# EXPERIMENTAL INVESTIGATION OF PIN REMOVAL REACTIVITY WORTHS FOR A WESTINGHOUSE SVEA-96+ ASSEMBLY IN THE PROTEUS RESEARCH REACTOR

**A. Meister, M. Murphy, A. Lüthi, R. Seiler,**
**P. Grimm, R. van Geemert, F. Jatuff, and R. Chawla***
Paul Scherrer Institute, Nuclear Energy and Safety Research Department
CH-5232 Villigen PSI, Switzerland
(*) Co-affiliation: Swiss Federal Institute of Technology
CH-1015 Lausanne, Switzerland
Fabian.Jatuff@psi.ch

**R. Jacot-Guillarmod**
Elektrizitäts-Gesellschaft Laufenburg AG
Lerzenstrasse 10, 8953 Dietikon, Switzerland
Roland.Jacot-Guillarmod@egl.ch

## ABSTRACT

Measurements and analyses have been carried out for the reactivity effects of removing selected fuel pins from a Westinghouse SVEA-96+ BWR fuel assembly. The experiments were performed at the PROTEUS research reactor of the Paul Scherrer Institute. The assembly codes HELIOS, CASMO-4 and BOXER have been used for the analysis of the measurements, in order to validate the assembly codes' capabilities to predict reactivity differences between BWR fuel assemblies of different designs, e.g. with a varying number of part-length rods. The results reported are "first-of-their-kind" in terms of the type of experimental investigation carried out.

## 1. INTRODUCTION

Accurate measurements and detailed analysis have been performed for the reactivity effects of removing selected fuel pins from a Westinghouse SVEA-96+ BWR fuel assembly. The experiments have formed part of the LWR-PROTEUS Phase I programme jointly conducted by PSI and the Swiss Nuclear Operators. Figure 1 shows a cut-away view of the multi-zone PROTEUS research reactor with the main zones indicated. For the experiments reported here, the PROTEUS reactor was equipped with a test zone consisting of 3x3 SVEA 96+ fuel assemblies [1] that could be moved axially by the test tank drive.

A SVEA 96+ fuel assembly comprises 96 fuel pins arranged in four sub-bundles, each containing 24 pins on a square pitch around a central water canal. The $^{235}$U enrichment varies both axially and radially in the range 2% to 5% and 14-16 pins contain additionally gadolinium in different concentrations as a burnable absorber (see Figure 2).

The pin removal reactivity measurements aim at providing a new type of experimental database for the validation of calculation methods for modern BWR fuel assembly designs with strong radial and

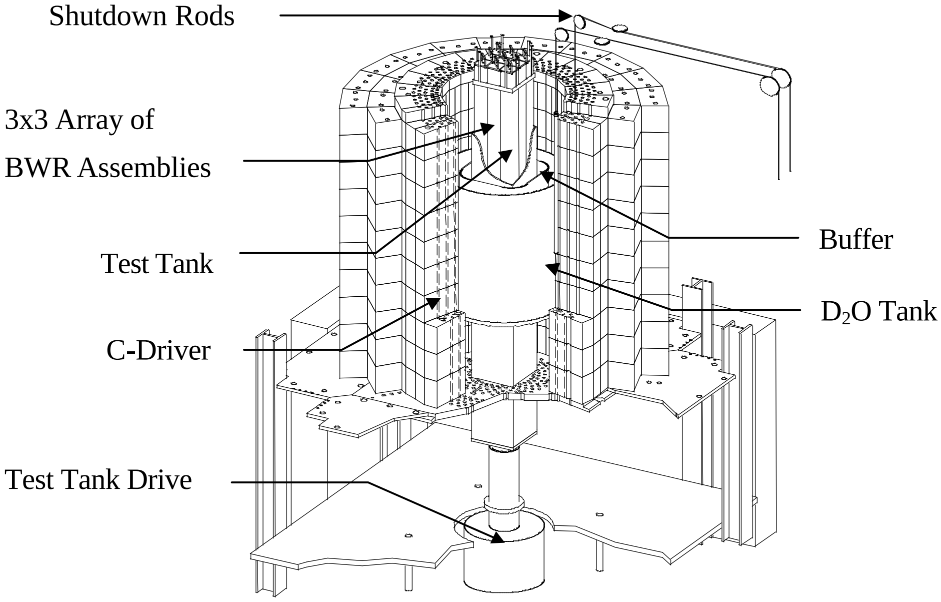


Figure 1. Cut-away view of the LWR-PROTEUS facility with indication of the main zones and components.

