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ALAADIN/FLS – A BWR Fast Lattice Design Simulation Tool

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This paper describes a BWR fast lattice design simulation tool - ALAADIN/FLS which will be used in a BWR assembly lattice optimization (BALO) system. ALAADIN is a graphical user interface. FLS, a fast lattice simulator, provides a quick solution of three nuclear characteristic curves of lattice at three voids (0%, 40% and 80%): infinitive multiplication factors (Kinf) vs. burn up, maximum pin power vs. burn up, F-eff vs. burn up. FLS employs the following algorithms: massive non-linear two dimensional interpolations with a perturbation library, superposition and pin power re-normalization. For each single fuel pin, the non linear interference between variations of enrichment and Gd weight is taken into account in the algorithms. Among pins, the enrichment perturbations show that the linear superposition is a good approximation. But among Gd pins, the linear superposition is good only for sparse and scattered Gd pins, not for Gd clusters. A correction matrix must be added to the perturbation library to accommodate Gd clusters. For normal designs with no Gd clusters, FLS has shown very good results over the entire design range from 0 GWD/MT to 70 GWD/MT for enrichments from 0.71% to 5% and Gd weights from 0% to 8%. Compared with CASMO4, the time to obtain results is measured in seconds instead of hours, with Kinf accuracy about 0.01% without Gd pins or after peak reactivity with Gd pins (within 0.1% before peak reactivity with Gd pins) and maximum pin powers about 1%.

KEYWORDS: Fast lattice simulator, ALAADIN, Nuclear fuel lattice design, Boiling Water Reactor

1. Introduction

ALAADIN/FLS is part of Framatome ANP's current effort to develop a package of software tools for BWR core neutronic design optimization. The optimization program includes fuel assembly nuclear design, control rod pattern determinations (KAMROD)[(1)], core loading pattern development (PRIMO-BWR)[(2)] and licensing analysis. A successful nuclear design is the outcome of an iterative process involving both fuel assembly and reactor core analysis. The best assembly designs should deliver nuclear characteristics that best fit reactor core design requirements for multiple cycle operation. Lattice design optimization is the starting point for this process.

Three nuclear characteristics curves are used for lattice design at Framatome ANP: infinitive multiplication factor Kinf vs. burn up, maximum pin power (MPP) vs. burn up and F-eff vs. burn up, where F-eff is a correlation factor for local peaking dependence and mechanical design dependence within ANFB[(3)] and, SPCB[(4)] critical power correlations. To

generate these curves, many time consuming lattice burn up calculations involving 2D neutron transport codes such as CASMO3/4[5], are required. Sometimes an optimized assembly design is challenging because of schedule constraints. ALAADIN/FLS is designed to solve this problem by delivering much faster solutions with adequate accuracy.

After many testing calculations with ALAADIN[6] /CAZAM[7] /CASMO4, the values of Kinf, MPP, and F-eff vs. variation of U235 Enrichment on single pin and multiple pins show very good linearity over entire design ranges of burn up and voids. But these values vs. variation of Gd weight on single Gd pin show non linearity around the peak reactivity where Gd burned out and changed from one linear rate to another. Also, the dual variations of U235 enrichment and Gd weight of single Gd pin show non linearity because of interaction between U235 and Gd of the pin. Among pins, tests show that the linear superposition method is a good approximation for lattices with sparse and scattered Gd pins if each single pin's perturbation is estimated correctly.

ALAADIN/FLS employs the algorithms of massive two dimensional (3x3 points) interpolation, superposition and pin power renormalization with a perturbation library created by ALAADIN/CAZAM/CASMO4. The accuracy of FLS is about 0.01% for Kinf without Gd pins or after peak reactivity with Gd pins, within 0.1% before peak reactivity with Gd pins, and 1% for MPP and F-eff over all the interested design ranges. The speed of ALAADIN/FLS is seconds vs. hours compared with CASMO4.

