Enhancements of BWR Core Analysis Code

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Abstract

The sources of inaccuracy in BWR nodal core analyses have been isolated by comparing 2-D quarter-core heterogeneous multi-group transport calculations with analogous homogenized two-group nodal diffusion calculations.
More than 100 BWR core configurations (near-homogeneous and multi-enrichment cores) have been examined to estimate the inaccuracy of BWR nodal core solutions (especially on the assembly power distribution and eigenvalues), and the sources of the inaccuracy were extracted by comparing with reference full core solutions.
The assembly-averaged two-group cross sections and surface-averaged discontinuity factors were modified to improve the accuracy of nodal diffusion calculations. Enhancements previously developed for PWR MOX core analysis were applied to BWR cases, and they lead to improved results. The single-assemlbly discontinuity factors (ADFs) were also modified to treat their dependence on local leakage.
As a result of the enhancements introduced here, the observed errors in power distributions and eigenvalues were reduced, with no apparent sensitivity to BWR core loading configurations.

1. Introduction

Recent comparisons between computed and measured BWR power distributions (via bundle gamma scans of Ba-140/La-140) have shown that cores with very large mismatches in bundle enrichments lead to larger errors in the calculated power distributions than those observed on traditional cores. In an effort to improve the accuracy of BWR calculations, extensive efforts have been directed at understanding the sources of the computational errors, and improving the computational models.

The possible sources of errors in the computational models include: nuclear data, lattice physics methods, thermal hydraulic models, and the various sub-models of the 3-D nodal core simulator. This paper summarizes tests performed to isolate sources of inaccuracy in the 3-D core simulator by

comparing full-core (2-D) heterogeneous multi-group transport calculations with analogous homogenized two-group nodal diffusion calculations. This approach allowed isolation of the errors because the same heterogeneous multi-group transport model was used in both for the generation of the 2-group nodal lattice data and for the reference 2-D solutions.

2. Reference Calculations

The CHAPLET[1] code was used to provide reference heterogeneous multi-group transport solutions. CHAPLET is a characteristics transport code, which incorporates direct neutron path linking (DNPL) technique to a multi-assembly system. DNPL technique enables to connect neutron tracking paths of neighboring assemblies directly beyond their border (see Fig.1).

