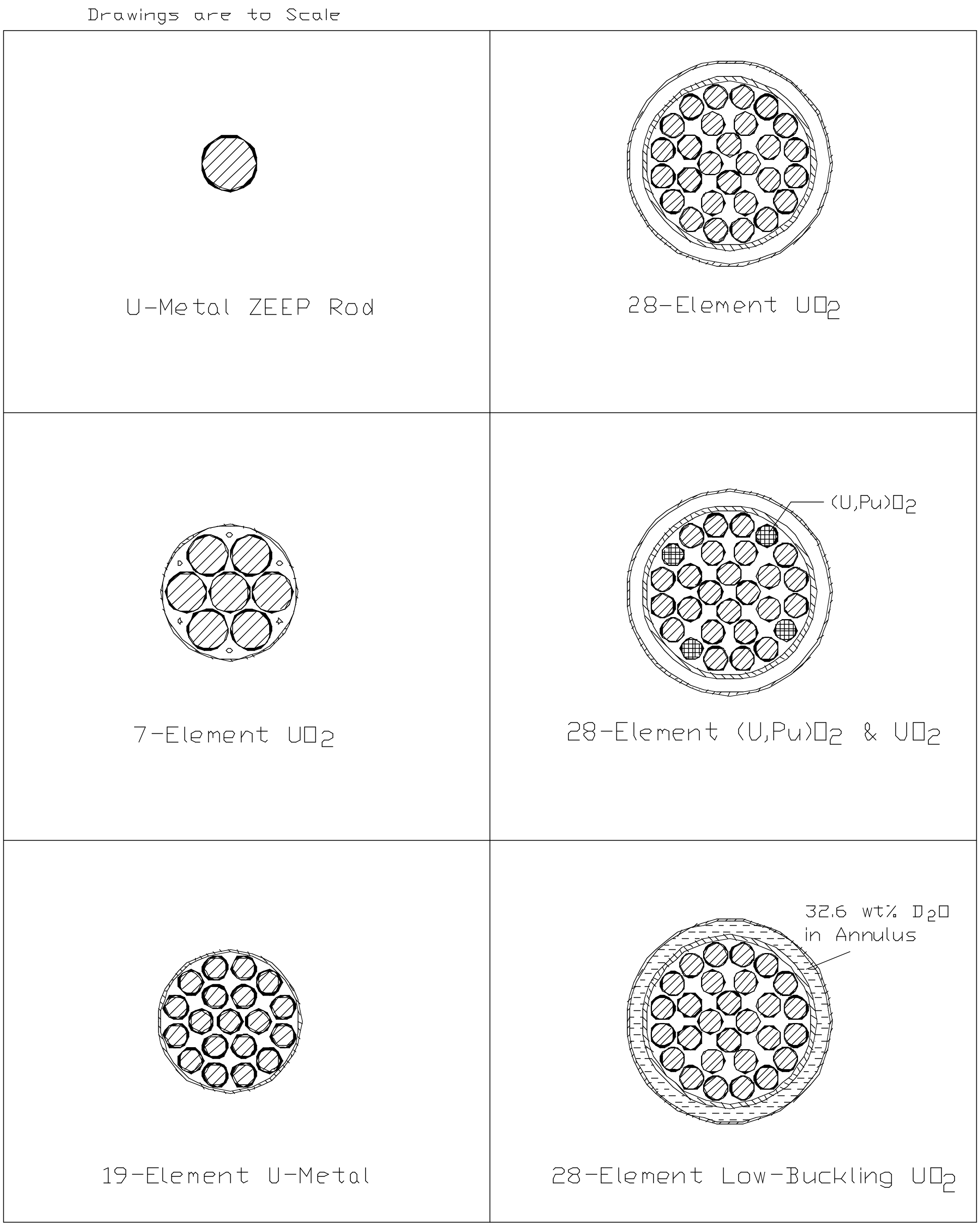

Figure 1: Range of fuels used for validating the substitution method

