CONCEPTUAL DESIGN OF A SMALL-PRESSURIZED WATER REACTOR USING THE AP1000 FUEL ASSEMBLY DESIGN

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Abstract: This paper presents the conceptual design of a 300 MWt small modular reactor (SMR) using fuel assemblies of the AP1000 reactor. Numerical calculations have been performed to evaluate a proper active core size and core loading pattern using the SRAC code system and the JENDL-4.0 data library. The analysis showed that Doppler, moderator temperature, void, and power reactivity coefficients are all negative over the core lifetime. Semi-analytical thermal hydraulics analysis reveals acceptable radial and axial fuel element temperature profiles with significant safety margin of fuel and clad surface temperature. The minimum departure from nucleate boiling ratio (MDNBR) is also calculated. The results indicate that a cycle length of 2.22 years is achievable while satisfying the operation and safety-related design criteria with sufficient margins.

Keywords*: small modular reactor, AP1000 reactor, neutronic analysis, thermal hydraulics analysis.*

1. INTRODUCTION

In recent years, the small modular reactors (SMRs), new generation reactors designed with an electrical output up to 300 MWe, have been received increasing attention within the nuclear energy community due to a number of advantages. Because of the small size, the SMRs require less capital investment and construction time compared to traditional commercialized reactors, so that financial risks could be reduced. The SMR designs can adopt most of the advanced safety features of the current technologies. One of the advantages is that the components of the reactor system can be fabricated at factories and transported modularly to the plant site for installation. It is also more flexible to choose locations for the SMRs than the traditional reactors, and therefore, it would be a suitable solution for a wide range of users and applications, for instance remote areas with smaller electricity demand. The SMRs are being developed for a number of principal reactors including advanced light water reactors, heavy water reactors, and the generation IV reactors such as high temperature gas cooled reactors (HTGRs), liquid-metal, sodium and gas-cooled fast reactors (LMFR, SFR, GFR), and molten salt reactors (MSRs).

About 50 SMR designs are being under developed world-wide for both electrical generation and non-electrical application such as desalination of seawater, district heating, hydrogen production and other process heat application. Among those, three industrial demonstration SMRs are in construction including CAREM (integral PWR with the output of 150 – 300 MWe) in Argentina, HTR-PM (HTGR) in China and KLT-40S (compact PWR for a floating nuclear power plant) in Russia. The integral pressurized water reactor (IPWR) technology is one of the major near term SMR designs, of which primary components are contained in the reactor vessel. CAREM is an example of the IPWR technology. CAREM-25, a prototype reactor with the power of 27 MWe, is under construction. Other designs of IPWRs are SMART (Korea), Nuscale (US), mPower (US), Westinghouse SMR (US). The IPWR of the Westinghouse Electric Company is based on a partial-height 17x17 fuel assembly used in the AP1000 reactor. This reactor utilizes passive

safety systems and proven components from the AP1000 plant design. All primary components including the steam generator and the pressurizer are located inside the reactor vessel [3].

In the present work, a conceptual design of a small PWR core with thermal output of 300 MWt based on the AP1000 fuel assembly has been presented. Neutronics analysis has been performed to determine the core height, the number of fuel assemblies and core configuration. The neutronic analysis has been conducted using the SRAC code system and the JENDL-4.0 library. Thermal hydraulics analysis has been conducted to investigate the safety parameters of the core. Reactivity coefficients regarding the change in temperature of fuel, coolant, etc. were also investigated to ensure the safety feature of the newly designed SMR core.