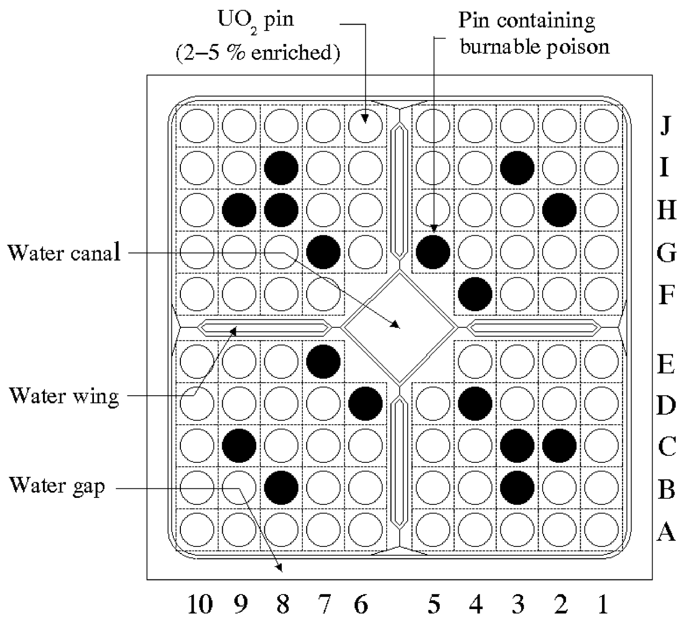


Figure 2. Westinghouse SVEA-96+ fuel assembly. Shaded areas correspond to the location of Gd-containing fuel pins in the upper assembly region.

axial heterogeneities, including part-length fuel pins. The reactivity change of the highly heterogeneous SVEA-96+ assembly with an individual pin removed and replaced by water varies quite strongly between the different pin types (having different compositions/enrichments) and pin positions (with varying local neutron spectrum). Removing a $UO_2$ pin from the nominal assembly decreases the reactivity, the absolute values varying, depending on the pin composition and position, by a factor of about four. Removing a fuel pin that contains Gd increases the reactivity, and the absolute values are larger than those for the $UO_2$ pins. Different categories of fuel pins have been investigated, such as pins close to the central water canal, pins with two burnable poison neighbors, corner pins and pins with relatively uniform surroundings.

In the current paper, results are reported for the reactivity effects of removing selected fuel pins from the central SVEA-96+ assembly in both the lower (test zone configuration 1A) and upper (configuration 1B) axial regions of the assembly with $H_2O$ moderator at ambient temperature. While the lower region corresponds to an average $^{235}$U-enrichment of 4.02% with 14 Gd-containing pins, the upper region, being less reactive, has 3.70% average enrichment and 16 Gd-containing pins.

Also included are the results for certain other LWR-PROTEUS test zone configurations, essentially representing modifications of configuration 1A, in that (i) an L-shaped $B_4C$ absorber blade was inserted into the inter-assembly gap along the north and west sides of the central assembly (configuration 2C), (ii) the central assembly was shifted from its original position towards the south-eastern corner to simulate a variation of the inter-assembly gap (configuration 7A), and (iii) part of the $H_2O$ moderator was substituted by polyethylene inserts in order to modify the moderator density (configuration 4A).

