Fast Calculation Program for Nuclear Fuel Lattice Design of Boiling Water Reactors

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Abstract

A methodology for 10x10 fuel lattice design for BWR's was developed. A linear equation based on a matrix of coefficients (change ratio of relative power due to U-235 enrichment changes) was proposed for estimating pin by pin relative powers of a fuel lattice. Based on above description the fast calculation program *PreDiCeldas* was developed which allows diminishing the maximum Local Power peaking Factor (LPPF). This program uses a simple search algorithm varying the distribution of U-235 within the fuel lattice, and also maintaining its average enrichment as a constant. The pin relative power estimation accuracy is of the order of 0.04% with respect to HELIOS transport code calculations. With *PreDiCeldas* program it was possible, in a short calculation time, to redesign a reference fuel lattice diminishing the maximum LPPF, at the beginning of the life, from 1.405 to 1.225.

KEYWORDS: BWR, Fuel Lattice Design, Fuel Optimization

1. Introduction

A BWR fuel assembly is divided into several axial zones. Also at different design stages, it is possible to assess the fuel assembly performance as well as of each one of its axial zones. For each one of these stages, at Instituto Nacional de Investigaciones Nucleares of Mexico (ININ), it has been making some studies in order to optimize each fuel cycle design stage for Laguna Verde Nuclear Power Plant (LVNNP) [1, 2 and 3]. So, *PreDiCeldas* is intended for LVNNP fuel lattice optimization. In order to *PreDiCeldas* to be tested a redesign of a fuel lattice was made. The redesigned fuel lattice was calculated by HELIOS code [4], and a performance comparison of *PreDiCeldas* calculations with respect to HELIOS ones was made.

2. Description

2.1 *PreDiCeldas* program

In *PreDiCeldas* process calculations the main parameters to be established are both the U-235 enrichment distribution and gadolinia concentration. The variables to examine are both fuel

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lattice reactivity and pin by pin relative power. For this purpose the HELIOS transport code is used. In the analysis, the maximum fuel lattice power peaking is very important. It is calculated under temperature reactor operation rated conditions and at typical void fractions. In the fuel lattice design it is advisable to have a fast calculation program, and precise enough to make exhaustive evaluations. That is the main reason for *PreDiCeldas* program development.

In a 10x10 fuel lattice, by symmetry reasons it is enough to consider 51 fuel pines. The possible U-235 (w/o) enrichments and gadolinia concentrations are restricted to a set of pre-established values, basically for security and manufacture reasons.

The fuel lattice fast calculation consists of the construction of a 51x51 coefficients square matrix. That matrix is obtained through HELIOS calculations considering a reference fuel lattice, starting from that, pin by pin enrichment is modified. The matrix that describes power changes with respect to enrichment variations is denoted by **A**(51x51). Then,

$$\begin{bmatrix} p_c^1 \\ . \\ . \\ p_c^{51} \end{bmatrix} = \begin{bmatrix} p_b^1 \\ . \\ . \\ p_b^{51} \end{bmatrix} + \begin{bmatrix} a_{1,1} & a_{1,2} & . & a_{1,51} \\ a_{2,1} & . & . & . \\ . & . & . & . \\ a_{51,1} & . & . & a_{51,51} \end{bmatrix} \times \left\{ \begin{bmatrix} u_c^1 \\ . \\ . \\ u_c^{51} \end{bmatrix} - \begin{bmatrix} u_b^1 \\ . \\ . \\ u_b^{51} \end{bmatrix} \right\}$$
$$= \begin{bmatrix} p_b^1 \\ . \\ . \\ p_b^{51} \end{bmatrix} + \begin{bmatrix} a_{1,1} & a_{1,2} & . & a_{1,51} \\ a_{2,1} & . & . & . \\ . & . & . & . \\ a_{51,1} & . & . & a_{51,51} \end{bmatrix} \times \begin{bmatrix} \Delta u^1 \\ . \\ . \\ \Delta u^{51} \end{bmatrix} \qquad (1)$$

Where,

Ub(51) is the base fuel lattice U-235 enrichment vector,
Pb(51) is the HELIOS relative powers vector
Uc(51) is the new fuel lattice U-235 enrichment vector
Pc(51) is the new fuel lattice relative powers vector