2. CODE AND DESIGN PROCEDURE

The SRAC2006 code system [4] and the JENDL-4.0 nuclear data library [5] were used for performing the design process of the SMR core. For the core burnup calculation process is divided into two steps. Firstly, cell burnup calculation using the PIJ module was conducted to produce few-group burnup dependent homogenized macroscopic cross-sections. Secondly, the COREBN [6] was used for three-dimensional core burnup calculation based on the macroscopic cross-section interpolation. In order to confirm the core design criteria, thermal hydraulics analysis for the hottest channel in the core was performed to establish adequate heat removal capability of the design. Analytical models and equations are utilized for heat conduction within the fuel element and convection to the coolant [7]. Calculations of the MDNBR have also been performed for the hottest channel using empirical correlation and W-3 correlation [8]. The design process consists of two steps as follows:

a) Estimation of core size: The objective of this step is to determine the active fuel length and the number of fuel assemblies. Neutron transport calculations have been performed for an infinite core by imposing reflective boundary condition in the assembly level model. From the mass of uranium per assembly, the required number of fuel assemblies for the core can be determined. In this determination of core size, a four-year core lifetime, the average discharge burnup of 40 GWd/t with a single batch refueling scheme and a capacity factor of 1.0 were assumed.

b) Determination of core loading pattern: Once the required number assemblies are achieved, a symmetrical arrangement of the fuel assemblies in the active core zone is proposed for the initial core configuration. The core loading pattern is developed for the core design to meet the design criteria. Fuel assemblies with higher U-235 enrichment are selected with a high priority, and located in the peripheral core locations to achieve a uniform power distribution and maximum fuel utilization. Finally, the core that meets the specified performance requirements is selected for further analysis.
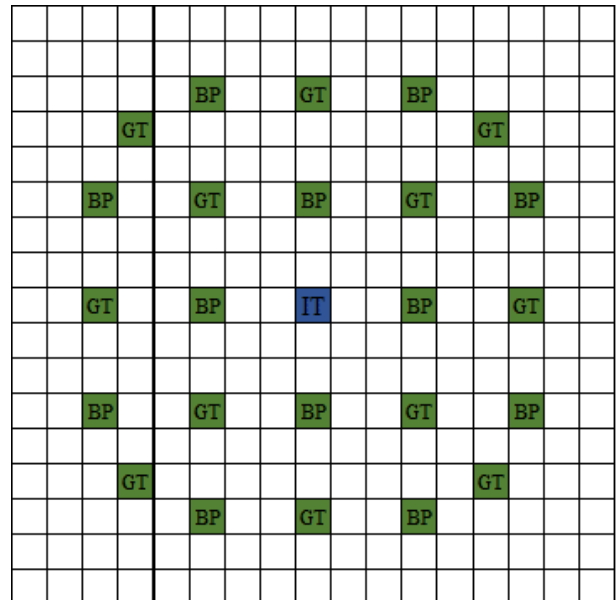

Fig. 1. Locations of fuel rods, guide thimbles (GT) and instrumentation thimble (IT) in a fuel assembly.

3. CORE DESIGN AND PERFORMANCE ANALYSIS

3.1. Core parameters

The Robust Fuel Assembly (RFA) design is used in the AP1000 reactor. The typical fuel assembly, with 17x17 array, contain 264 fuel rods, 24 guide thimbles, and 1 instrumentation thimble as shown in Fig. 1 [3]. The SMR core is designed with a thermal output of 300 MWt. The typical uranium oxide fuel rods (UO_2) with 2.35, 3.40, and 4.95 wt.% U-235 enrichments are used in the current SMR [9]. The main design parameters and targets for the SMR are specified in Table 1. In the AP1000 reactor design, in order to control excess reactivity and flatten power distribution, burnable absorber rods and integral fuel burnable absorbers are also used. In this study, only fuel assemblies without burnable absorber are considered to design a new core. For the control element assemblies (CEAs), the standard 24 finger Ag-In-Cd (AIC) rod control cluster assembly is exploited.

