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Experimental Validation of Pin Power Distributions for a BWR Assembly with Hafnium Control Blades

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The accurate estimation of reactor physics parameters related to the presence of cruciform absorber blades in BWRs is important for safety assessment and for achieving a flexible operation during the cycle. Characteristics that are affected strongly include the pin power distribution for controlled regions.

The Paul Scherrer Institute and the Swiss Nuclear Utilities are conducting experimental reactor physics investigations and code validation activities related to modern LWR fuel as employed in the Swiss nuclear power plants, the so-called LWR-PROTEUS programme. A part of LWR-PROTEUS Phase I was devoted to the characterization of highly heterogeneous BWR fuel assemblies in the presence of absorber blades. The current paper presents the comparison of controlled-assembly pin power distributions calculated (C) by CASMO-4, HELIOS and BOXER with experimental (E) values measured in a Westinghouse SVEA-96+ assembly under full-density water moderation conditions in the presence of Westinghouse hafnium absorber blades. The results using detailed models show that typical *rms* deviations of the pin-by-pin (C-E) distributions are in the order of 1.5-1.6% for the three codes, a remarkably good agreement which is in fact quite similar to that obtained for the non-bladed configurations investigated in LWR-PROTEUS Phase I.

KEYWORDS: LWR-PROTEUS, BWR fuel, hafnium control blade, code validation, pin power distribution, CASMO-4, HELIOS, BOXER

1. Introduction

In a controlled BWR core region, there is a global power tilt towards the absorber blades. With the absorber blades inserted, the total power developed by the perturbed assembly is relatively low. The strong power tilt, however, significantly alters the burnup distribution inside the assembly. This effect can have an important impact when the absorber blades are withdrawn later in the cycle to compensate for the core reactivity loss due to burnup. One of the LWR-PROTEUS goals has been the characterization of highly heterogeneous BWR fuel assemblies in the presence of absorber blades. [1] It is of particular interest to validate controlled-assembly pin power distributions, which are assigned typical uncertainties of 5-7%, whereas corresponding values for uncontrolled assemblies are typically 3-4%.

The current paper presents the comparison between experimental values of the pin power distribution measured in a fresh Westinghouse SVEA-96+ assembly, affected by the presence of two Westinghouse

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hafnium absorber blades, and the predictions of modern lattice codes, viz. HELIOS, CASMO-4 and BOXER. [2-4] Use of the same experimental data for analogous validation of PHOENIX was briefly reported in Ref. [5]. The investigated assembly was surrounded by eight other SVEA-96+ assemblies, inside an aluminum test tank containing full-density water and driven critical by the outer reactor regions. The difficulties in analyzing this test zone, the so-called LWR-PROTEUS Phase I Core 2A configuration, stems from (a) the overall flux and power tilt across the assembly from the farthest rod (in the sense of rod distance to the absorber blades vertex) to the closest rod, and (b) the strong neutron-spectrum and flux variations superimposed upon this tilt as a fine flux structure resulting from the assembly's significant material and geometrical heterogeneity (present independent of the absorber blades).

2. LWR-PROTEUS Phase I Experiments

2.1 Core Configuration

In LWR-PROTEUS Phase I, a central test tank contained nine commercial BWR fuel assemblies and was “driven” critical by varying the driver fuel loading of the outer regions. The Phase I configurations provided appropriate LWR neutron spectrum environments to a centrally located Westinghouse SVEA-96+ fuel assembly in which the measurements were carried out (the “test assembly”). The test assembly was surrounded by 8 other identical assemblies, the 3x3 arrangement being located inside an aluminum test tank. The test tank was surrounded by outer radial regions (buffer, D_2O-driver, graphite driver and graphite reflector) which govern the reactor criticality, thus allowing experiments for a wide range of test lattice k_∞ values. The reactor instrumentation channels, as well as the control and safety systems, are located in the outer regions, so that the experiments at the center can be performed under “clean” conditions.

During 1999-2000, measurements in the central Westinghouse SVEA-96+ fuel assembly were carried out under both full-water-density and voidage-simulated neutron moderation conditions. Investigations were conducted to characterize the different enrichment and burnable-poison distributions in the fuel assemblies, considered over each of the two axially homogeneous regions as well as across the axial enrichment boundary.