2. ALAADIN

ALAADIN is a graphical user interface tool, written in Smalltalk, that provides visualization for the assembly design process. Historically, ALAADIN provided a graphical user interface for running CAZAM/CASMO3/4. It has been modified to interface with FLS (Fast Lattice Simulator). It provides the ability to change enrichments and Gd weights from a pin map using point and click technology, creates input files, runs FLS and post processes the results. It displays the results, including the three above mentioned nuclear characteristic curves, Gadrat curves (Gadolinia rod to UO2 rod power peaking ratio vs. Burnup) and pin power distributions. Comparisons between FLS and CASMO3/4 results can be performed graphically.

ALAADIN assumes HPUX[8] version 11.0 or higher, and running in the Korn Shell with monitors having a minimum 1280 X 1024 resolution. Figure 1 shows the standard MENU bar and a typical lattice view.

3. Perturbation Library

To develop a fast lattice simulator, a perturbation library must be generated in advance with CASMO3/4, and it should cover all the design ranges. In our library, the U235 enrichment range is from 0.71% to 5%, Gd weight is from 0% to 8%, voids are 0%, 40% and 80%, and burn up is from 0 GWD/MT to 70 GWD/MT. Also, the libraries are geometry dependent and ALAADIN will automatically choose the right one for users, see Figure 2. Of course, the general library will be a large database. But today's technology allows us to store this kind of lager data without any difficulty. Also, once ALAADIN identifies the right one for a lattice

case, only the used part for the lattice case will be initially read in as Plib which will be used for the whole optimization process. Plib is designed dynamically and uses dynamic memory allocation, and thus, is limited in problem size only by the physical restrictions of the computer platform it is running on.

The perturbation library, as a property or a resource pool, can be generated gradually and evolutionary, one by one, for all interested kind of fuel assemblies. Usually it takes a couple of days to create a new one to add into the pool, depending on computer speed.