3.2. Estimation of core size

In order to determine the active fuel length, a three-dimensional infinite core model was developed based on an assembly level model with reflective boundary condition using the SRAC code system. The model consists of an active fuel zone and two reflector zones at the top and the bottom. The AP1000 fuel assembly with the highest U-235 enrichment, i.e., 4.95 wt.%, was selected for the active fuel zone. Reflective boundary condition was assumed for peripheral core, and extrapolated boundary condition was set at the top and the bottom. Fig. 2 shows the evolution of the infinite neutron multiplication factor (k-inf) at the begin of cycle (BOC) and the number of assemblies loaded into the core as functions of the active fuel length.

It can be seen that when the active fuel length is less than 190 cm, the k-inf

Table 1. Main design parameters and conditions (k-eff: effective neutron multiplication factor).

| Design parameters	Values
Reactor thermal power, [MWt]	300
Reflector thickness	
Top, [cm]	25.4
Bottom, [cm]	25.4
Side, [cm]	38.1
Assembly pitch, [cm]	21.4173
Fuel cell	
Pellet radius, [cm]	0.4096
Inner clad radius, [cm]	0.4178
Outer clad radius, [cm]	0.4750
Fuel cell pitch, [cm]	1.2598
Operating pressure, [MPa]	15.5
Nominal inlet coolant temperature, [K]	553
Nominal fuel temperature, [K]	1000
Nominal moderator temperature, [K]	575
Maximum 3D PPF (Fxyz), [-]	< 2.60
Maximum 2D PPF (Fxy), [-]	< 1.59
DNB correlation, [-]	W-3
MDNBR at nominal conditions, [-]	≥ 2.80
Maximum fuel temperature, [K]	< 2866.5
Maximum clad temperature, [K]	< 1477.6
Maximum critical boron concentration, [ppm]	< 2700
Temperature coefficients, [pcm/K]	< 0
CEAs performance	
Maximum k-eff over cycle for CZP, [-]	< 1.0
Maximum k-eff over cycle for HFP, [-]	< 1.0
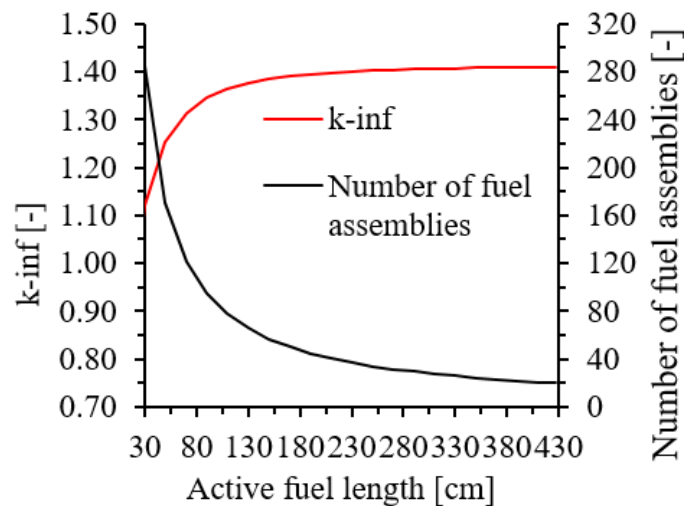
Fig. 2. Variation of infinite multiplication factor and required number of assemblies with increasing active fuel length.

increases rapidly with the increase of the active fuel length. The k-inf value is nearly unchanged with the active fuel length greater than 190 cm. Therefore, the active fuel length of 190 cm was selected, and the number of fuel assemblies in the core was determined as 45 assemblies.

3.3. Determination of core loading pattern

In order to determine the core loading pattern, a uniform power distribution and maximum fuel utilization, three core configurations with 45 fuel assemblies of the SMR were proposed in Fig. 3 for further analysis. Table 2 summarizes the analysis results of the three cores. It is found that replacing the fuel assemblies with high U-235 enrichment in the inner core zone by the fuel assemblies with lower U-235 enrichment results in reducing the two-dimensional power peaking factor (PPF) in radial direction (Fxy). The maximum two-dimensional PPFs in axial direction (Fxz) are nearly unchanged, and the maximum three-dimensional PPFs (Fxyz) of the core models are met the design criteria. But the Fxy and the MDNBR of Cores 1 and 2 are not met the requirement. As a result, Core 3 has been selected as the final design for further analysis.

