Core Design Studies for a BWR-Based Small Modular Reactor with Long-Life Core

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INTRODUCTION

Researches are underway at Purdue University on a BWR-based small modular reactor (SMR) with long-life core – 50 MWe Novel Modular Reactor (NMR-50) [1]. It is a design based on GE's SBWR-600 [2] and Purdue's SBWR-200 [3] with renovations to encompass SMR concepts. NMR-50 combines passive safety features of the latest BWR technologies on small and modular scales. One outstanding attribute of the NMR-50 is its long-life core that achieves a 10-year lifetime without refueling. A long-life core can facilitate specific applications in remote sites or with small grid systems. The NMR-50 is favorable to be deployed in locations where industrial infrastructure is under-developed or the unit cost of electricity is too high with conventional technologies.

The primary core design objective of the NMR-50 is to realize a 10-year core lifetime with no refueling. In order to achieve the targeted 10-year fuel cycle length under the current industrial constraint of 5 wt% fuel enrichment, a core design with reduced specific power as well as a single batch fuel management scheme was adopted. In addition to design requirements of negative reactivity feedback coefficients and a sufficient shutdown margin, two main thermal design constraints were considered. One is the maximum fuel linear power density (MFLPD), which characterizes the limit of peak clad temperature during the loss of coolant accident (LOCA). The other is the minimum critical power ratio (MCPR), which characterizes the critical heat flux (CHF) when flow dryout occurs in a BWR-type reactor [4]. The MFLPD and MCPR for the NMR-50 were designated to be consistent with the ones from its reference reactor SBWR-600 [2]. These design criterions, as well as some design objectives, for the NMR-50 are summarized in Table I.

Table I. Design objectives and constraints for the NMR-50

Property	Parameter
Thermal power (MW)	165.0
Burn fuel length (years)	10.0
Maximum fuel enrichment (%)	5.0
Axial peaking factor	1.5
MFLPD (kW/m)	45.0
MCPR	1.3

COMPUTATIONAL MODELS FOR THE NMR-50

The core design study was performed using the lattice physics code CASMO-4 [5], the core neutronics simulator PARCS [6] and the system thermal-hydraulics (T/H) analysis tool RELAP5 [7]. The study started with CASMO-4 calculations at the fuel pin and assembly levels to generate few group cross section libraries. Parametric studies on fuel assembly design were also taken place at this stage to obtain an optimal fuel assembly design for the subsequent core analysis in terms of fuel cycle length and safety related parameters. After cross section libraries were prepared, the core simulation was performed with PARCS to obtain core performance information such as k_{eff}, power distribution, fuel burnup, etc. This procedure was coupled with RELAP5 T/H calculations to account for proper thermal feedbacks. The coupling calculations between PARCS and RELAP5 were performed via a message transfer interface supported by parallel virtual machine (PVM) [8]. A diagram illustrating the interactions between these codes is shown in Fig. 1. Core design parameters for the NMR-50 were determined iteratively from coupled calculations of CASMO-4, PARCS, and RELAP5 to eventually meet all the design criterions.

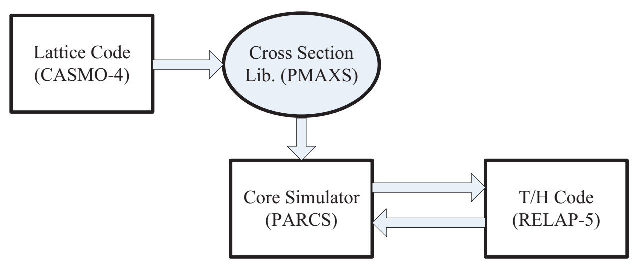

Fig. 1. Core design analysis code system used in the study.