The accuracy of this calculation depends on what closed is the new fuel lattice with respect to the base one. But in an iterative process the results are improved. In this process the following equation is used:

$$\begin{bmatrix} p_c^1 \\ . \\ . \\ p_c^{51} \end{bmatrix} = \begin{bmatrix} p_r^1 \\ . \\ . \\ p_r^{51} \end{bmatrix} + \begin{bmatrix} a_{1,1} & a_{1,2} & . & a_{1,51} \\ a_{2,1} & . & . & . \\ . & . & . & . \\ a_{51,1} & . & . & a_{51,51} \end{bmatrix} \times \left\{ \begin{bmatrix} u_c^1 \\ . \\ . \\ u_c^{51} \end{bmatrix} - \begin{bmatrix} u_r^1 \\ . \\ . \\ u_r^{51} \end{bmatrix} \right\}$$

$$= \begin{bmatrix} p_r^1 \\ . \\ . \\ p_r^{51} \end{bmatrix} + \begin{bmatrix} a_{1,1} & a_{1,2} & . & a_{1,51} \\ a_{2,1} & . & . & . \\ . & . & . & . \\ a_{51,1} & . & . & a_{51,51} \end{bmatrix} \times \begin{bmatrix} \Delta u^1 \\ . \\ . \\ \Delta u^{51} \end{bmatrix} \quad (2)$$

Where,

Ur(51) is the reference fuel lattice enrichment vector,
Pr(51) is the reference fuel lattice relative powers vector, calculated by HELIOS.

The iterative process was implemented considering a U-235 average enrichment pre-established value of fuel assembly. A similar work to the present was reported in Ref.[5]. In that paper a MOX enrichment distribution optimization in typical LWR assemblies is presented.

3. Results

3.1 HELIOS transport code calculations

With the main purpose of to obtain a fuel lattice with a small local power peaking factor for using it in the LVNPP cycle 13 (that fuel lattice was called ININ302, I302 for short). An axial lattice zone placed at the bottom of reactor core was taken as a reference, that fuel lattice is identified as 1K5. This fuel lattice corresponds to a fuel assembly used in the previous cycle of the reactor. This fuel assembly has an average enrichment of 3.69 of U-235 w/o. The relative power pin by pin obtained from HELIOS transport code calculations is shown in Fig. 1. These results were calculated at hot full power uncontrolled condition, 40% void in the reactor core, and with an exposure of 0.0 MWd/T.

Figure 1: Relative power pin by pin obtained from HELIOS calculations for the reference fuel lattice 1K5.

	1	2	3	4	5	6	7	8	9	10
1	0.9206	1.2330	1.1441	1.1544	1.1495	1.2098	1.3306	1.3748	1.2236	1.1209
2	1.2330	1.0646	0.3454	0.8546	0.3732	0.8838	1.0925	1.0419	1.3886	1.2400
3	1.1441	0.3454	0.6497	0.3468	0.7312	0.3834	0.9364	0.3861	1.0781	1.3254
4	1.1544	0.8546	0.3468	0.7273	0.8816	wr	wr	1.0067	1.1994	1.3099
5	1.1495	0.3732	0.7312	0.8816	1.0555	wr	wr	1.0771	0.9699	1.3643
6	1.2098	0.8838	0.3834	wr	wr	1.0585	0.9888	0.3884	0.9267	1.3486
7	1.3306	1.0925	0.9364	wr	wr	0.9888	0.3719	0.7229	1.1159	**1.4054**
8	1.3748	1.0419	0.3861	1.0067	1.0771	0.3884	0.7229	0.3755	1.0542	1.3181
9	1.2236	1.3886	1.0781	1.1994	0.9699	0.9267	1.1159	1.0542	1.2883	1.2504
10	1.1209	1.2400	1.3254	1.3099	1.3643	1.3486	**1.4054**	1.3181	1.2504	1.1352

The maximum LPPF reported by HELIOS was equal to 1.4054. Its position into the fuel lattice is shown in Fig.1. Also in above Fig.1 "wr" is used to denote a water rod within the fuel lattice.