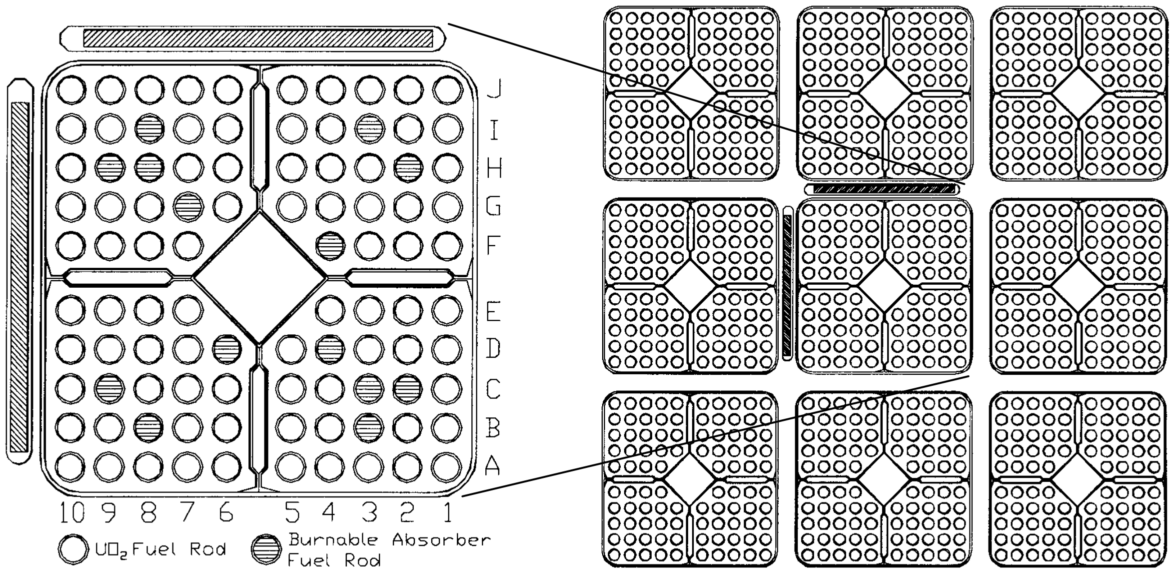

Fig. 1: Test assembly and test zone configuration for LWR-PROTEUS Phase I Core 2A

A SVEA-96+ fuel assembly comprises 96 fuel pins arranged in four separate sub-bundles, each containing 24 pins on a square pitch around a central water canal. [6] The ^{235}U enrichment varies both axially and radially in the range 2-5% (4.0% average) and some pins contain, additionally, gadolinium as burnable poison in different concentrations. The lateral assembly dimensions are about 14 cm across. The central test assembly and the test zone in LWR-PROTEUS Phase I Core 2A, with two hafnium absorber blades located along the north and west sides, are depicted in Fig. 1. The Westinghouse blades were made from stainless steel plates with a width of about 12 cm and a thickness ~0.8 cm, with cylindrical and trapezoidal end tips. These blades had horizontally drilled holes filled with hafnium pins (diameter ~0.5 cm) and seal welded.

3. Measurements in LWR-PROTEUS Phase I Configuration 2A

3.1 Gamma-scanning Technique and Irradiation Strategy

An automatic fuel rod γ-scanning machine was used to measure delayed γ-rays, from fission and activation, in individual fuel rods of the test assembly following irradiation in PROTEUS. The γ-scanning machine is a purpose-built, fully automatic device which enables the cyclic γ-scanning of activated fuel rods up to 4m in length. [7] The machine consists of five main components, a 10-pin storage rack, a horizontal axis, a grab, a vertical-axis and a measuring station. The pneumatic grab transfers rods one by one along the horizontal axis to the measuring position and back. Once an individual rod is located in the measurement head, it is transported to the required vertical position by means of the vertical drive. The overall positional reproducibility is better than 1 mm. During measurement, the rod is rotated to eliminate the effect of azimuthal activity variations within the pin.

At the measurement position, there are two horizontally opposed germanium γ-ray detectors installed behind γ-ray collimators and shielding. The detectors are connected to EG&G Ortec DSPec devices, each combining a spectrometry amplifier and a multi-channel analyzer and employing digital signal processing to produce an optimum pulse shape that gives good resolution and peak position stability over a wide range of count-rates.