## 2. COMPARISON OF CALCULATED AND MEASURED VALUES

The main measurements were performed by the compensation technique utilizing a calibrated automatic control rod. Stable period measurements were made also as a check for possible systematic errors. The experimental effects were in the range of about 1 to 35 cents, the accuracy of the individual reactivity worth values being better than 1%. Whereas the absolute reactivity worths of individual pins are specific to the experimental facility as a whole (the LWR-PROTEUS multi-zone configuration), their relative values for different pins are specific to the SVEA-96+ fuel assembly under the particular test zone conditions being investigated. For comparing the calculated and experimental reactivity worths, the results can therefore be normalized in an appropriate manner, e.g. such that the average C/E-value for the entire set of measured pins is unity.

For analysis of the experiments, calculations of the pin removal worths were performed with the assembly codes HELIOS [2] (version 1.4), CASMO-4 [3] and BOXER [4]. The calculations with HELIOS are for the full test zone comprising the 3x3 SVEA-96+ fuel assemblies and with reflective boundary conditions at the test tank. The calculations with CASMO-4 are for the central test assembly with reflective boundary conditions in the middle of the inter-assembly gap. Only the BOXER calculations are for the whole PROTEUS reactor. Comparisons of the calculated (C) and experimental (E) reactivity worths were done taking into account the finite LWR-PROTEUS outer zone effects. These were assessed on the basis of the BOXER whole-reactor model, analogously to the methods used previously for the comparison of reaction rate distributions [5, 6].

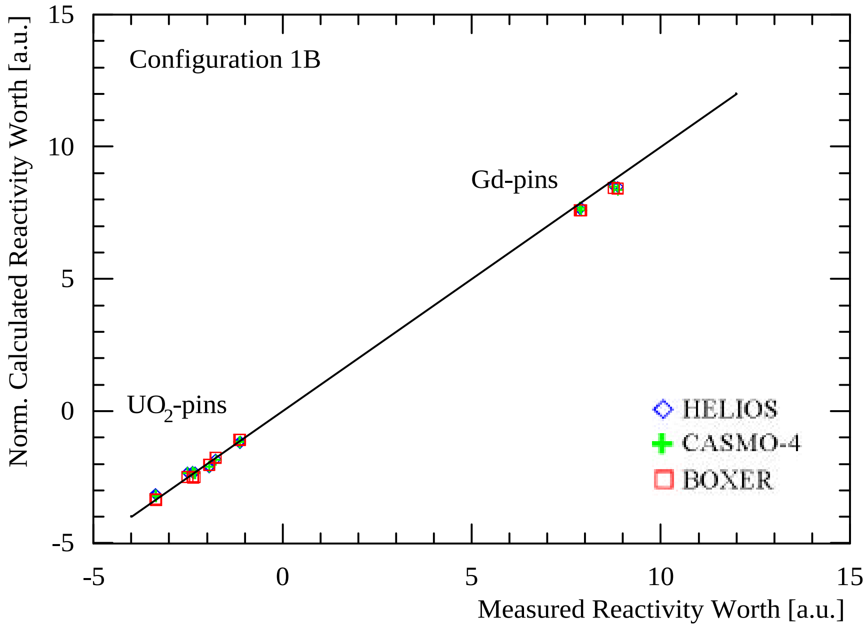


Figure 3. Calculated and measured LWR-PROTEUS reactivity worths for selected pins in the upper SVEA-96+ region.