3.2 *PreDiCeldas* program calculations

In *PreDiCeldas* process calculations the main parameters to be established are the U-235 (w/o) for each fuel pin into the lattice. These **1K5** parameters as well as the matrix of coefficients **A**(51x51) prepared specifically for this fuel lattice, were introduced to *PreDiCeldas* as input data. Later on, *PreDiCeldas* was executed and after 48 iterations a solution was obtained, the I302 fuel lattice. The relative powers reported by this program are shown in Fig. 2.

Figure 2: Relative power pin by pin for I302 obtained from *PreDiCeldas* calculations.

	1	2	3	4	5	6	7	8	9	10
1	1.2185	1.1425	1.1599	1.1735	1.1790	1.1563	1.1971	1.1307	1.1503	1.1898
2	1.1425	1.1468	0.3842	0.8632	0.3814	0.9884	1.1368	1.2047	1.1528	1.1663
3	1.1599	0.3842	0.7043	0.3527	0.7993	0.3910	1.0392	0.3966	1.1594	1.1611
4	1.1735	0.8632	0.3527	0.7823	0.9566	wr	wr	1.1232	1.1606	1.1868
5	1.1790	0.3814	0.7993	0.9566	1.1400	wr	wr	1.0972	1.2019	1.1397
6	1.1563	0.9884	0.3910	wr	wr	1.1501	0.9967	0.3959	1.1480	**1.2250**
7	1.1971	1.1368	1.0392	wr	wr	0.9967	0.3750	0.8753	1.1726	1.1630
8	1.1307	1.2047	0.3966	1.1232	1.0972	0.3959	0.8753	0.3813	1.2178	1.1491
9	1.1503	1.1528	1.1594	1.1606	1.2019	1.1480	1.1726	1.2178	1.1674	1.1752
10	1.1898	1.1663	1.1611	1.1868	1.1397	**1.2250**	1.1630	1.1491	1.1752	1.1903

The maximum LPPF reported by *PreDiCeldas* was equal to 1.2250. Its position into the fuel lattice is shown in Fig.2.

3.3 HELIOS vs. *PreDiCeldas* LPPF calculations

The main comparison parameters between HELIOS and *PreDiCeldas*, for 1K5 and I302 fuel lattices, are shown in Tab. 1. The fuel lattice and assembly average enrichments are also shown in this Tab. 1. In order to verify the *PreDiCeldas* calculations made for I302, a HELIOS calculation was made for the same fuel lattice, the results are shown in Fig. 3.

Table 1: Comparison results between HELIOS and *PreDiCeldas* for I302 fuel lattice.

Maximum LPPF Absolute difference (%)	0.04
Pin-by-pin relative power absolute difference (%)	0.03

The diminishing between the maximum LPPF in I302 fuel lattice made by *PreDiCeldas* with respect to the reference fuel lattice 1K5, is 13.68%. And it was also observed an average diminishing in reactivity between above fuel lattices of around 500 pcm's. The smaller reactivity values correspond to I302 fuel lattice. See Figs. 4 and 6.

Figure 3: Relative power pin by pin for I302 fuel lattice. HELIOS calculation.

	1	2	3	4	5	6	7	8	9	10
1	1.2235	1.1259	1.1592	1.1751	1.1805	1.1558	1.1974	1.1065	1.1426	1.1782
2	1.1259	1.1674	0.3812	0.8650	0.3784	0.9926	1.1431	1.2112	1.1514	1.1585
3	1.1592	0.3812	0.7088	0.3496	0.7982	0.3878	1.0408	0.3940	1.1543	1.1540
4	1.1751	0.8650	0.3496	0.7855	0.9555	wr	wr	1.1271	1.1662	1.1825
5	1.1805	0.3784	0.7982	0.9555	1.1457	wr	wr	1.1002	1.2093	1.1266
6	1.1558	0.9926	0.3878	wr	wr	1.1560	0.9959	0.3933	1.1528	**1.2255**
7	1.1974	1.1431	1.0408	wr	wr	0.9959	0.3752	0.8756	1.1758	1.1610
8	1.1065	1.2112	0.3940	1.1271	1.1002	0.3933	0.8756	0.3817	1.2199	1.1434
9	1.1426	1.1514	1.1543	1.1662	1.2093	1.1528	1.1758	1.2199	1.1560	1.1633
10	1.1782	1.1585	1.1540	1.1825	1.1266	**1.2255**	1.1610	1.1434	1.1633	1.1901

On next figures the LPPF and k-infinity behavior through burnup (MWd/T), for 1K5 and I302, are presented. These results were generated through HELIOS transport code calculations.