The overall design of the NMR-50 was initiated from the SBWR-200 [3], a derivative design of the SBWR-600 with some novelties, by reducing the axial dimensions (while retaining the radial dimensions) using the three-level scaling method developed by M. Ishii et al. [1]. The axial dimensions were reduced by half mainly from economic considerations to reduce the height of the reactor

*Z. Wu currently works at NIST Center for Neutron Research, Gaithersburg, MD 20899-8560 pressure vessel (RPV) while maintaining natural flow circulation capability in the vessel. The core volume was thereafter reduced by half while the power was reduced by a factor of four (from 660 MWt to 165 MWt). As a result, the power density of NMR-50 is half of that of SBWR-200. This reduced power density naturally doubles the cycle length for the same discharge burnup.

A single batch fuel management scheme was adopted for the NMR-50 to maximize the cycle burnup with the same fuel enrichment. For the purpose of obtaining an optimal fuel assembly design for the NMR-50 to fulfill the promise of 10-year fuel cycle length, a series of parametric studies were performed using CAMSO-4 on BWR type fuel assemblies originated from GE or AVERA's designs. The studied parameters include average U-235 wt%, burnable poison (Gadolinium) enrichment, fuel rod diameter, and so on. Based on these parametric studies, an assembly design similar to AREVA's Atrium-10B was obtained for the NMR-50 core. The fuel rod configuration of the assembly design is depicted in Fig. 2 with the associated design and performance parameters summarized in Table II.

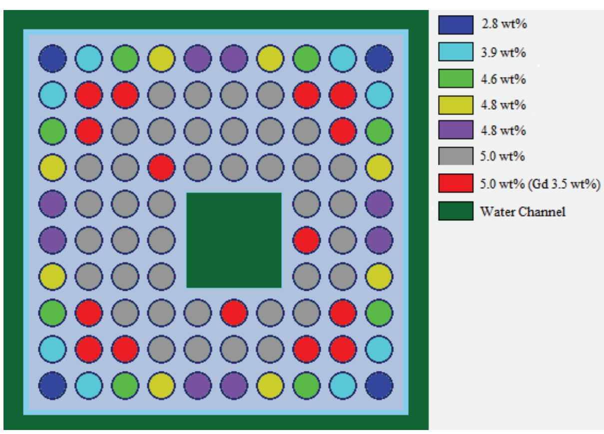

Fig. 2. A schematic view of the NMR-50 assembly model.

Table II. Design and performance parameters of the NMR-50 fuel assembly

Property	Parameter
Average U-235 wt%	4.75
Average Gd wt% in Gd rod	3.50
Fuel rod diameter (mm)	10.55
Water/Fuel ratio	2.33
Specific power (W/gU)	8.76
Cycle burnup (GWd/T)	33.40
Cycle length (years)	10.44
Local peaking factor	1.27
k_{inf} at BOC	1.06059

As can be seen in Fig. 2, the assembly consists of 91 fuel rods laid over a 10×10 grid with a square–shaped coolant channel in the center. Different fuel rod color shown in the figure indicates different fissile enrichment in the fuel. Fuel rods enriched with Gadolinium are drawn with red color. All fuel rods have 1.372 meter length of active fuel and 0.1524 meter length of graphite reflector at the top and bottom of active fuel respectively.

The full core consists of 256 fuel assemblies in a 18×18 layout and 57 cruciform control blades. The equivalent core diameter is 2.73 meters. A schematic view of the quarter core of the NMR-50 is shown in Fig. 3.

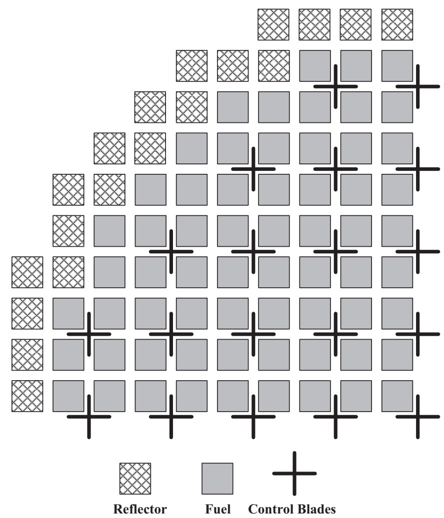

Fig. 3. X-Y view of the NMR-50 quarter core model.