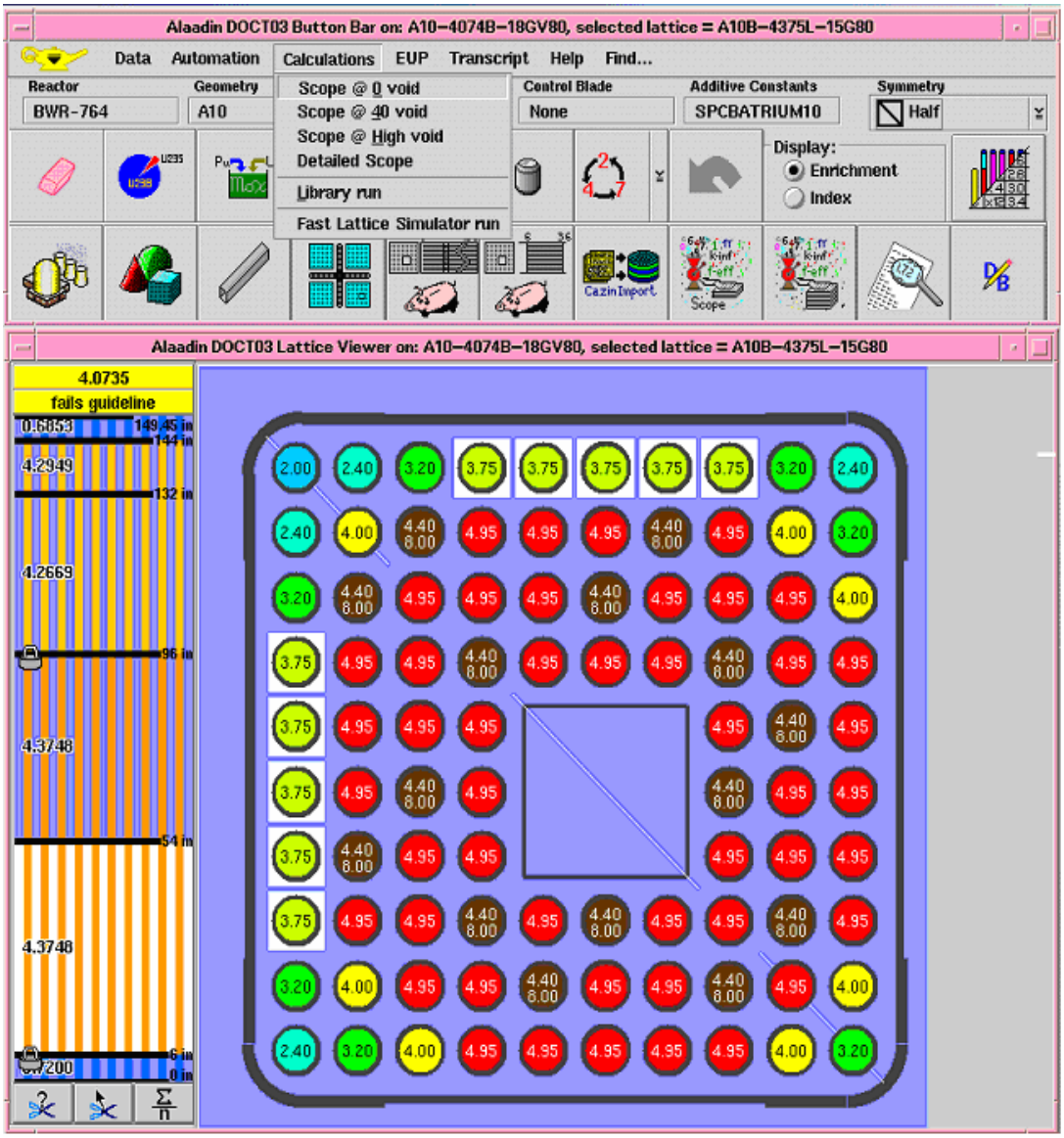

Figure 1 ALAADIN Standard Menu Bar And A Typical Lattice View

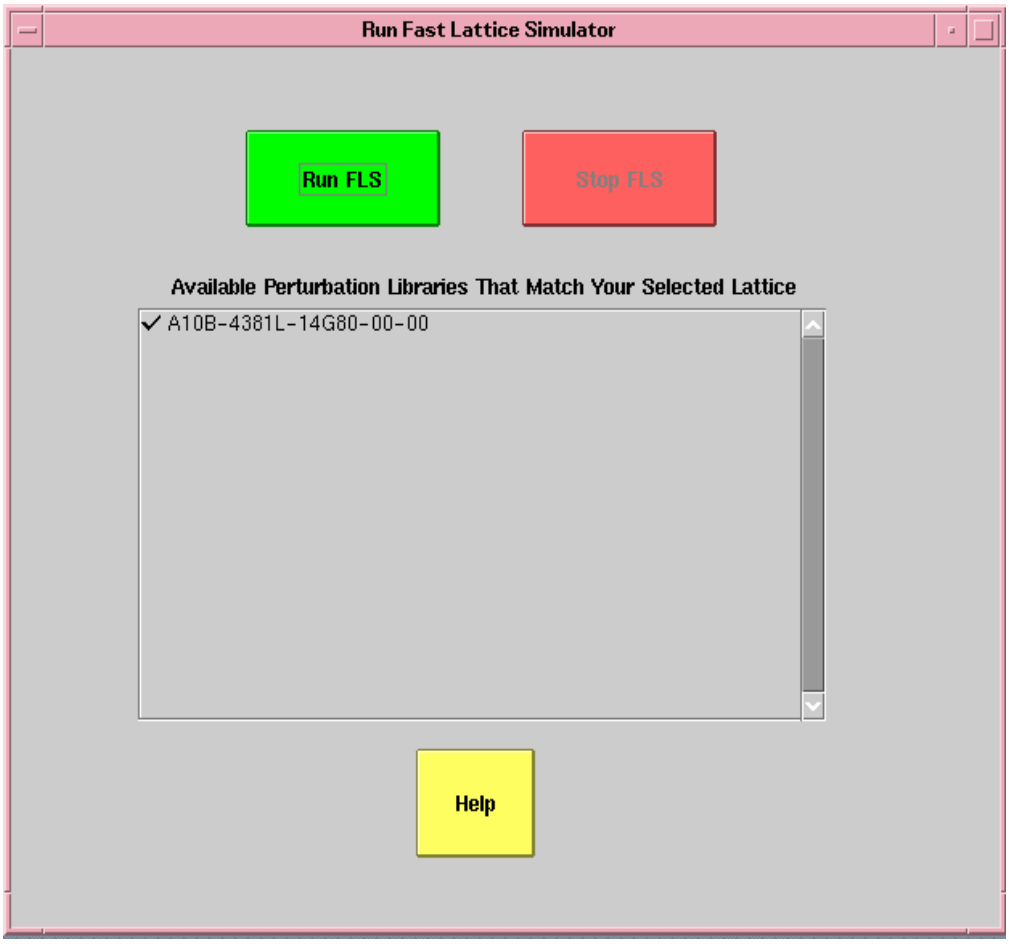

Figure 2 ALAADIN Chooses Libraries For Users

4. Fast Lattice Simulator (FLS)

The Fast Lattice Simulator (FLS), written in the C language, is designed to deliver fast nuclear lattice solutions with accuracy comparable with CASMO. Its use of dynamic data and file structures accommodate any size lattice. To run FLS, it is first necessary to create a two dimensional (U-235 enrichment and gadolinia weight) perturbation library (Plib) using ALAADIN/CAZAM/CASMO3/4. FLS uses the Plib in a massive two dimensional 3x3 Lagrangian interpolation algorithm to obtain values of Kinf and pin power at each void and each burnup step, and then ALAADIN/FLS uses pin power distributions to calculate F-efff. Our investigation shows that most perturbation cases can be assumed to be linear, such as single variation of U-235 enrichment in a fuel pin. But non-linear perturbations have been observed when both U-235 enrichment and gadolinia weight in a fuel pin are varied. This is caused by the interaction between the two. This non-linearity is adequately handled by the two dimensional 3x3 interpolation algorithm in FLS. At peak reactivity when gadolinia burns out, this non-linear interaction disappears and a turning point occurs. The typical two dimensional 3x3 Lagrangian interpolation algorithm as the following equation (1):

$$F(x,y)=\sum_{r=i}^{i+2}\sum_{s=j}^{j+2}\left(\prod_{\substack{K=i\\k\neq r}}^{i+2}\frac{x-x_k}{x_r-x_k}\right)\left(\prod_{\substack{l=j\\l\neq s}}^{j+2}\frac{y-y_l}{y_s-y_l}\right)F(x_r,y_s) \qquad \textbf{(1)}$$