Figure 4: Hot Uncontrolled K-infinity at 0%, 40%, 70% void, for 1K5 and I302 lattices.

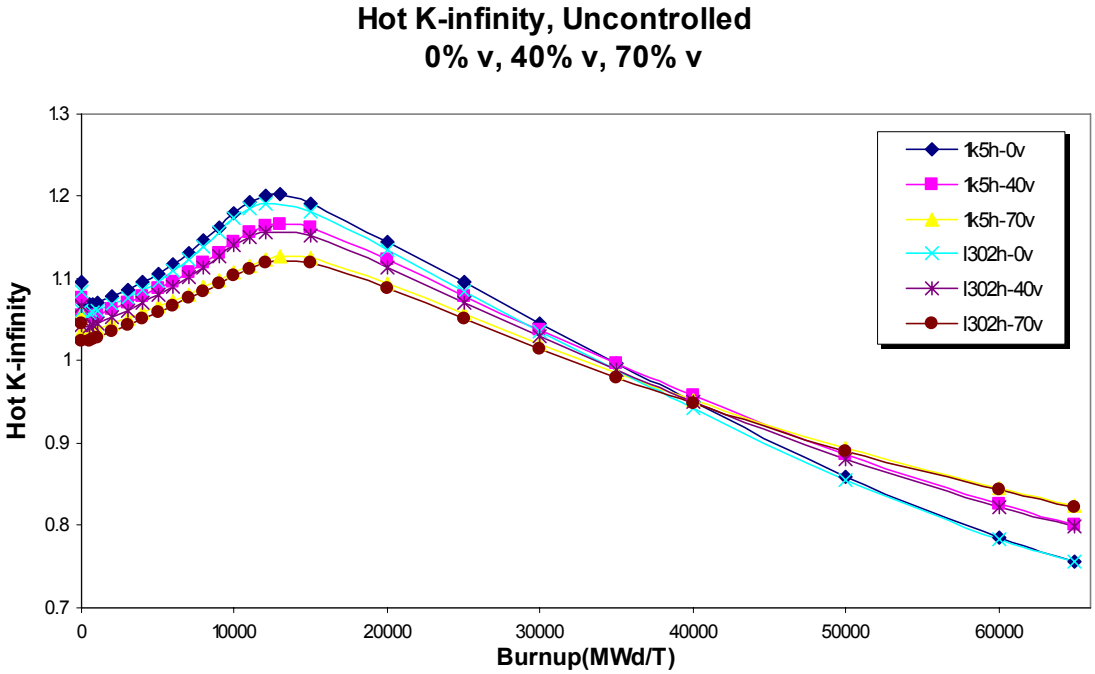


Figure 5 Hot Max. uncontrolled LPPF at 0%, 40%, 70% void, for 1K5 and I302 lattices