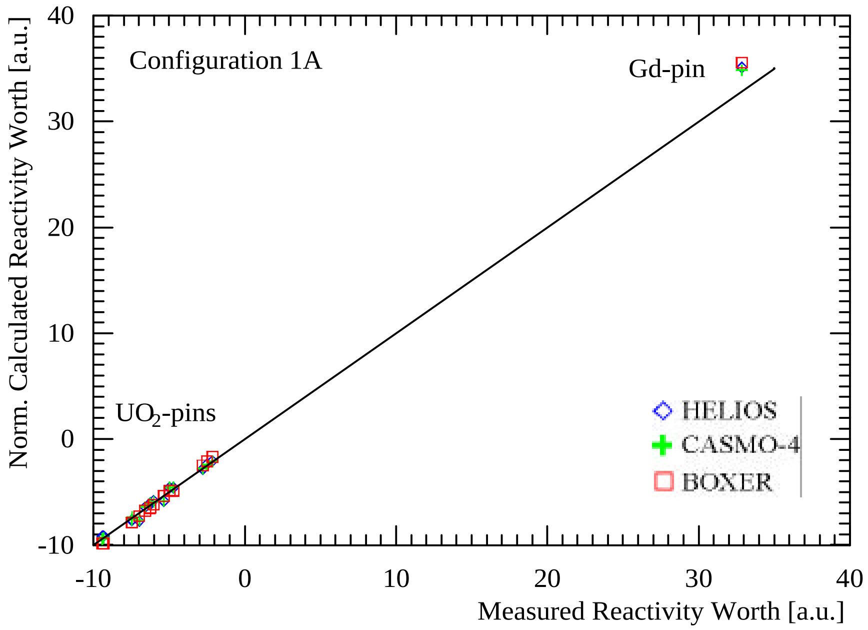


Figure 4. Calculated and measured LWR-PROTEUS reactivity worths for selected pins in the lower SVEA-96+ region.

Table I. Root-mean-square deviations (rms), maximum, and minimum (C/E-1) values for the fuel pins measured in the two SVEA-96+ axial enrichment regions.

| | rms (%) | min, max (%) |
|---|---|---|
| Upper Region: (configuration 1B) | | |
| HELIOS | 5.3 | -7.8, +9.4 |
| CASMO-4 | 4.7 | -6.7, +8.5 |
| BOXER | 4.0 | -4.9, +7.6 |
| Lower Region: (configuration 1A) | | |
| HELIOS | 5.2 | -7.3, +11 |
| CASMO-4 | 4.6 | -7.7, +9.4 |
| BOXER | 8.8 | -21, +8.2 |

Table II. Root-mean-square deviations (rms), maximum, and minimum (C/E-1) values for the fuel pins measured in configurations 2C, 4A, 7A of the lower SVEA-96+ assembly region (for further details see text).

| | rms (%) | min, max (%) |
|---|---|---|
| Configuration 2C: | | |
| CASMO-4 | 5.5 | -7.0, +11 |
| BOXER | 3.1 | -5.0, +4.8 |
| Configuration 4A: | | |
| CASMO-4 | 3.6 | -6.5, +5.7 |
| BOXER | 5.8 | -15, +5.7 |
| Configuration 7A: | | |
| CASMO-4 | 4.9 | -6.8, +9.3 |
| BOXER | 5.0 | -13, +4.4 |

The measured and calculated pin removal reactivity worths for the SVEA-96+ test assembly are shown in Figures 3 and 4 for configurations 1B and 1A, respectively. The figures show the strong positive reactivity effects due to removing Gd-containing fuel pins and the broad range of negative reactivity effects due to removing different $UO_2$ pins. It can be seen that the normalized values lie largely on a straight line for each calculational code and configuration, reflecting the consistency of the comparisons. The straight lines in Figures 3 and 4 indicate the relation C=E. The experimental accuracy is better than 1%; hence deviations of the C/E values for some of the pins from the straight line are due to discrepancies in the calculation of the pin removal worth. In particular, it is seen that the worth of the Gd pin measured in the lower SVEA zone (the large positive value) is over-predicted by all three codes, but for the upper zone the worths of Gd pins are generally under-predicted.

A quantitative comparison between the C and E values has been done in terms of pin-by-pin (C/E-1) differences, where the calculated and experimental results have been first normalized such that the average of the C/E ratios for the whole set of measured pins in a given configuration (15 to 18 pins, depending on the configuration) equals unity. The root-mean-square deviation (rms) together with maximum and minimum (C/E-1) values obtained in the comparisons with the different codes are shown in Table I for configurations 1A and 1B; the agreement in terms of rms is about 5% for most of the cases. While the HELIOS and CASMO-4 results are of similar quality for the upper and lower regions, the C/E values for BOXER appear significantly better in the upper region.