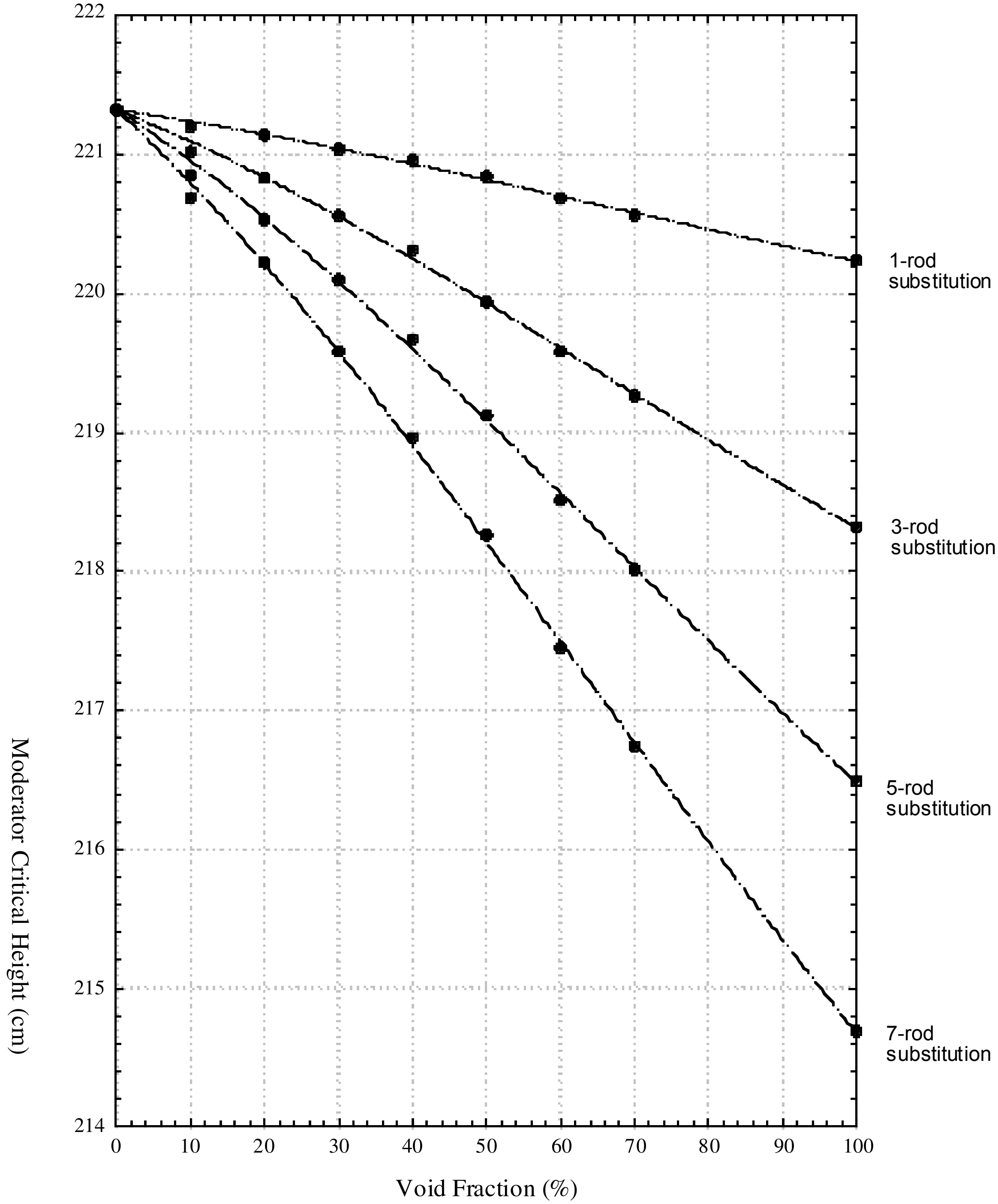

Figure 2: Critical heights as a function of void fraction and number of substituted rods