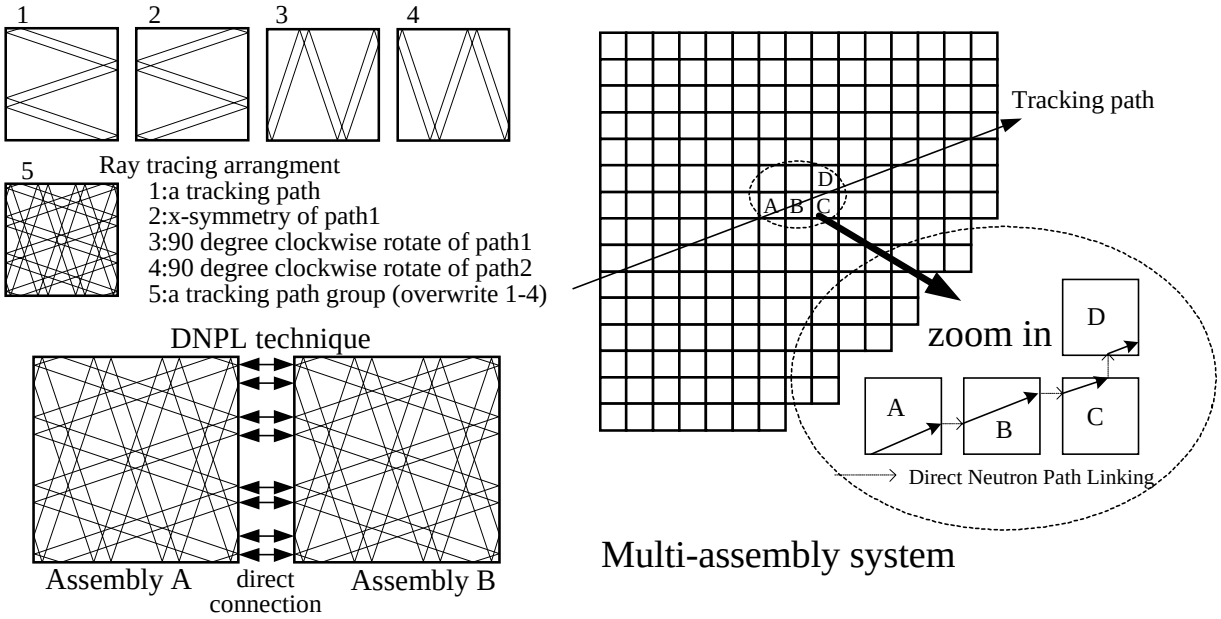

Figure 1. Ray tracing sample with DNPL technique

Using DNPL technique, the identical accuracy whole core solution is obtained without performing whole core ray tracing. This makes it possible to reduce required memory size and calculate a large heterogeneous core system, such as a BWR-5 quarter-core, with less computer power than that of whole core ray tracing characteristics calculation.
CHAPLET has been extensively verified versus: single-assembly and multi-assembly CASMO-4[2] lattice calculations, direct calculation of small core critical configurations[1], and measured reaction rate distributions in actual PWR. In the tests reported here, CHAPLET calculations were performed for a large number of 2-D core loadings in which the distributions of fuel temperature, void, and control rods are specified (i.e. no feedback).

3.Simulator Calculations

The SIMULATE-3 advanced nodal code[3] was used to perform core calculations which precisely parallel the reference CHAPLET calculations. The lattice data for SIMULATE-3 calculations were generated by performing single-assembly CHAPLET lattice calculations (with reflective boundary

conditions). These calculations provided assembly-averaged two-group cross sections, diffusion coefficients, and surface-averaged discontinuity factors[4] for each lattice state. In this analysis, all diffusion coefficients were computed by flux-volume weighting sigma-transport and then energy collapsing 1/(3 sigma-transport).

4.Test Cases

More than 100 core configurations have been examined. The most significant differences arose with three different types of BWR core loadings, some with very large spectral mismatches between fuel assemblies (cf. Fig.2):

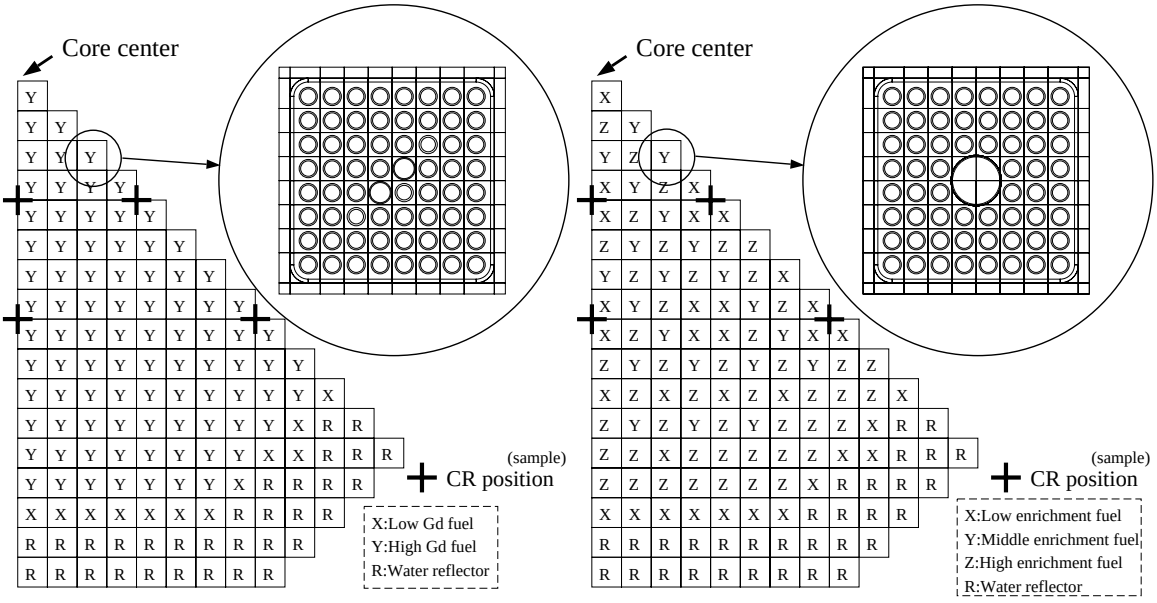

Figure 2. Core configuration samples.