To account for the thermal feedback during the core simulation, RELAP5 was employed to model the T/H components in the NMR-50. The nodalization diagram used in REALP5 is illustrated in Fig. 4.

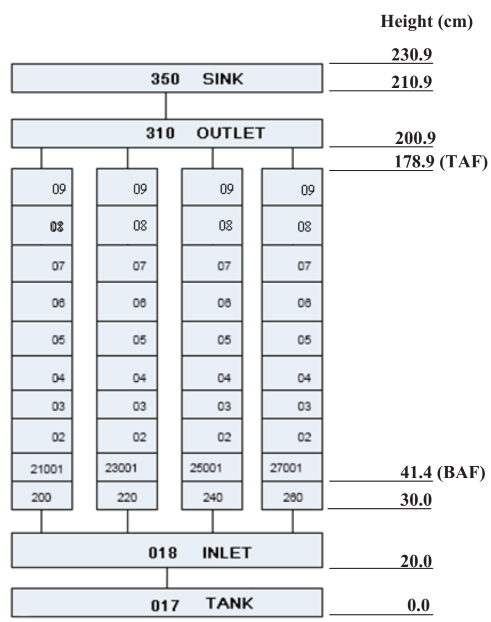

Fig. 4. RELAP5 nodalization diagram of the NMR-50 core.

The coolant flow inside fuel assembly boxes is assigned to three flow channels, representing the hot, average and peripheral channels, respectively. The inter-assembly water flow is represented with a separate bypass channel. The inlet and outlet plenum in the primary loop of the reactor are also presented explicitly in the T/H model shown in Fig. 4. The boundary conditions of the T/H model were derived from the calculation of the complete primary system model. The main T/H parameters of the NMR-50 are given in Table III.

Table III. T/H parameters for the NMR-50 T/H model

Property	Parameter
Coolant rate (kg/h)	2.230×10^6
Nominal pressure (MPa)	7.178
Average quality	0.143
Coolant saturation temperature (ºC)	2.873×10^2
Inlet temperature (ºC)	2.785×10^2
Total flow area (m^2)	4.013
Bypass flow area (m^2)	1.763

RESULTS

The core simulation started with a criticality calculation at the beginning of cycle (BOC) with all fresh fuel assemblies. The critical status was achieved by adjusting control rod position inserted to the core. The control rod insertion at BOC was not very significant since a large number of burnable poison enriched fuel rods in the fresh fuel assembly considerably hold down the excess reactivity. The resulting radial power distribution of the core at BOC is illustrated in Fig. 5.

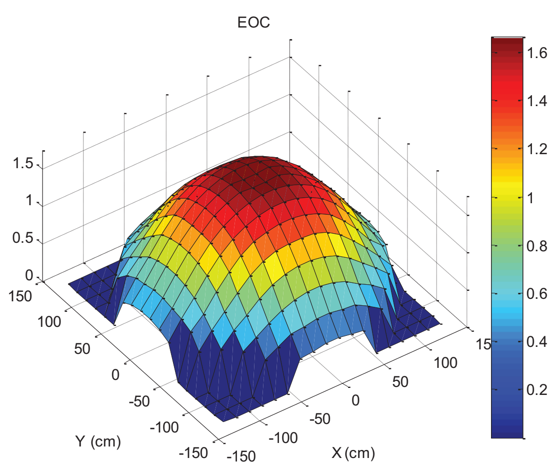

Fig. 5. Radial power distribution of the NMR-50 at BOC.

The BOC power behavior depicted in Fig. 5 is a converged solution of the iterative neutronics and T/H calculations between PARCS and RELAP5 models. In the RELAP5 calculations, the fuel assemblies were grouped into three channels based on their relative thermal power. The representative axial power distribution at BOC in the three different thermal channels are shown in Fig. 6.