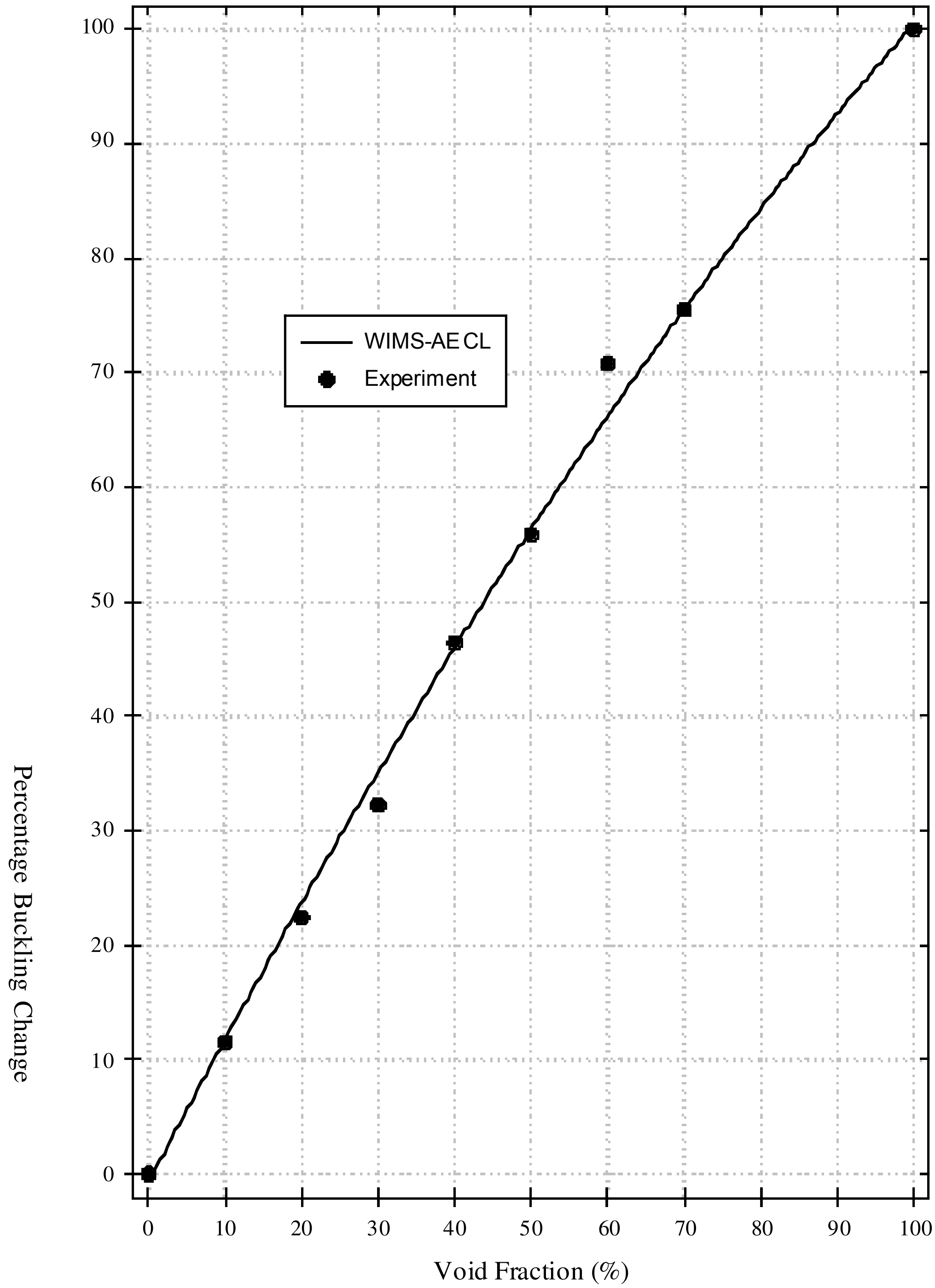

Figure 3: Buckling change with void fraction