where x and y are the variables, r and k are the point numbers on the axis of variable x, s and l are the point numbers on the axis of variable y, and F is the function. Usually, a case need perform more than 10,000 interpolation calculations. In our programming, the fast massive interpolation method has improved the speed.

Normally, among fuel pins, the linear superposition of perturbation is a good approximation. But for gadolinia rod clusters, the linear superposition can cause significant errors, depending on the shape of the clusters. Errors of about 1% for Kinf and 5% for their pin powers have been observed. These errors are from the overestimated or underestimated impacts of Gd clusters, dependent on the case. Since gadolinia rod clusters are not usually part of a lattice design and their pin powers are far lower than other pins, it is not a concern in the current FLS version. But we have looked at the impact of certain Gd pin configurations and plan to add the necessary correction matrix for gadolinia rods clusters in the future. Ignoring these special cases, we conclude that FLS delivers very good agreement with CASMO4 for U-235 enrichments from 0.71% to 5% and gadolinia weights from 0 to 8% over the entire design range from 0 GWD/MT to 70 GWD/MT. Compared with CASMO4, the time to obtain results is measured in seconds instead of hours, with Kinf accuracy about 0.01% without Gd pins or after Gd burn out, within 0.1% before Gd burn out, and pin power about 1%. The accuracy and speed met our criteria as a fast lattice design simulation for BALO (BWR Assembly Lattice Optimizer).