Results from the measurements in modified configurations (with respect to configuration 1A) of the lower region of the SVEA-96+ assembly are compiled in Table II. These modifications influence to a significant degree the neutron flux and spectrum in the pin positions of the central test assembly, which leads to different variations of the pin removal reactivity worths in the various assembly positions. The results given in Table II show that the quality of predictions of pin removal worths by the codes BOXER and CASMO-4 do not strongly change when the experimental conditions are varied.

To provide a more detailed view of the C/E values, these are shown in Figure 5 for the individual pins. The results for different pin types (having different enrichments in $^{235}U$) are indicated by different symbols; the symbols ▲, ▶, ▼, ■, ● and ✚ specify (in this sequence) pins types with increasing enrichment (2% to 5%). The strongly heterogeneous nature of the SVEA-96+ assemblies causes variations of the neutron flux and spectrum from pin position to pin position. The pin removal reactivity worth for a given pin type will therefore depend on its position in the assembly, and conversely the space-dependent neutronics in a certain position can be characterized by the pin removal reactivity worth itself. Therefore, instead of an extensive individual description of each pin, the pins will be characterized in the following discussion in terms of the reactivity worth.

Figure 5 shows the C/E ratios obtained for both the upper and lower SVEA regions (configurations 1B and 1A) from the comparison of the experiments with the BOXER, CASMO-4 and HELIOS calculations. It is noticeable that the pattern of the individual C/E ratios appears similar in the CASMO-4 and HELIOS cases, and that this differs from that of the BOXER results. The spread of the C/E ratios for highly enriched pins positioned around the central canal in configuration 1A (symbol ●), and for pins with an average enrichment and having Gd pins as neighboring pins in configuration 1B (■), is lower with BOXER than with CASMO-4 and HELIOS. The spread of the C/E ratios for the pins with the highest enrichment in configuration 1A (✚) is very large and shows a systematic tendency with BOXER, but not with CASMO-4 and HELIOS. An explanation for this tendency with BOXER (the under-prediction, by name, for pins C7, E8, D8), as well as for the case of 10% over-prediction (by name, for pins H7 and B9, each having two direct Gd-neighbors) by CASMO-4 and HELIOS in configuration 1A, is given in reference [7]. The data marked by ▶ (configuration 1B) and ▼ (configuration 1A) are both for symmetrical pins close to the corners and at the central canal, respectively. Their spread points to possible effects of geometrical discrepancies between experiment and calculational model. The data marked by ▲ are for the four corner pins. These C/E ratios agree well with all three codes for configuration 1A, but they show similar spreads with all three codes in configuration 1B. Furthermore, the presentation in Figure 5 shows clearly that the large rms value for configuration 1A with BOXER (see Table I) is mainly caused by the highly enriched pins (✚) with low pin removal worths. The rms deviations in the CASMO-4 and HELIOS cases are rather caused by the variation of the C/E values for the same pin types at different positions in the assembly. Finally, it should be mentioned that the main conclusions drawn here for the reference configuration 1A hold, in qualitative terms, also for the investigated variations of reactor conditions (configurations 2C, 4A, and 7A; see above).

The currently made observations have given rise to further investigations of (i) the basic physics of the reactivity worth change due to fuel pin removal and (ii) the sensitivity of the pin removal reactivity worth to the physical data and variations in reactor conditions. The corresponding studies conducted are being presented in a separate paper at this conference [7]. It is obvious that the calculation and analysis of the present reactivity effects is a rather complex task, which implies taking into account the direct effect of substituting the fuel pin by a water column as well as effects due to changes in the neutron flux and spectrum in the surroundings of the removed pin.

