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DESIGN OPTIMIZATION USING DEPLETION PERTURBATION THEORY*

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Analysis of the fuel cycle performance of a reactor requires knowledge of the entire fuel burnup history. The optimal design depends upon the desired performance parameter or combination of parameters to be minimized (or maximized). The emphasis to date has been to use some combination of iterations involving a number of direct calculations, static perturbation theory, binary exchange methods, and empirical relationships.^{1,2,3} The object of this study is to demonstrate an approach to optimization based upon Depletion Perturbation Theory (DPT).⁴

The DPT equations directly couple the nuclide burnup equations and the neutron balance equations. The equations require the calculation of forward and adjoint solutions for the neutron flux and nuclide transmutations. Any number of flux calculations can be performed during the burnup period; the DPT accounts for flux renormalization to maintain the desired reactor power. The calculated sensitivities are generally used for (1) determining effects of design changes upon parameters evaluated at various times during the fuel cycle and (2) assessing importance of parameters and performing uncertainty analysis. This work, however, uses the sensitivity data for design optimization.

The application is for analysis of a modular HTGR. The reactor has axially dependent fuel loadings in order to achieve an axial power shape that keeps fuel temperatures below a specified maximum. For this reason, the axial power shape must remain stable over the fuel burnup period of five years. Boron is used as a burnable poison.

The design optimization involves minimizing, in a least-squares sense, the change in region-averaged power densities over the irradiation period of five years. Specifically, we seek to minimize the function

$$y = \sum_{i=1}^I \sum_{j=1}^J [P_{ij} - \frac{1}{J} \sum_{k=1}^J P_{ik}]^2 \quad (1)$$

where P_{ij} = region-averaged power density in region i at time j in the burnup period

I = number of regions

J = number of time points to be examined during burnup period.

Restricting the free parameters to nuclide loadings, the calculated power density sensitivity data are b_{ijk} , defined by

$$b_{ijk} \equiv \frac{\partial P_{ij}}{\partial n_{ik}} \quad (2)$$

where n_{ik} = nuclide density for nuclide k .

The change in P_{ij} is estimated to first order by the sum

$\sum_k b_{ijk} \Delta n_{ik}$, so equation (1) can be rewritten as

$$y = \bar{a}^T + \Delta \bar{n} \bar{B} \Delta \bar{n}^T \quad (3)$$

where \bar{a} = row vector consisting of combinations of the b_{ijk}

\bar{B} = square matrix consisting of combinations of the b_{ijk}

$\Delta \bar{n}$ = row vector of the changes in the nuclide loadings.

To test the optimization procedure, three axial loading regions were chosen and three nuclides were varied: ^{235}U , ^{232}Th , and ^{10}B , for a total of 9 independent variables. Eleven flux and ten burnup calculations were performed over the five year cycle, but the number of time points to be considered was limited to two, beginning- and end-of-cycle.

The nuclide loading changes were constrained and the function y was minimized to give a set of Δn 's. The direct calculations were performed with the 'optimized' loadings and the results are listed in Table 1 under case 1. Use of the new loadings reduced the objective function by a factor of 0.03. The maximum change in region-averaged power density was 0.06 watts/cm³ as compared to 0.34 for the reference case. The peak region-averaged power density increased slightly.

To examine whether the peak region-average power density could be decreased while also decreasing the objective function, an additional constraint of 5.80 watts/cm³ on the peak region-averaged power density was imposed. As shown in the table, the objective function y increased only slightly from case 1 and was still much smaller than the reference case.

In summary, this work demonstrates an application of DPT that is unique because of its use in design optimization over the entire fuel cycle. A single flux adjoint calculation for each flux calculation is sufficient to obtain all sensitivities over the cycle, and the use of a large number of parameters can be dealt with efficiently.

Table 1. Region-Averaged Power Densities for a Modular HTGR

Reactor Design: 250 MW(t), Core Height = 6.34 m,
 Core Diameter = 3.5 m,
 Average Power Density = 4.1 Watts/cm³,
 High-Enriched Uranium/Thorium Fuel Cycle,
 Five-year Refueling Period.

Region-Average Power Density (Watts/cm³)

	Axial Loading Region*	Reference	Case 1	Case 2
<u>Beginning-of-Cycle</u>	1	5.82	5.95	5.76
	2	3.41	3.12	3.31
	3	1.35	1.36	1.57
<u>End-of-Cycle</u>	1	5.95	5.98	5.80
	2	3.07	3.06	3.27
	3	1.42	1.38	1.52

*Region 1 is top half of core; region 2 is next quarter of the core;
 region 3 is bottom quarter of the core.

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