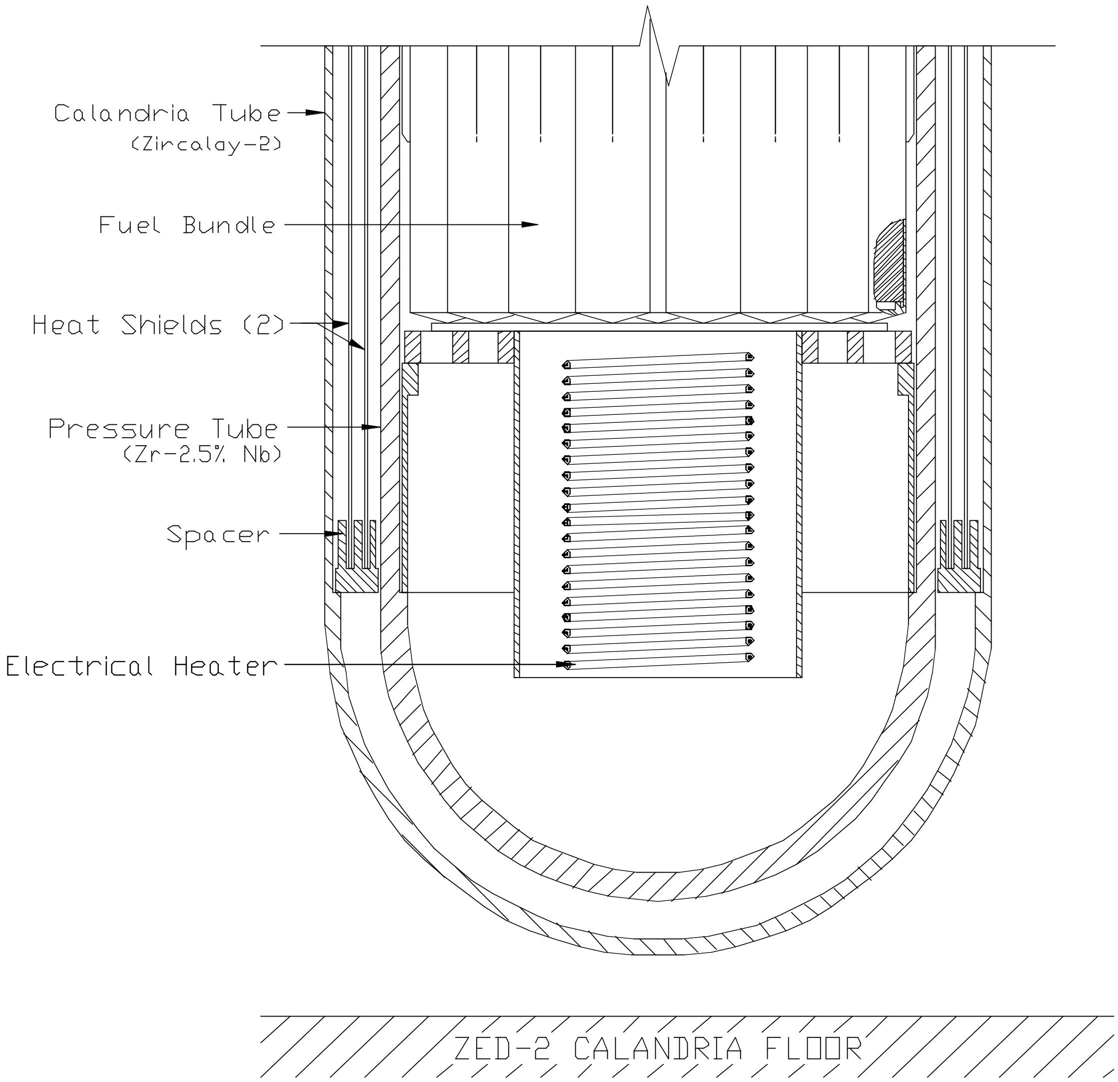

Figure 4: Hot channel details

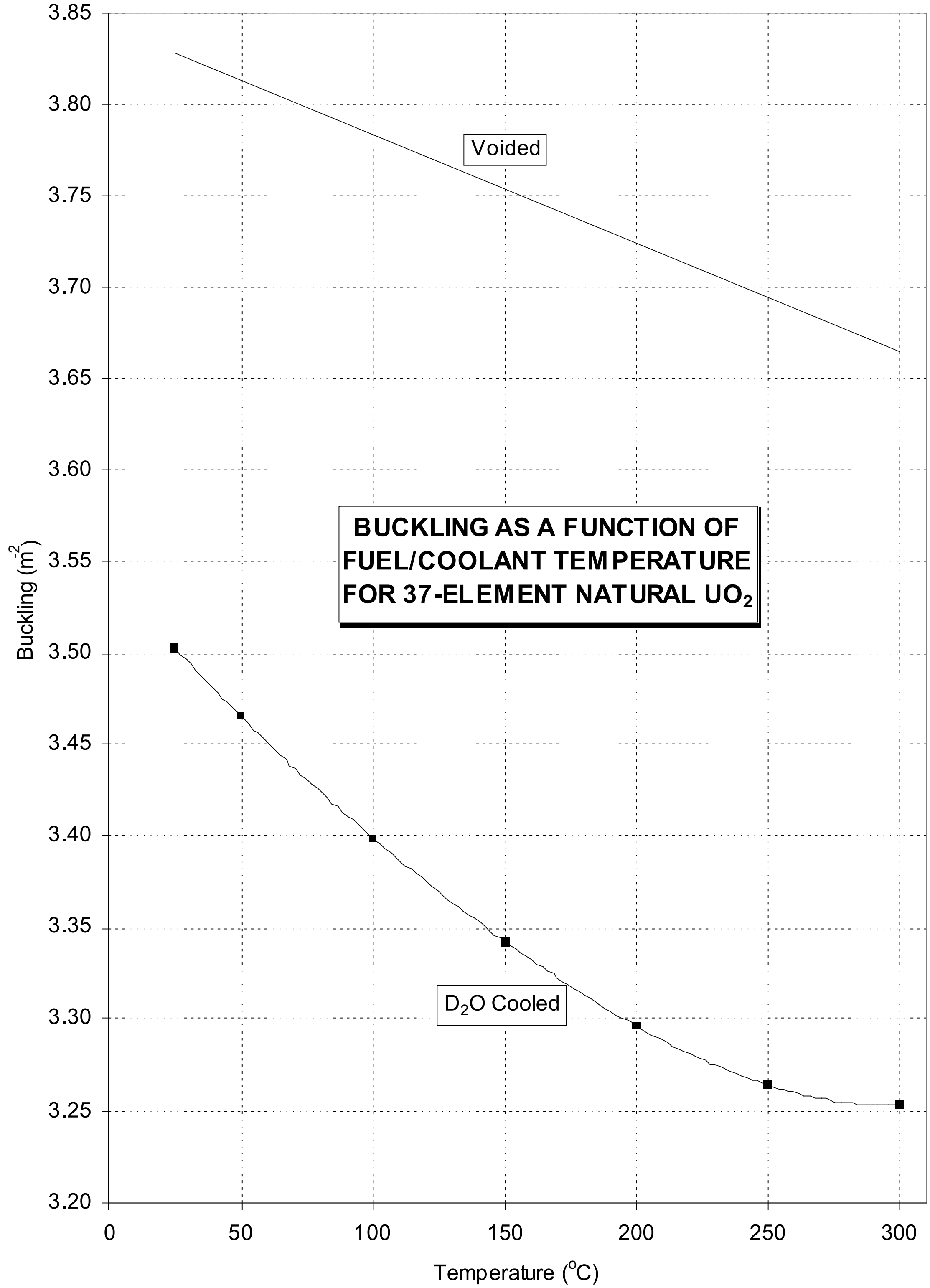