Six main γ-scanning measurements were made, each with ten fuel rods. A final normalizing irradiation was done with selected rods from each of the previous six scans. The irradiations were timed as starting at 37% of the intended irradiation power, at a constant doubling time, and ending at reactor shutdown. A nominal power of 30 watts during one hour was used for all of the γ-scan irradiations. Each spectrum collected was analyzed; the background continuum was subtracted, peak areas were deconvoluted, nuclides were identified, and decay corrections were made. The statistical uncertainties of the measured fission rate distribution are within the range 0.4-1.0%, depending on the individual pin.

3.2 Geometrical Characterization of the Test Zone

Because of the severe neutron flux tilt expected in a controlled-assembly, it was essential to carefully evaluate the departure from nominal conditions in the experimental configuration. By “nominal conditions” is meant the set of numerical values describing standard input for the reactor physics evaluation of the lattice, i.e. the definition of pin-by-pin fuel and cladding compositions (including uranium enrichments) and the fuel assembly geometry on the basis of the quality assurance records of the fuel vendor and as used by the utilities for their production models.

In practice, an accurate description of the actual system departs slightly from the nominal data provided. For instance, the “measured” enrichments for a certain batch of fuel rods may be different from the standard values by as much as 0.7% (relative). Other sources for departure from nominal conditions are associated with the mechanical fabrication of the fuel assemblies. For example, instead of being perfectly straight, an axial bending of as much as ~1 mm may be expected for the channels of fresh fuel assemblies. In the case of controlled regions, the position of the blades had also to be carefully characterized. The effects of mechanical tolerances and actual material compositions on reaction rate distributions, relative to results obtained using nominal data, were evaluated using assembly codes. The following slight departures from nominal conditions were found significant compared with experimental errors: ^{235}U enrichment, horizontal length of the absorber in the blades, external dimensions of the blades, position of the blades (distance to the vertex and distance to the assembly), position of the sub-bundles in the sub-channels, and inter-assembly gaps.

The use of actual fuel assemblies in LWR-PROTEUS has thus brought the opportunity to study the sensitivity of integral parameters to typical departures from nominal specifications. Using the assembly-specific material compositions provided by the fuel vendor and the geometrical characterization performed in-house, models appropriate to the experimental configuration were developed and have currently been used for the comparison of calculational and experimental results.

4. Calculations Performed

Different two-dimensional models were investigated using HELIOS, CASMO-4 and BOXER in a manner representative of routine production calculations.

The simplest model employed for Configuration 2A consisted of a controlled assembly with reflective boundary conditions. This model was used with all three assembly codes, although its relative simplicity did not allow a direct comparison between calculational results and measurements. In fact, the reflective boundary conditions represent a full cross (four blades), over-emphasizing the power tilt compared to the actual experiments (only two blades, see Fig. 1). The reflected-assembly results were nevertheless found to be very useful for the inter-comparison of the codes, as well as to study in detail the physics involving a detailed flux structure (with a characteristic length of a mean free path) superimposed upon a strong global flux tilt with a characteristic length similar to the assembly size. Fig. 2 shows a typical CASMO-4 reflected-assembly calculation of the pin power distribution.