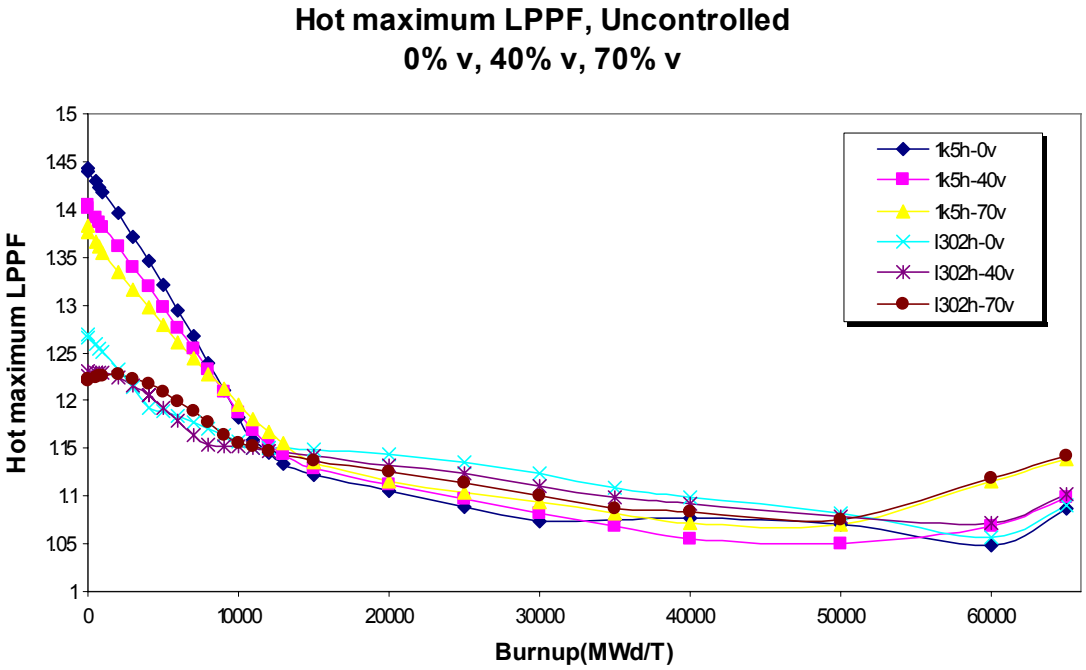


Figure 6: Cold uncontrolled K-infinity at 0%, 40%, 70% void, for 1K5 and I302 fuel lattices.

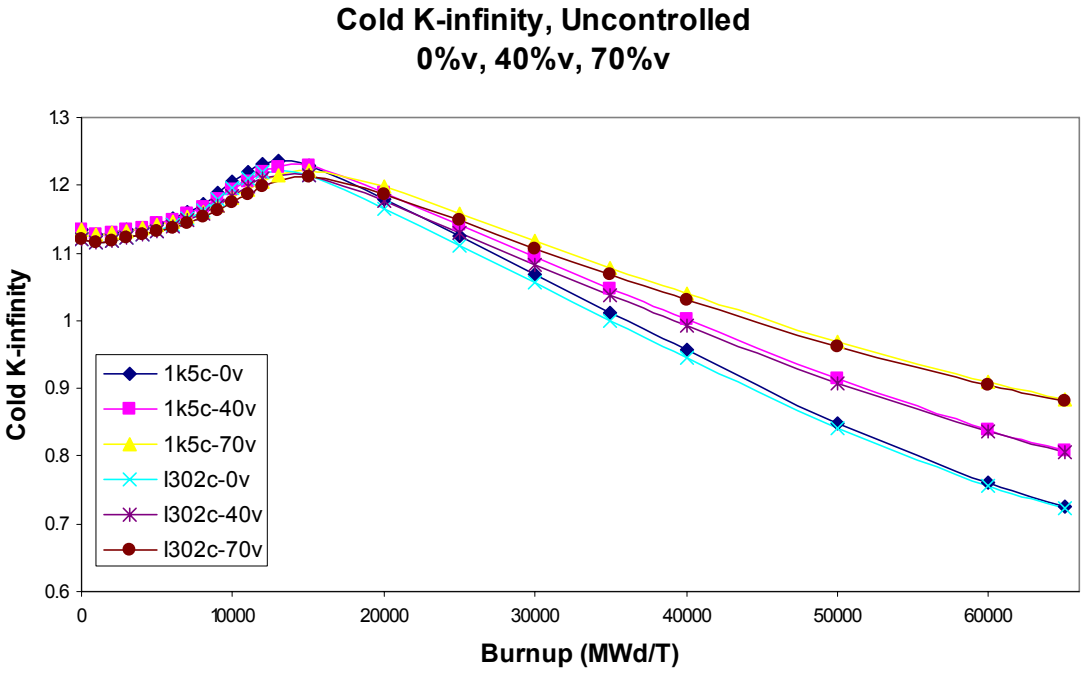
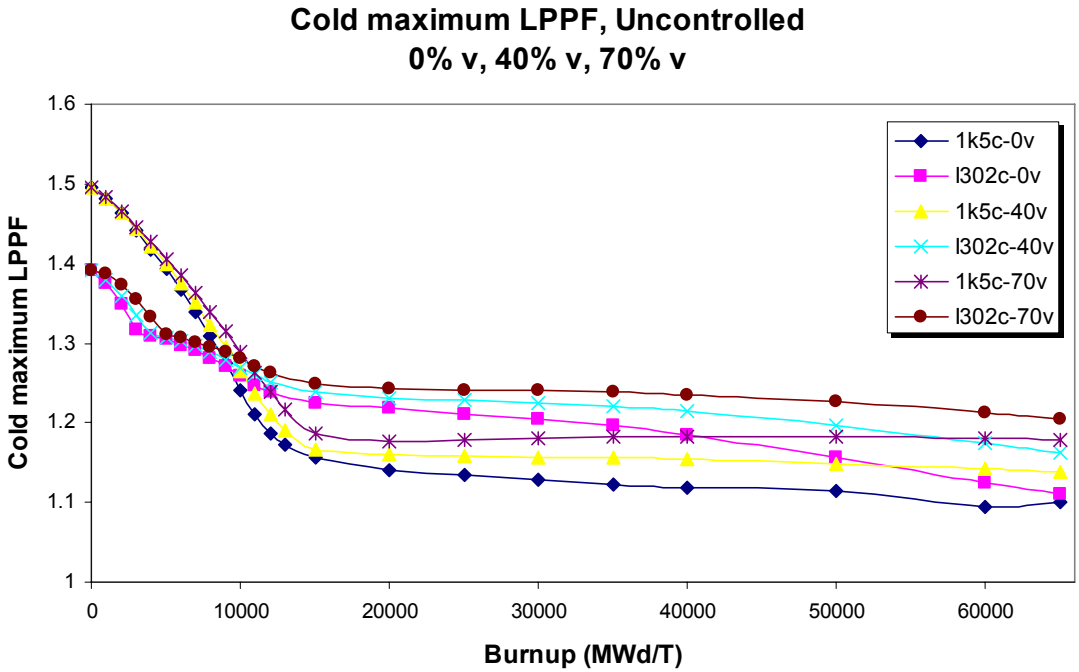