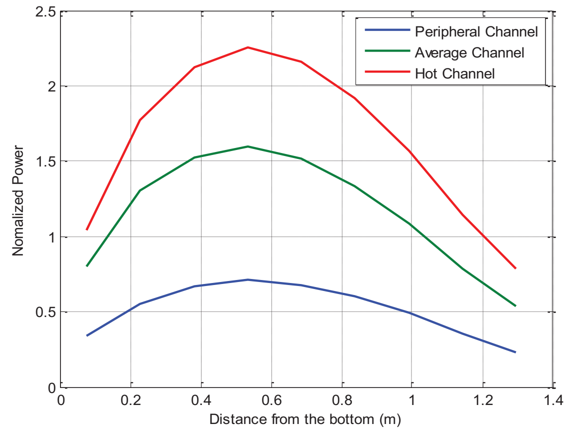

Fig. 6. Axial power distribution at BOC for different flow channels.

To examine the feasibility of the long fuel cycle operation of the NMR-50, a full cycle depletion calculation was performed using the PARCS and RELAP5 coupled models. In the burnup calculation, the core criticality was maintained at every burnup step by searching the critical control rod position. Besides k_{eff} and the critical control rod position, the MFLPD and MCPR were also calculated at every burnup step to ensure thermal design limits were satisfied during the entire operating cycle.

The depletion calculation results indicate that the fuel cycle can be successfully extended to 10 years with the assembly and core designs shown in Fig. 2 and 3, respectively, while satisfying the constraints defined in Table I. For representative purpose, the calculated results at the beginning, middle and end of the cycle are reported in Table IV.

Table IV. The NMR-50 core performance at BOC, MOC and EOC of the 10 years operation life time.

Property	BOC	MOC	EOC
Burn time (years)	0.00	4.83	9.99
k_{eff}	0.99988	1.00010	1.00011
Notch[a]	1454	34602	7963
Avg. burnup (GWd/T)	0.00	14.79	30.61
MFLPD (kW/m)	15.36	14.26	15.80
MCPR	2.25	1.97	2.79

[a]The notch value is the sum of notches for all inserted control rods.

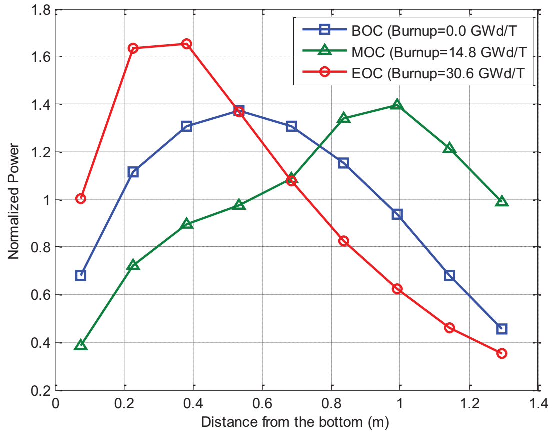

Fig. 7. Axial power shape at BOC, MOC and EOC.

Figure 7 depicts the core averaged axial power distributions at BOC, MOC and EOC. As can be seen, the axial power shape shows significant variations with burnup because of the movement of control rods (recall control rods are inserted from the bottom of the core in BWR) and the depletion of burnable poison. The axial peaking factor for BOC, MOC and EOC are 1.37, 1.40 and 1.65, respectively (see Fig. 7). Though the axial peaking factor at EOC is slightly higher than the selected limit given in Table I, it is acceptable with the consideration of the MFLPD for the NMR-50 is far below the limited criterion 45.0 KW/m (see Table I). Moreover, the axial peaking factor can be reduced with further optimization of fuel assembly design and core configuration.

CONCLUSION

Core design studies were carried out for a BWR-based small modular reactor with long-life core, NMR-50, using CASMO-4, PARCS and RELAP5 codes. Coupled neutronics and T/H calculations were performed at BOC and for full fuel cycle to examine the core performance. Preliminary results indicate that the targeted 10-year fuel cycle length is achievable while satisfying the thermal and material related design criterions. More detailed parametric studies are being conducted to optimize the fuel assembly and core configuration to minimize the fissile fuel loading.

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