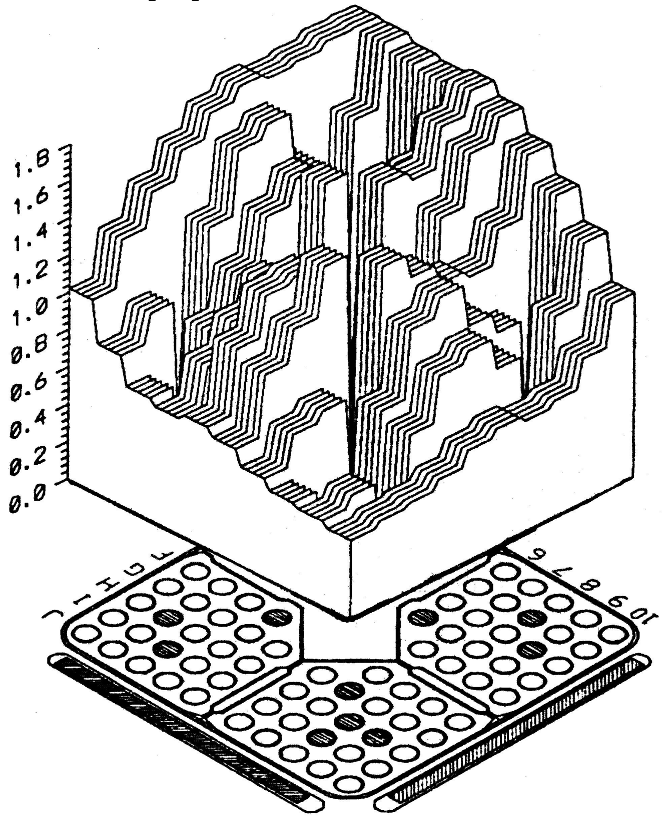

Fig. 2: Pin power distribution calculated with CASMO-4 using a reflected-assembly model

Additionally, full-core models were developed for HELIOS and BOXER. In the HELIOS calculation, a horizontal section of the PROTEUS reactor was modeled in full detail. In the BOXER model, each pin cell in the test zone was represented explicitly, but the modeling of the outer regions was simplified, in particular replacing circular zone boundaries by square boundaries enclosing the same cross-sectional area. The results of these 2D full-core models were used directly to validate these two codes against the experimental values, as well as to derive correction factors (defined as the ratio of full-core to reflected-assembly pin powers) to be applied to CASMO-4 reflected-assembly calculations before comparing the latter results with the measurements.

5. HELIOS, CASMO-4 and BOXER Validation

Fig. 3 shows the pin-by-pin comparison of calculated (C) and measured (E) total fission rate values, presented in the form of a (C-E) map obtained with the three codes. Both calculated and measured distributions were first normalized to an average pin power of unity for the measured pins in the test element. The average (C-E) is thus zero for each of the considered distributions.

The (C-E) distributions indicate in general very good agreement. The *rms* deviations of these distributions are 1.5-1.6% for the three codes, with maximum values in the order of a few percent (see Table 1).