Core 1) near-homogeneous BWR-5 initial core (near uniform enrichment)
Core 2) multi-enrichment BWR-5 initial core (bundle-average enrichments from 0.7% to 3.6%)
Core 3) multi-enrichment ABWR initial core (bundle-average enrichments from 0.7% to 3.7%)

For each core, a variety of fixed void distributions and control rod (CR) pattern conditions were examined by comparing reference 7-group (sometimes 23-group) CHAPLET heterogeneous characteristic calculations with analogous 2-group SIMULATE-3 calculations.

The RMS errors of the SIMULATE-3 assembly power distribution and eigenvalues obtained using assembly-averaged cross sections (AXSs) and assembly discontinuity factors (ADFs) are shown in Table 1.

Table.1 Results of Conventional Nodal Calculations

Case (Void =0.0%)		RMS Error in Power Distribution (%)	Error in k-eff (%)
Core 1	All rods out	1.22	-0.00
	CR pattern 1	2.05	+0.02
	CR pattern 2	2.53	+0.03
Core 2	All rods out	2.54	-0.24
	CR pattern 1	2.97	-0.26
	CR pattern 2	3.50	-0.22
Core 3	All rods out	2.41	-0.15
	CR pattern 1	2.59	-0.16
	CR pattern 3	2.62	-0.11

The magnitude of the errors in the SIMULATE-3 calculations increase with the degree of bundle enrichment mismatch and the number of inserted control rods.

5.Model enhancements

The reproducibility of nodal calculation using reference cross sections (RXSs) and reference discontinuity factors (RDFs) was verified in advance of these studies. RXSs[4] are the assembly homogenized cross sections collapsed from the reference CHAPLET flux solutions, and RDFs[4] are the discontinuity factors defined as the ratio of reference assembly surface flux and computed homogeneous nodal surface flux with fixed surface current from the reference solutions as their boundary conditions.
Though small errors can be seen, the accuracy is enough good to consider these RXSs and RDFs as proper references of nodal constants (see Fig.3).

The error in power distribution was decomposed into the elements from cross section error and discontinuity factor error, by comparing the errors from the nodal calculations in which AXSs or ADFs were replaced with their reference values (RXSs, RDFs). (cf. Fig.4)

Much work has been performed in recent years to improve the accuracy of SIMULATE-3 for applications to MOX-fueled PWR cores[5]-[8]. PWR MOX cores have larger spectral mismatches, compared to those encountered in the BWR test cases studied here. Consequently, the starting point for improving the accuracy of SIMULATE-3 for BWR applications was to adapt the MOX methods improvements.

The spatial re-homogenization model of SIMULATE-3[6],[8] was applied to all BWR cases. This model assumes that the assembly-averaged cross sections are a function of the spatial flux tilt across each fuel assembly, and it permits the assembly-averaged cross sections to be updated as the nodal solution is obtained. By comparing RXSs and SIMULATE-3 re-homogenized cross sections, it was determined that the re-homogenization coefficients were slightly over-estimated when computed from zero leakage lattice calculations. Consequently, an attenuation factor was applied to all re-homogenization coefficients, and significantly improved predictions were obtained.