5 Test and Results

Figure 3 is a test 10x10 lattice map showing pin by pin U-235 enrichment and gadolinia weight distribution. Figure 4 is a perturbated lattice map showing 25 pins perturbated. Figure 5 shows Kinf curve comparisons for three different voids (0%, 40% and 80%) between FLS and CASMO4. Similarly, Figure 6 shows MPP curve comparisons and Figure 7 shows F-eff curves comparisons. All these curves show very good agreement of FLS with CASMO4 over the entire design range.

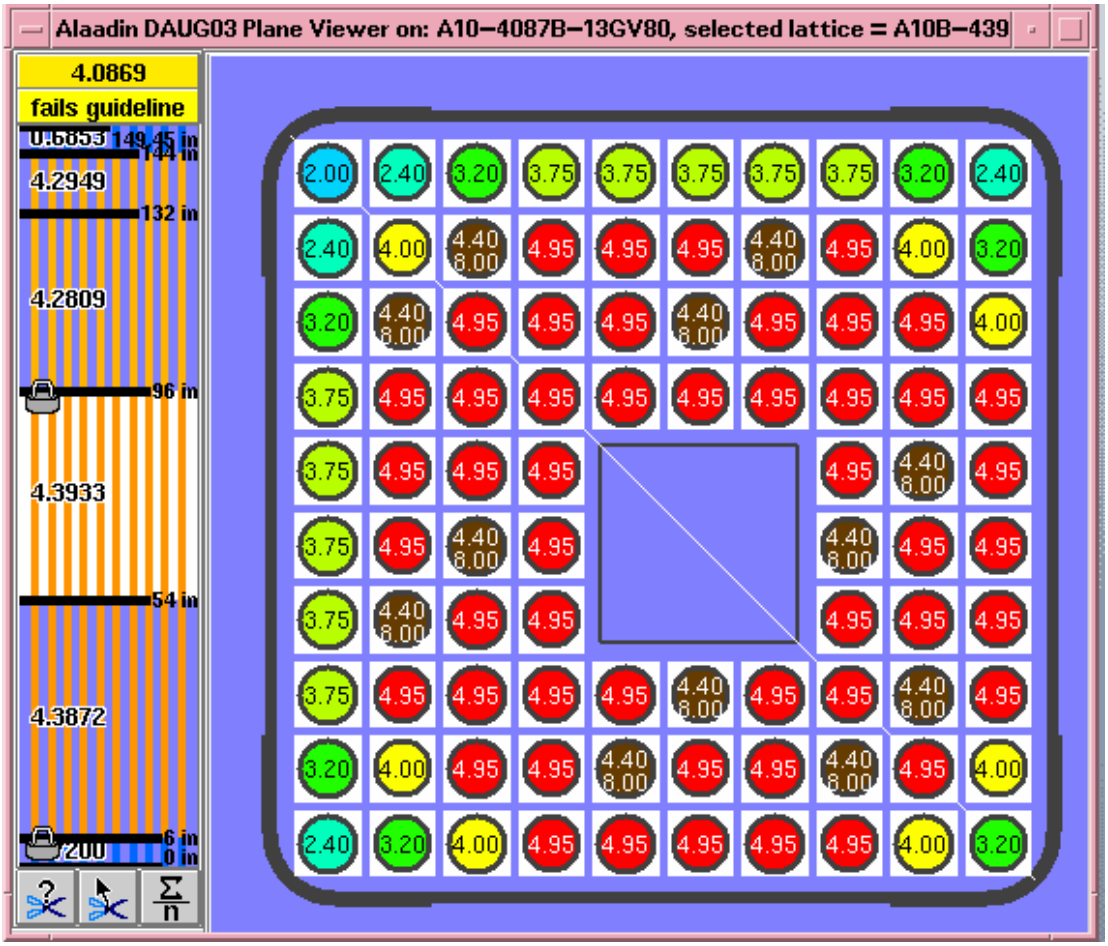

Figure 3. A Test 10x10 Lattice Map

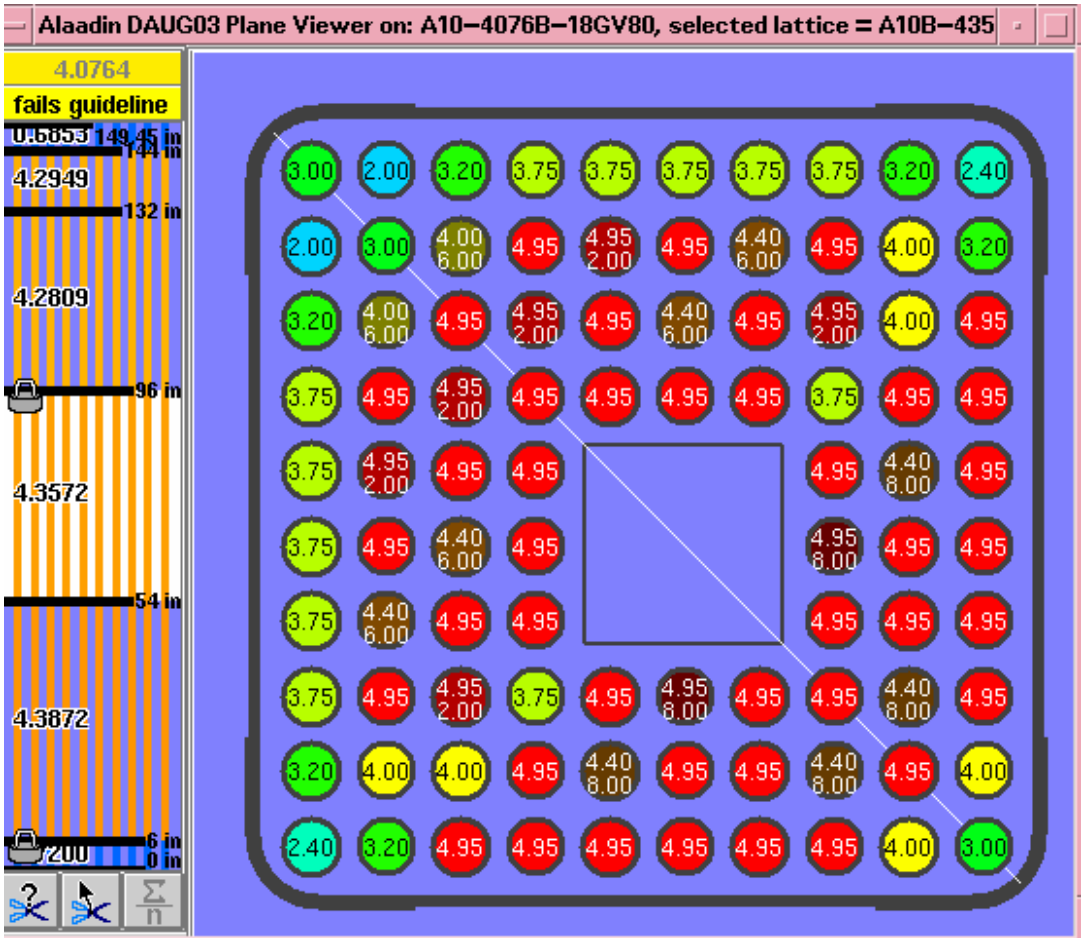

Figure 4. Perturbated Lattice

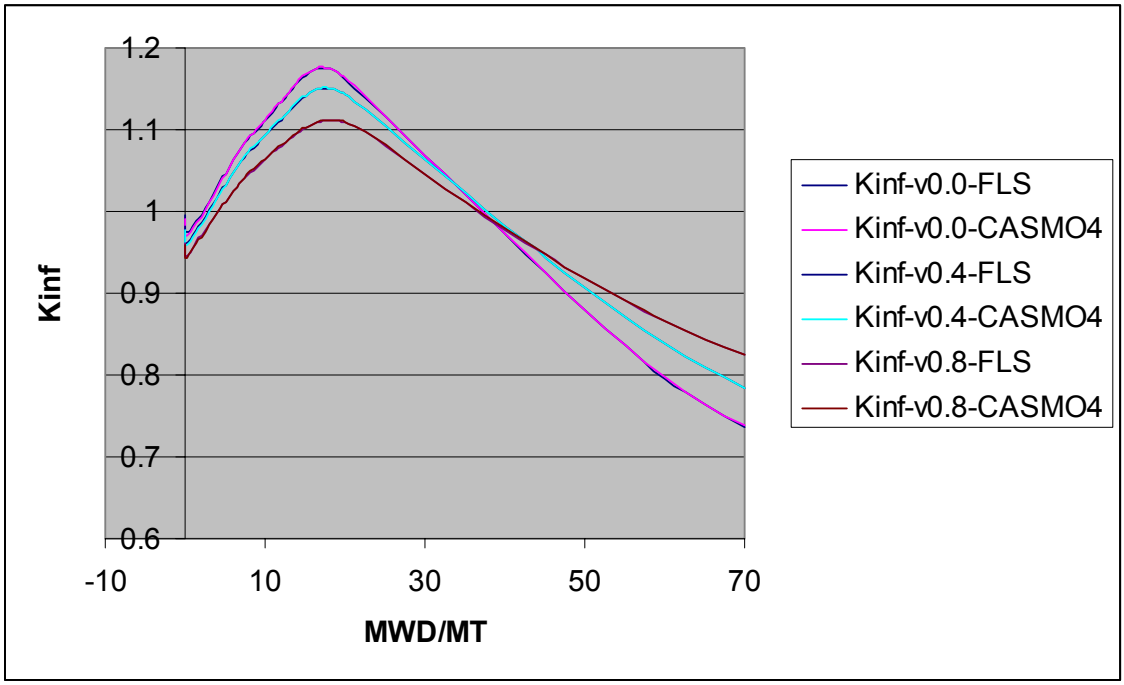

Figure 5. Kinf Comparison of FLS and CASMO4