Figure 5: Fuel/Coolant temperature dependent bucklings

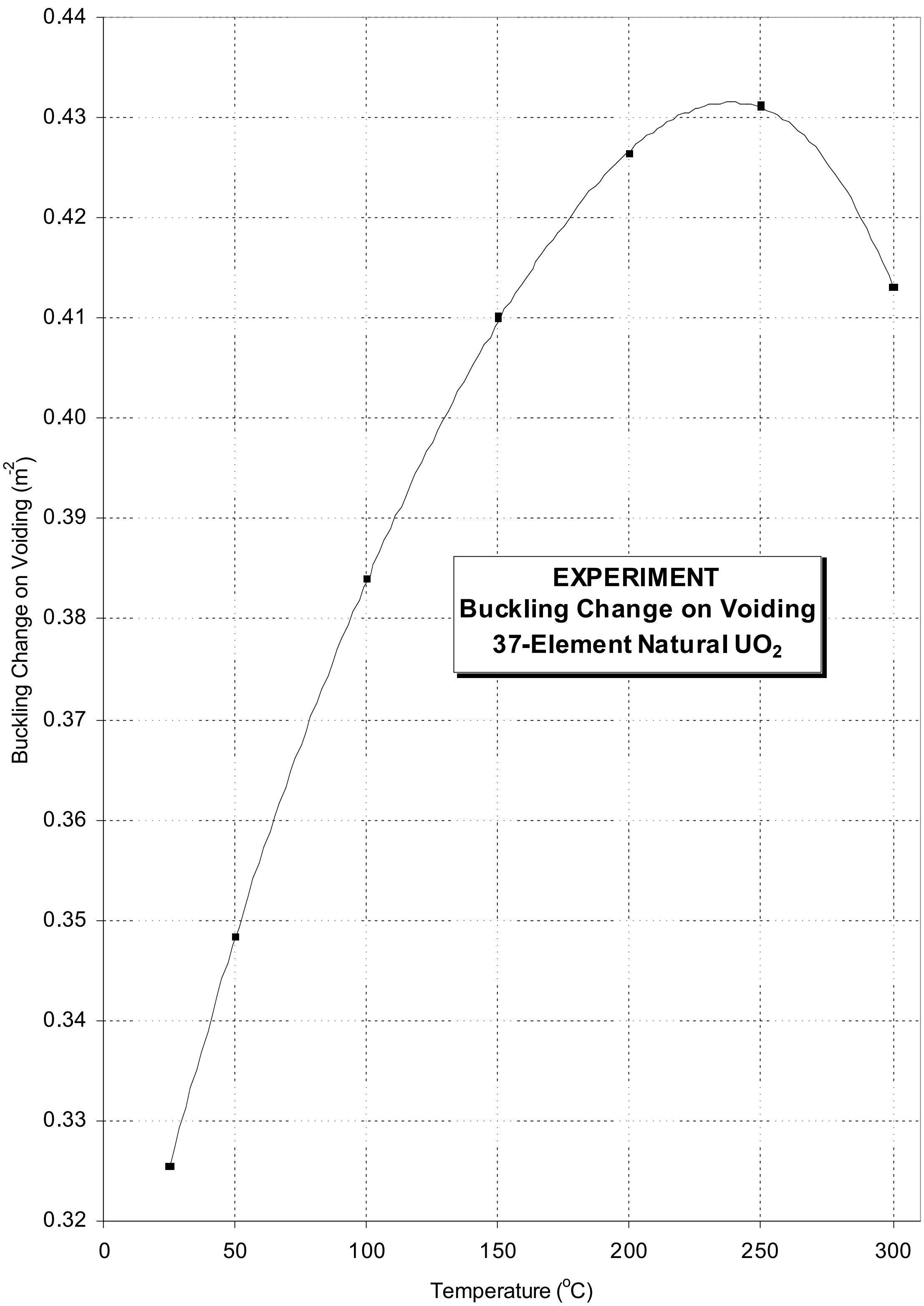