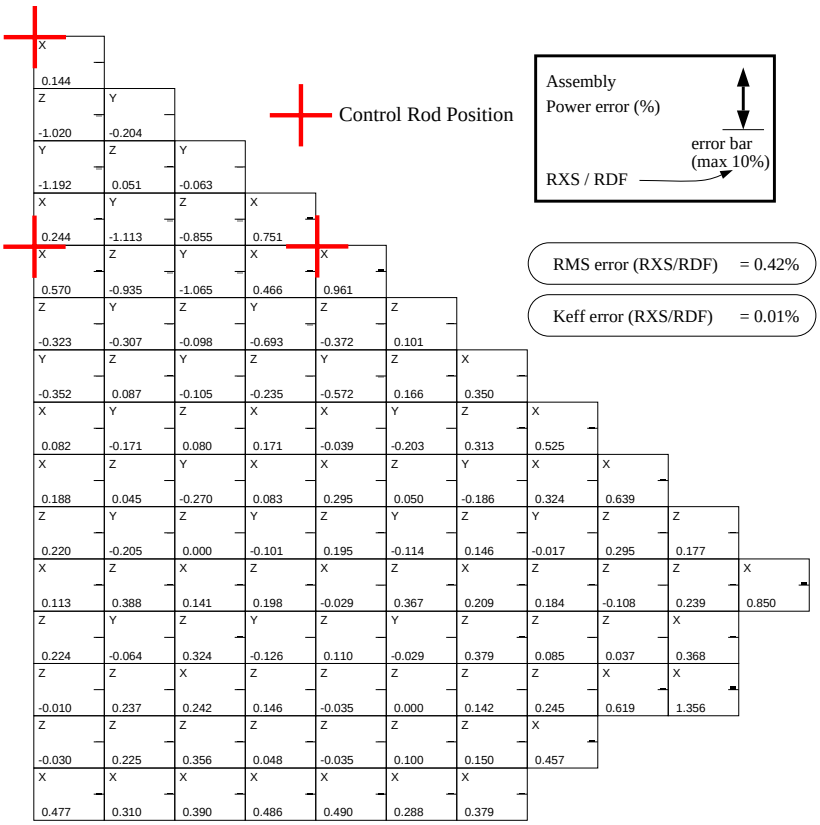

Figure 3. Assembly power error of RXS/RDF nodal calculation compared with CHAPLET. (Core 2, CR pattern 1)

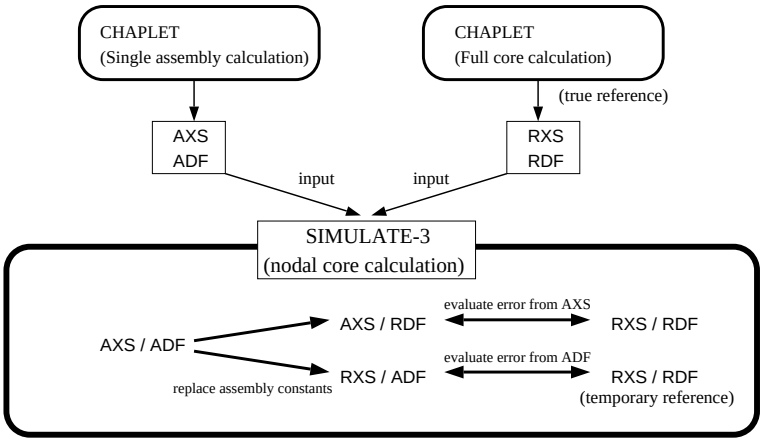

Figure 4. Image of decomposing error elements.

The spectral re-homogenization model of SIMULATE-3[(5),(7)] was also applied to all BWR test cases. This model assumes that the assembly-averaged cross sections are a function of the fast-group neutron leakage, and it permits the cross sections to be updated as the nodal solution is obtained. This leakage model partially corrects the errors normally introduced by energy collapsing in the single-assembly (zero leakage or critically-buckled) lattice spectrum.

Figure 5 shows the assembly power errors of nodal calculations using the cross sections before(AXS) and after modified(MXS) at CR pattern 1 of Core 2. Reference discontinuity factors are used in both cases. The RMS error is reduced from 2.3% to 1.2%. Especially the errors around control rod inserted assemblies are remarkably improved. Keff value is also improved by this cross section modification.