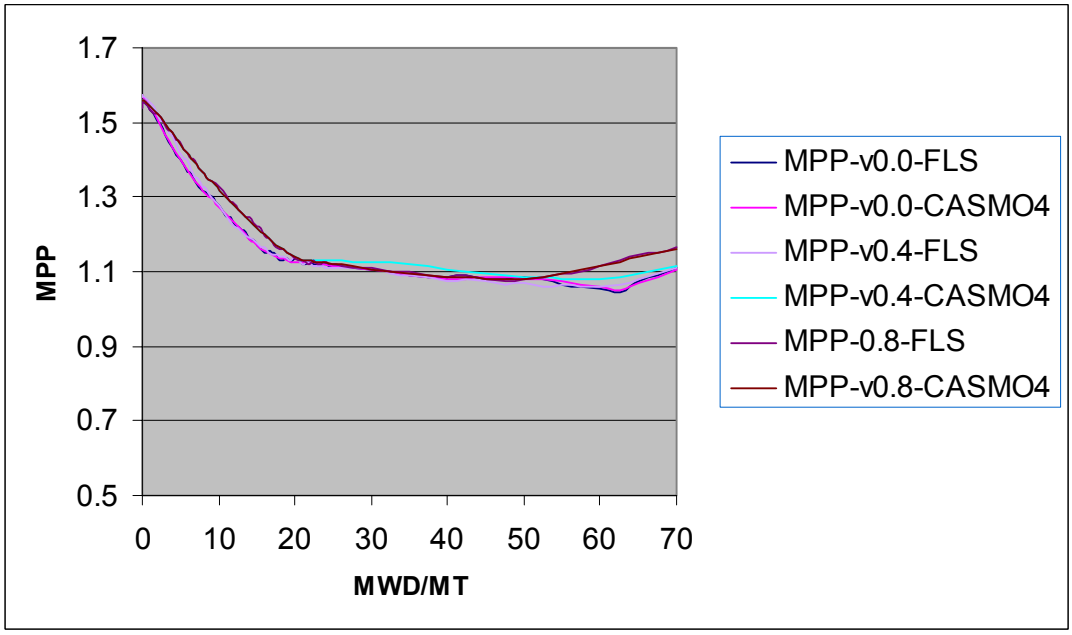

Figure 6. MPP Comparison Between FLS and CASMO4

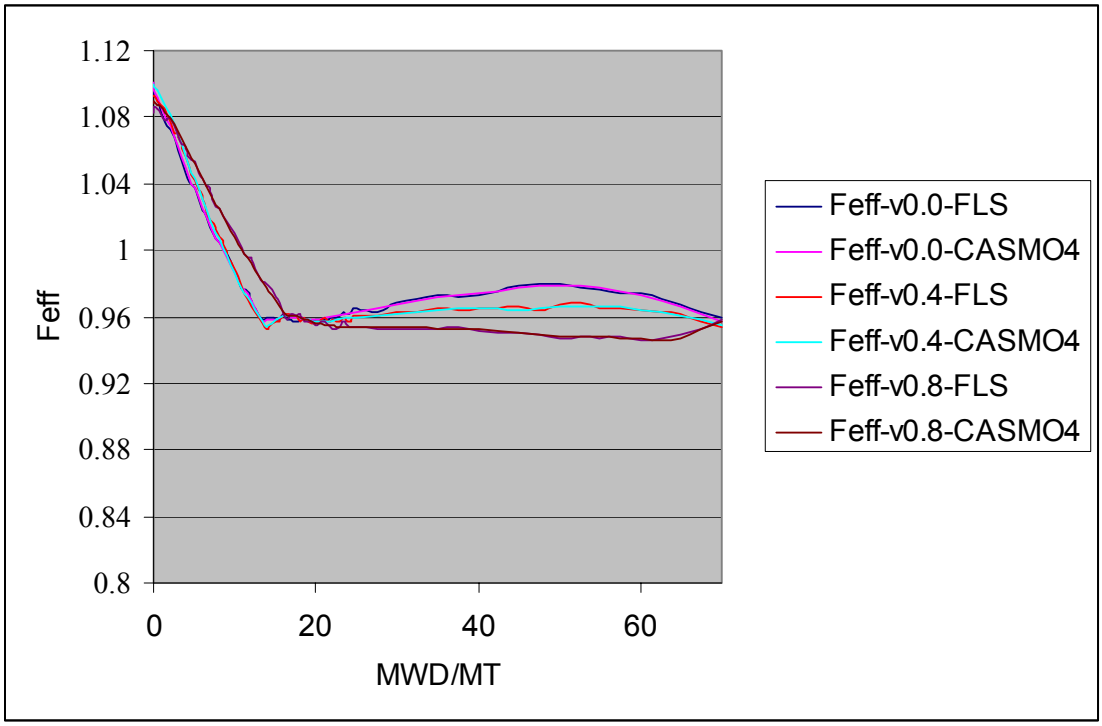

Figure 7. Feff Comparison Between FLS and CASMO4

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