Figure 7: Cold uncontrolled LPPF at 0%, 40% and 70% void, for 1K5 and I302 fuel lattices.



4. Conclusions

The *PreDiCeldas* relative power calculation accuracy for each pin is in average about 0.04%; that is good enough for pre-design calculations. Besides, the speed of calculation is acceptable, about 1,000 iterations by minute can permit an exhaustive search.

This algorithm was able to diminish about 13.68 % the maximum local power peaking (from 1.4054 to 1.2250) in a representative 10x10 fuel lattice. It was also noted that when a great diversity of U-235 enrichments was permitted a LPPF of 1.2 was obtained.

It is important to mention that although the maximum LPPF value was diminished in the fuel lattice a certain reactivity difference decreasing was observed as a consequence. However, the actual effects of this difference will be measure through 3D steady state calculations. This kind of studies will be carried out in the near future.

For obtaining the above results using *PreDiCeldas* it was necessary to build a matrix of coefficients by means of 51 HELIOS executions. When a different gadolinia either concentration or distribution occur into the reference fuel lattice, it will be necessary to re-build that 51x51-matrix of coefficients.

This sort of fuel lattice neutronic pre-design technique has as the main advantage the short necessary execution time. However a more robust combinatorial optimization technique is necessary to considerer for a greater scope in the solution of this problem.

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References

1) J. A. Castillo et al., "BWR Fuel Reloads Design Using A Tabu Search Technique", Ann. Nucl. Ener., **31**, 151 (2004).
2) J. L. Montes, et al., "Searching for full power control rod patterns in a boiling water reactor using genetic algorithms", Ann. Nucl. Ener, **31**(16), 1939 (2004).
3) J. J. Ortiz, Requena I., "An Order Coding Genetic Algorithms to Optimize Fuel Reload in a Nuclear Boiling Water Reactor", Nucl. Sci. Eng., **146**, 88 (2004).
4) J.J. Casal et al., "HELIOS: Geometric capabilities of a new fuel-assembly program", Intl Topical Meeting on Advances in Mathematics, Computations, and Reactor Physics, Pittsburgh, Pennsylvania, April 28-May 2, Vol. 2, 10.2.1 1-13 (1991).
5) G.F. Cuevas Vivas, T.A. Parish, and G.L. Curry, "Optimization of MOX enrichment distribution in typical LWR assemblies using a simplex method-based algorithm", Ann. Nucl. Ene, **29**, 2001 (2002).