Figure 6: Buckling change on voiding as a function of channel temperature

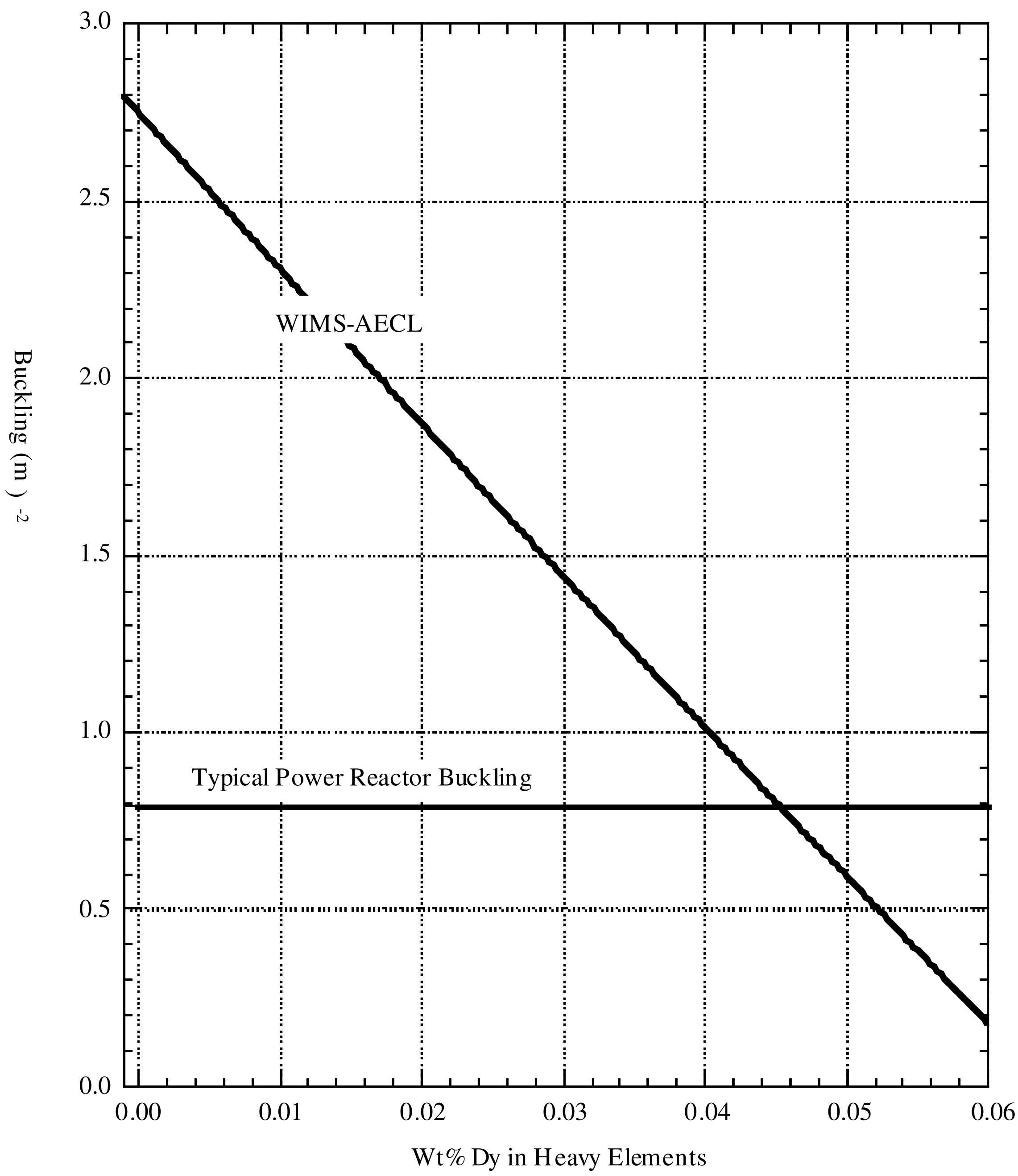

Figure 7: Effect of Dy on the buckling of MOX fuel