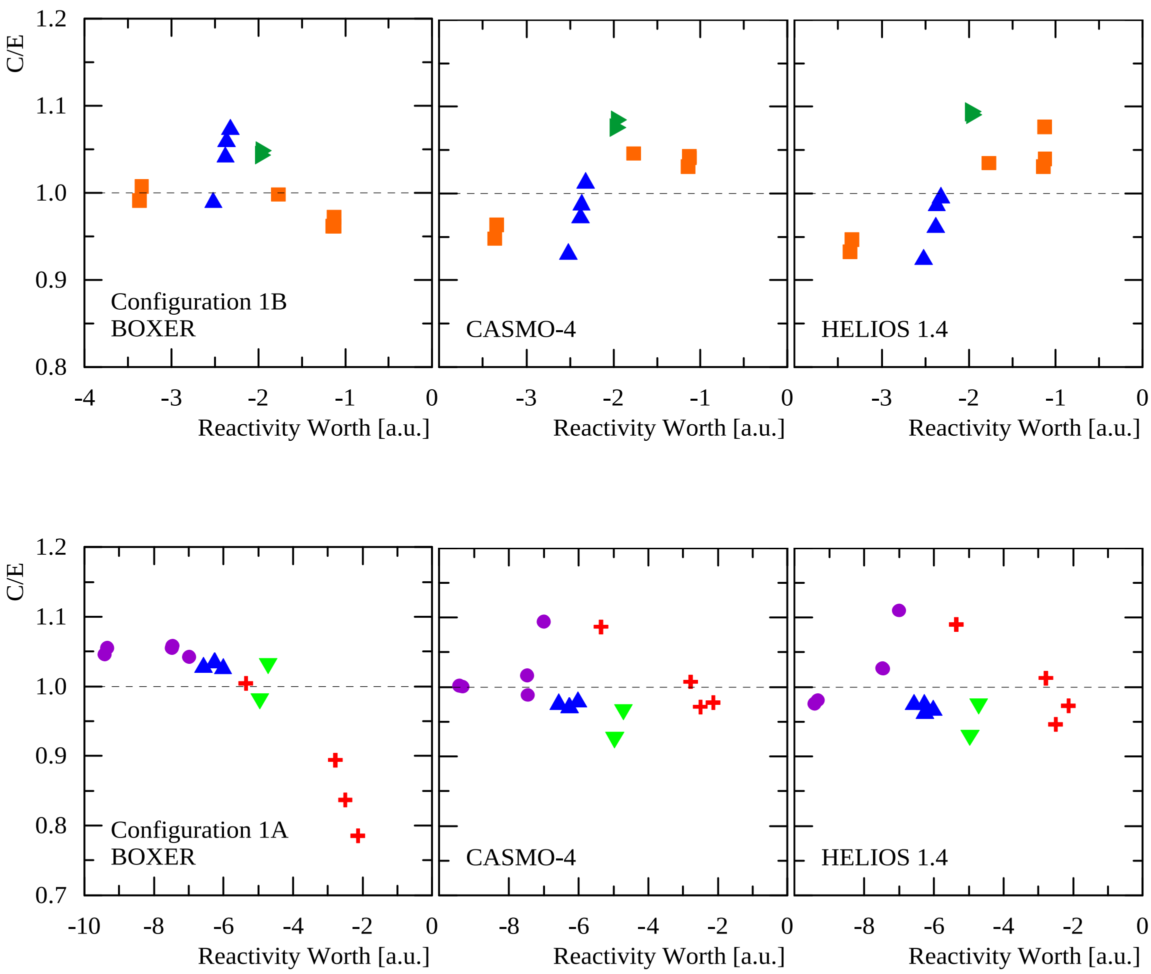


Figure 5. C/E ratios for the reactivity effects of removing individual $UO_2$ fuel pins from the upper (configuration 1B) and lower (configuration 1A) SVEA-96+ regions, corresponding to calculations with the BOXER, CASMO-4 and HELIOS codes. The C/E ratios for the different pin types are depicted as a function of the measured reactivity worth. The symbols ▲, ▶, ▼, ■, ● and ✚ specify the pins types by their enrichments (with increasing enrichment from 2% to 5%).

## CONCLUSIONS

Pin removal reactivity worth experiments in a SVEA-96+ BWR fuel assembly have been performed and analysed, in order to validate assembly code capabilities to predict reactivity differences between BWR fuel assemblies of different designs, e.g. with a varying number of part-length rods. The agreement between measured and calculated values, while generally satisfactory, has indicated the need for more detailed investigations to provide a breakdown of individual contributing effects in the currently presented experiments.

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