Improving Battery Reactor Core Design Using Optimization Method

Hyung M. Son[a], Kune Y. Suh[a,b*]
[a]*Seoul National University, 599 Gwanak Ro, Gwanak Gu, Seoul 151-744, Korea*
[b]*PHILOSOPHIA, Inc., 599 Gwanak Ro, Gwanak Gu, Seoul 151-744, Korea*
[*]*Corresponding author: kysuh@snu.ac.kr, kysuh@philosophia.co.kr*

1. Introduction

The Battery Omnibus Reactor Integral System (BORIS) is a small modular fast reactor being designed at Seoul National University to satisfy various energy demands, to maintain inherent safety by liquid-metal coolant lead for natural circulation heat transport, and to improve power conversion efficiency with the Modular Optimal Balance Integral System (MOBIS) using the supercritical carbon dioxide as working fluid [1].

This study is focused on developing the Neutronics Optimized Reactor Analysis (NORA) method that can quickly generate conceptual design of a battery reactor core by means of first principle calculations, which is part of the optimization process for reactor assembly design of BORIS [2].

2. Neutronic Design

The one-group neutron diffusion equation is used to estimate the critical dimension of the core. The effective one-group constants are determined by utilizing nuclear data obtained from the ENDF/B-VII.0 library over the energy region of interest for the fast spectrum core. The MCNP5 code is adopted to generate the neutron flux spectrum to be used for the group averaging procedure [3, 4 and 5].

2.1 One-group Constants

The one-group constants are evaluated in Fig. 1 using Pu+MA(20%)-U-N as the fuel composition, assuming triangular array, and utilizing the flux spectrum data generated by MCNP5.

2.2 Calculation Results

Variable values (pellet diameter, cladding thickness and pitch-to-diameter ratio) at the extremities are used to generate base cases. The critical core dimension is calculated using the diffusion equation and compared against the critical geometry found using MCNP5 with linear inter- and extrapolation prediction methods for these geometries. Following the linear relationship the critical buckling B is found from the regression analysis. The residual sum of squares and adjusted R^2 value are found to be 9.11762E-6 and 0.99091.

$$B_{MCNP} = 1.44119 B_{One-group} - 0.02935 \qquad (1)$$

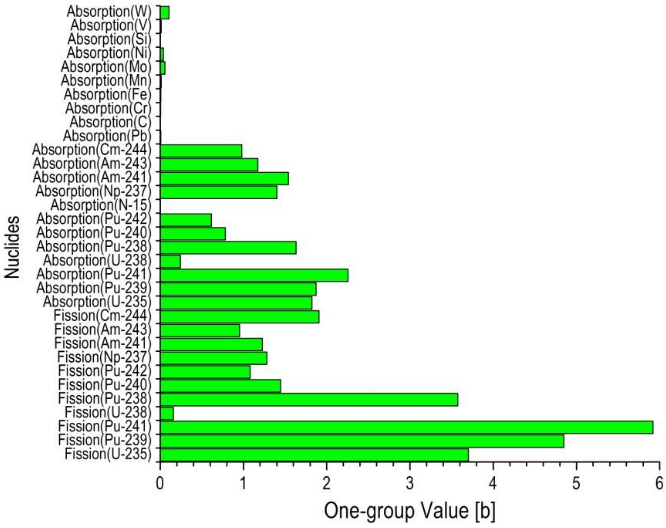

Fig. 1. Microscopic one-group constants.

Next, several test cases are selected from variable values between the extremities to test the applicability of evaluated relationship to other geometries. The critical geometry is determined using Eq. (1). The effective multiplication factor k_{eff} is calculated which showed near-critical core, as shown in Fig. 2.

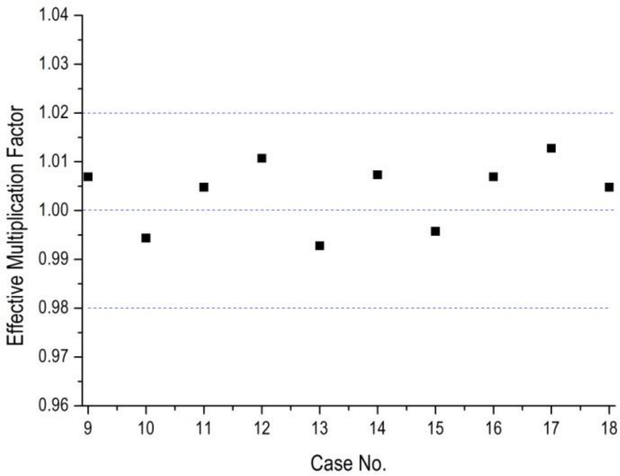

Fig. 2. Effective multiplication factor.

Once the critical geometry is obtained, one needs to render this to the heterogeneous one prior to moving on to next design stages. This is done by the procedure described in the literature which generates relationship between the number of fuel pins and the encircling boundary diameter [6].

The effective multiplication factor of the generated heterogeneous geometry is again evaluated using the MCNP5 code. Good results are shown around 1 with a maximum volume variation within 0.8%.

3. Optimized Design

As an extension, the above procedure is combined with the optimization method in NORA to come up with optimum core design in terms of cost effectiveness. The random jumping method is utilized where every independent variable is arbitrarily generated and the value of the objective function is evaluated repeatedly until the desired value of the objective function is obtained [7].

As objective function, the ratio between cost of the fuel at the beginning of irradiation and direct cost of the fuel is used. This turns out to be a function of the plant thermal efficiency, specific power, fuel residence time and capacity factor [8].

NORA is run 10 times each generating 1,000 design variable sets, as shown in Fig. 3. Next the case with a highest cost ratio value is chosen, which gives the core diameter of 83.637 cm and height of 76.997 cm with a total of 4,357 fuel pins (from the 2nd run). Fig. 4 shows the optimized core geometry generated by the NORA visualization module.

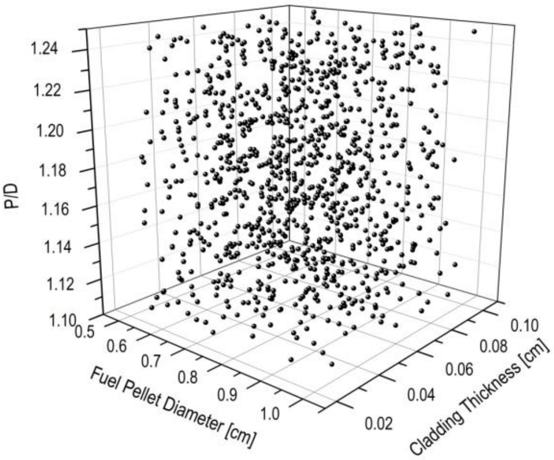

Fig. 3. Independent design variables distribution (2nd run).

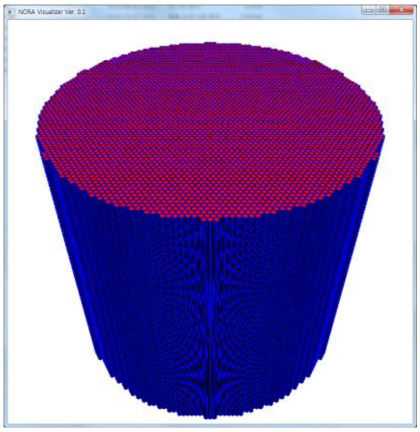

Fig. 4. Optimum core geometry.

Acknowledgments

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