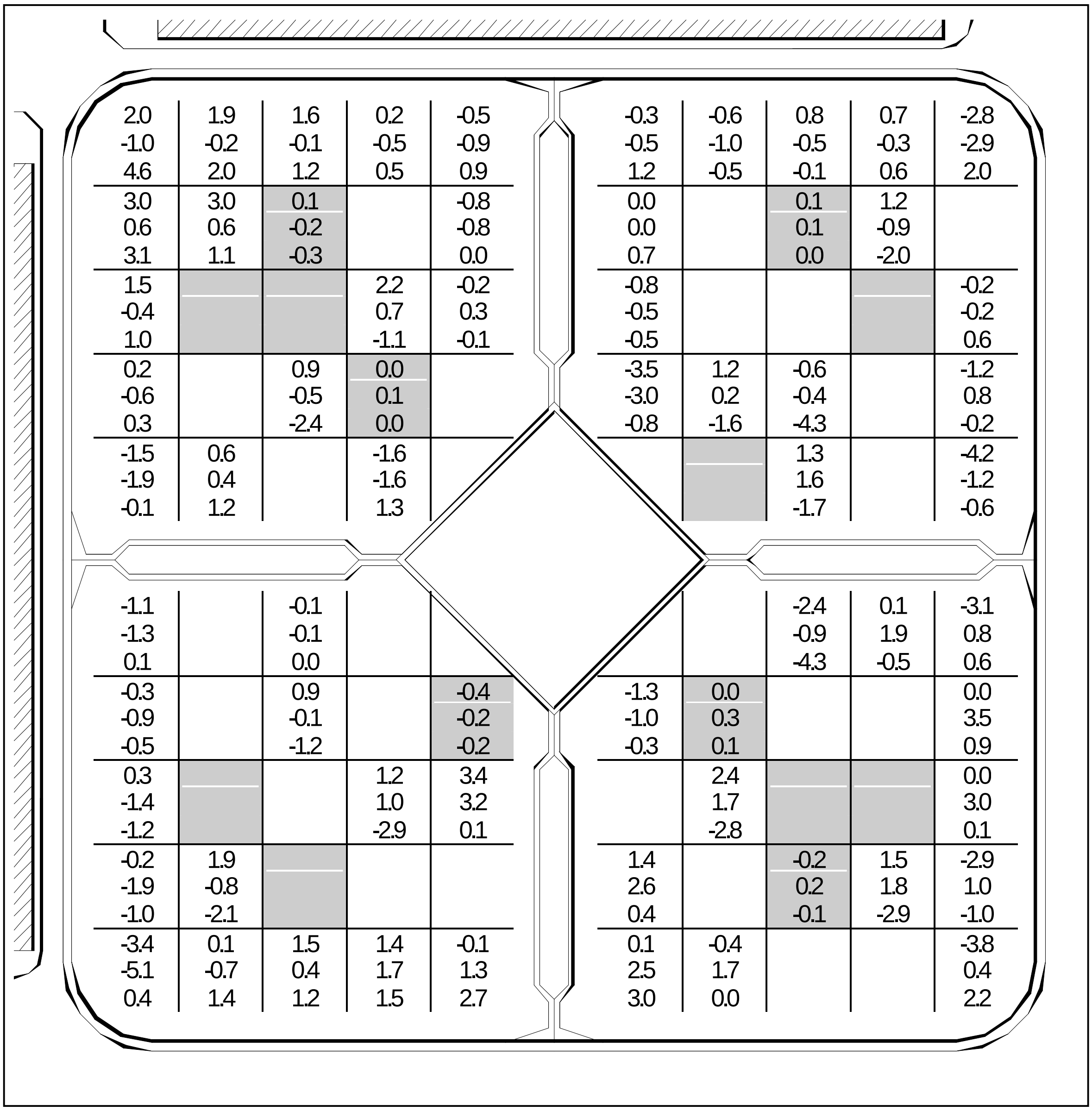

Fig. 3: (C-E) distributions (x100) for pin power as obtained with HELIOS (upper values), CASMO-4 (middle values) and BOXER (lower values).

To evaluate the accuracy of the power tilt prediction across the assembly, the pin powers were summed for each sub-bundle in the assembly (the south-east sub-bundle developing about 1.9 times the power of the north-west sub-bundle because of the tilt). Calculated and measured sub-bundle powers have further been renormalized to a sub-bundle average power of unity, and these have also been compared as (C-E) values. These sub-bundle power (C-E) values are also given in Table 1.

Table 1 Comparison of Calculated (C) and Experimental (E) Pin Power Distributions: Assembly and Sub-Bundle (C-E) Values.

Assembly	HELIOS	CASMO-4	BOXER
rms [%]	1.6	1.5	1.6
max [%]	3.4 (C6)	3.5 (D1)	4.6 (J10)
min [%]	-4.2 (F1)	-5.1 (A10)	-4.3 (E3)
Sub-Bundle-Average	HELIOS	CASMO-4	BOXER
north-west [%]	0.8	-0.4	0.8
north-east [%]	-0.6	-0.5	-0.4
south-west [%]	0.3	-0.3	-0.1
south-east [%]	-0.5	1.2	-0.3

The sub-bundle powers are predicted with discrepancies lower than 1.2% for the three codes, indicating that the main neutron transport effects related to the overall power tilt can be well represented. One also has an indication that the procedure of deriving correction factors for the validation of reflected-assembly CASMO-4 results is not introducing a significant bias.

As indicated in Fig.1, the investigated SVEA-96+ assembly had a diagonal symmetry (line passing through the pins A1 and J10), also in the presence of the two hafnium blades. Analysis of the individual pin power discrepancies, however, reveals a somewhat inconsistent picture at the north and west edges. In fact, the two blades could not be placed exactly at the same distance from the assembly walls. Although the correct average distance was used for the modeling in each case, other aspects, like the lack of perfect parallelism between the blades and the assembly channel, could not be taken into account.

It is also interesting to note that the most significant individual pin discrepancies are found for the corner pins (probably due to the difficulty to accurately model the region in the vicinity of the blades' tips), the peripheral pins and the pins close to the inner by-pass.

6. Conclusions

This paper describes the experimental validation efforts invested for the qualification of modern calculational codes used in the determination of pin power distributions in a 4.0wt% (average) enriched BWR fuel assembly under full-density water moderation conditions and strongly perturbed by the presence of hafnium absorber blades.

Generally, the results of the performed calculations agree well with the measurements. The largest observed discrepancies appear to be localized at individual pin locations where the most severe flux gradients occur. The *rms* values for differences between calculation and experiment for individual pins are 1.6% for BOXER and HELIOS, and 1.5% for CASMO-4. These are very good and in fact quite similar to those found for non-bladed configurations. [8]

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