a) Core model 1   b) Core model 2   c) Core model 3
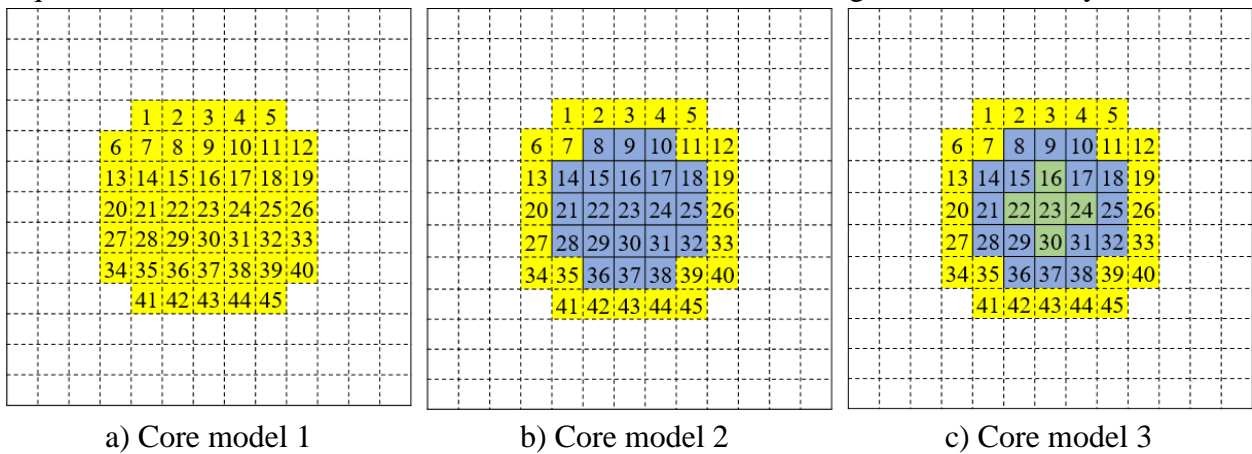
Fig. 3. Core configurations of the SMR (yellow, blue, and green blocks represent fuel assembly assemblies with 4.95, 3.40 and 2.35 wt.% U-235 enrichment, respectively. White block represents water filled position).

3.4. Analysis of temperature coefficients and control element assemblies

In order to investigate the feedbacks due to changes of fuel and coolant temperatures, the temperature reactivity coefficients have been investigated. A change in temperature of fuel material causes a change of neutron cross-section, which is so-called the Doppler broadening effect, resulting in a change in reactivity. Meanwhile, a change in coolant temperature results in the change of moderator density, which leads to a change in reactivity of the core. For safe operation, negative values of the temperature reactivity coefficients are desirable. In the numerical analysis, the temperature of fuel and/or coolant was increased by 50K. For the isothermal coefficient, both temperature of fuel and coolant were increased by 50K.

The shutdown margins of the control rod assemblies were analyzed to ensure that the core has sufficient control rod worth. Fig. 4 shows the map of the control element assemblies. The CEAs

Table 2. Summary of analysis results of the different core configurations.

Parameters	Core model 1	Core model 2	Core model 3
Maximum cycle length, [years]	2.87	2.36	2.22
Maximum k-eff over cycle, [-]	1.3383	1.2999	1.2826
Maximum 3D PPF (Fxyz), [-]	2.48	2.19	1.85
Maximum 2D PPF (Fxy), [-]	1.80	1.59	1.34
Maximum 2D PPF (Fxz), [-]	1.37	1.38	1.38
Maximum power density, [W/cm3]	189.8	167.4	141.1
MDNBR at nominal conditions, [-]	2.06	2.70	3.71
Maximum fuel temperature, [K]	1865	1711	1529
Maximum clad temperature, [K]	682	667	649
Maximum coolant temperature, [K]	615	607	599
Outlet coolant temperature, [K]	615	607	599
Maximum critical boron concentration, [ppm]	N/A	N/A	2555