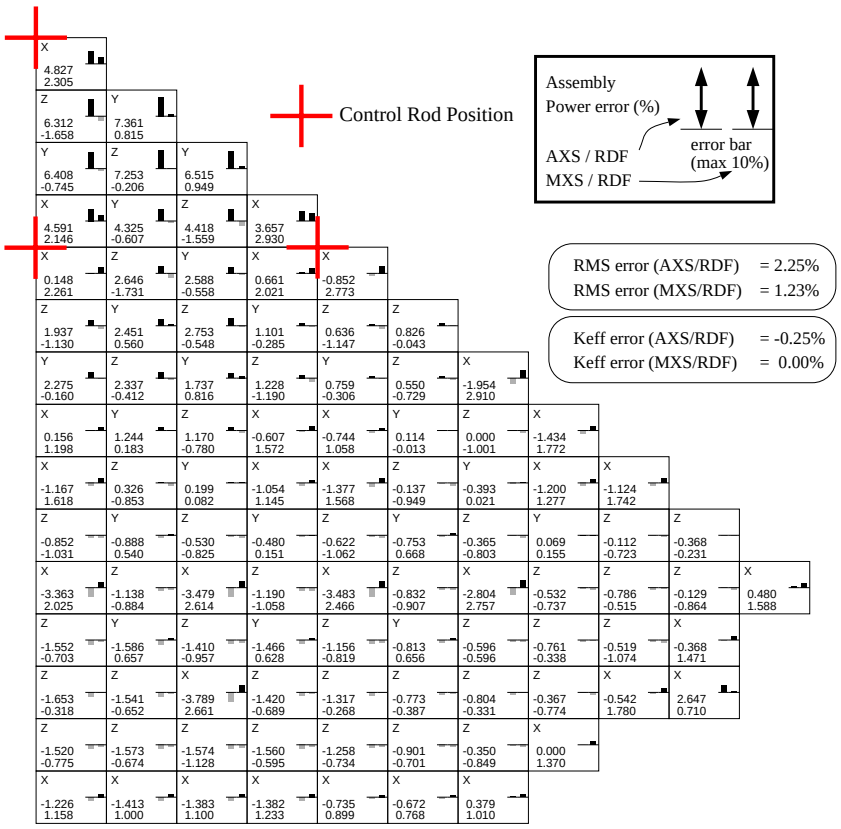

Figure 5. Assembly power error of AXS/RDF and MXS/RDF nodal calculation.
(Core 2, CR pattern 1)

Comparisons of reference fast-group discontinuity factors (RDFs) from the CHAPLET solutions and ADFs showed that the errors introduced by the fast group ADFs are quite small. However, comparisons showed that thermal-group ADFs often over-predict the magnitude of flux discontinuities between assemblies. In order to compensate for this, an *ad hoc* procedure was developed which applies the ADFs only to the asymptotic fraction of the node-surface fluxes. One result of implementation of this procedure is that the magnitude of the flux discontinuities between fuel assemblies becomes a non-linear function of the nodal solution (unlike application of conventional ADFs).

The assembly power errors of nodal calculations using the discontinuity factors before(ADF) and after modified(MDF) for CR pattern 1 of Core 2 is shown in Fig.6. Reference cross sections are used in both cases. Applying the procedure for adjusting discontinuity factors, the power errors are reduced.

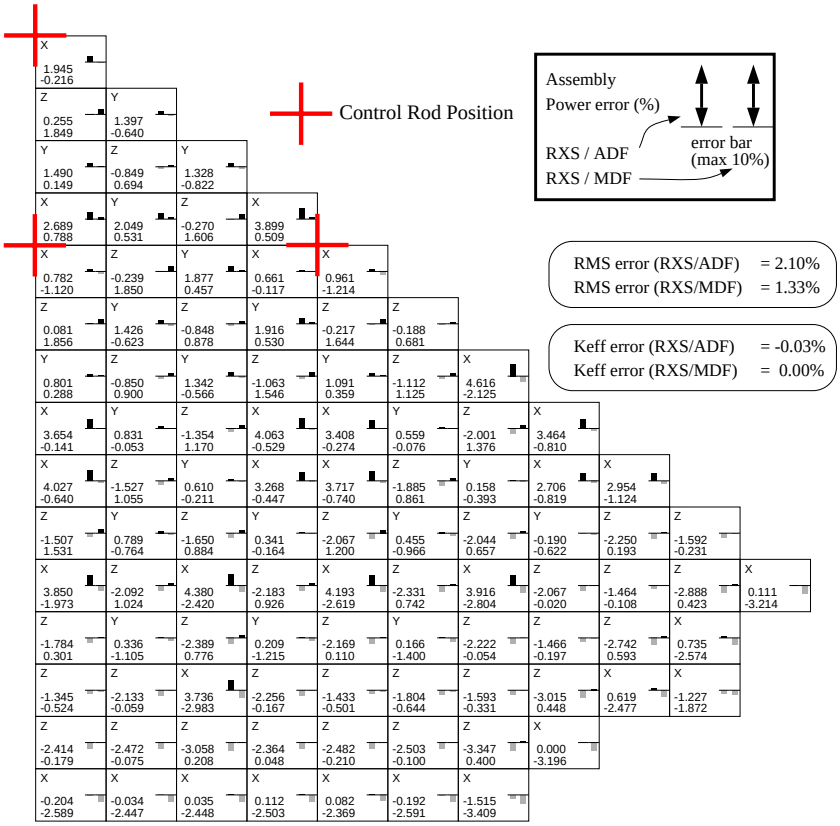

Figure 6. Assembly power error of RXS/ADF and RXS/MDF nodal calculation.
(Core 2, CR pattern 1)

The errors of the SIMULATE-3 assembly power distribution and eigenvalues obtained using these three model enhancements for CR pattern 1 of Core 2 is shown in Fig.7 and the summary results of enhancement cases corresponding to Table 1 are displayed in Table 2. The accuracy of nodal calculation is improved, independent of core configurations.

Table.2 Results of Improved Nodal Calculations

Case (Void =0.0%)		RMS Error in Power Distribution (%)	Error in k-eff (%)
Core 1	All rods out	0.75	-0.00
	CR pattern 1	0.82	+0.04
	CR pattern 2	0.73	+0.07
Core 2	All rods out	0.66	-0.00
	CR pattern 1	0.71	+0.02
	CR pattern 2	0.76	+0.05
Core 3	All rods out	0.69	+0.01
	CR pattern 1	0.78	+0.02
	CR pattern 3	0.83	+0.06

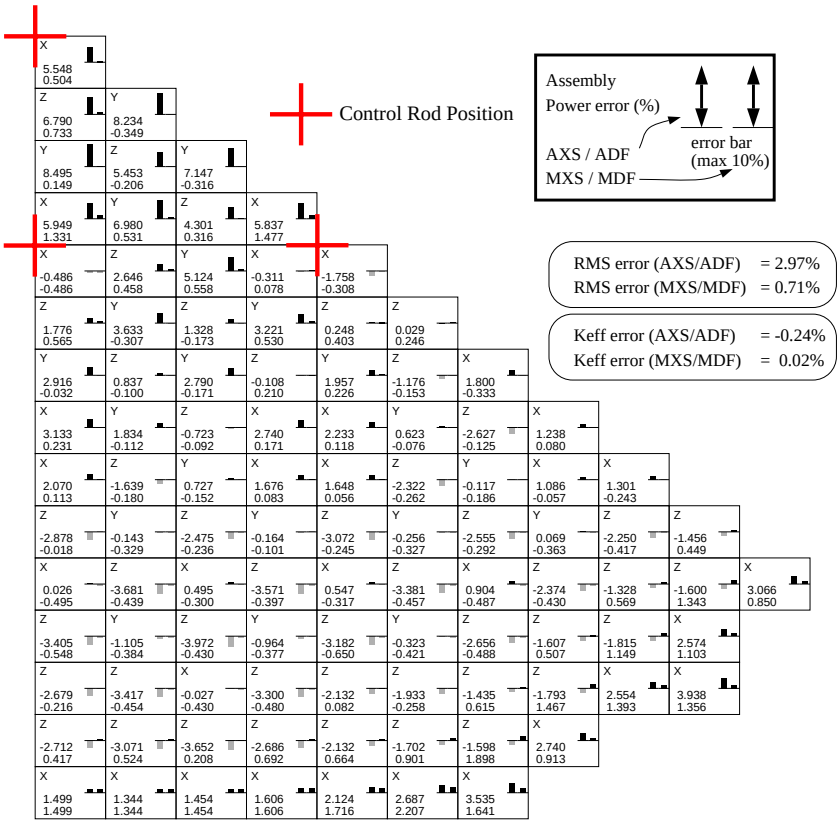

Figure 7. Assembly power error of AXS/ADF and MXS/MDF nodal calculation.
(Core 2, CR pattern 1)

6.Summary

The sources of error in BWR advanced nodal models have been isolated by comparing detailed full-core CHAPLET reference calculations with SIMULATE-3 nodal calculations.

Adaption of PWR MOX models to BWR applications and some improvements introduced here reduced the observed errors in power distributions and eigenvalues by approximately a factor of three in cores with large spectral mismatches.

The net result of these nodal model improvements is that the accuracy of the SIMULATE-3 nodal solutions (relative to reference, no feedback, multi-group transport calculations) are independent of core loading pattern, bundle enrichment mismatches, and control rod patterns.

References

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