are composed of shutdown banks (S) and regulating banks (R) located in the outer core and the inner core, respectively. The reactivity coefficients and CEAs performance of the selected core model (Core 3) at cold zero power (CZP) and hot full power (HFP) states are presented in Table 3. It can see that all coefficients are negative during the core lifetime. The CEAs of the core have sufficient shutdown margin.
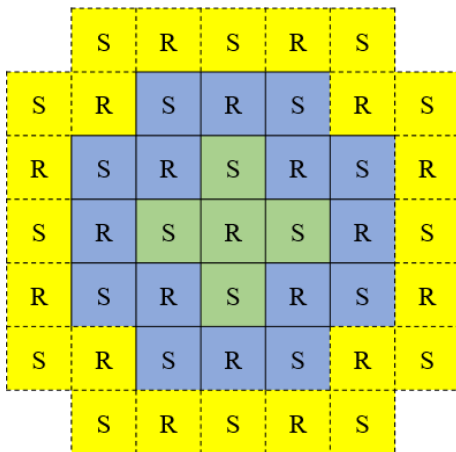
Fig. 4. Locations of the CEAs in the active core zone.

4.

Parameters	Values
Temperature coefficients, [pcm/K]	
Fuel temperature coefficient	< -1.91
Coolant temperature coefficient	< -76.63
Isothermal temperature coefficient	< -79.11
CEAs performance	
Maximum k-eff over cycle for CZP, [-]	0.9707
Maximum k-eff over cycle for HFP, [-]	0.8669

Table 3. Temperature coefficients and CEAs performance of the final core design.

CONCLUSIONS

Conceptual design of a 300 MWt SMR based on the fuel assemblies of the AP1000 reactor has been conducted. The core consists of 45 fuel assemblies with an active core height of 190 cm could operate up to 2.22 years without refueling. The Doppler and moderator temperature coefficients are negative throughout the core lifetime. Maximum values of fuel, cladding and

coolant temperatures are within the design limits. The DNBR remains greater than 3.71 for the the active core region. The analysis results represent that the final core design satisfies all the design criteria with significant safety margins.

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THIẾT KẾ KHÁI NIỆM LÒ PHẢN ỨNG ÁP LỰC NƯỚC NHẸ CÔNG SUẤT NHỎ SỬ DỤNG BÓ NHIÊN LIỆU CỦA LÒ PHẢN ỨNG AP1000

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Tóm tắt: Bài cáo này trình bày thiết kế khái niệm của lò phản ứng mô-đun nhỏ (SMR) với công suất 300 MWt sử dụng bó nhiên liệu của lò phản ứng AP1000. Các khảo sát được thực hiện nhằm tối ưu hóa kích thước vùng hoạt và mô hình nạp tải bằng chương trình SRAC và thư viện số liệu JENDL-4.0. Kết quả phân tích cho thấy các hệ số phản hồi Doppler, nhiệt độ chất tải nhiệt, độ rỗng chất tải nhiệt và hệ số phản ứng công suất đều âm trong quá trình vận hành. Kết quả phân tích thủy nhiệt cho thấy nhiệt độ theo chiều ngang và chiều dọc của thanh nhiên liệu đều trong ngưỡng an toàn của nhiên liệu và vỏ nhiên liệu. Hệ số MDNBR cũng được tính toán. Kết quả chỉ ra rằng lò phản ứng có thể vận hành lên tới 2,22 năm trong khi đáp ứng vẫn đáp ứng các tiêu chí thiết kế liên quan đến vận hành và an toàn của lò phản ứng.

Từ khóa: Lò phản ứng mô-đun nhỏ, lò phản ứng AP1000, phân tích nơtron, phân tích thủy nhiệt.