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Evaluation of the Control Rods Withdrawal in a Small Modular Sodium Fast Reactor and Analysis of the Impact on the Core Design

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Abstract

Nuclear reactors exhibit excess reactivity at start-up to ensure continuous operation over the length of the fuel cycle. For sodium fast reactors, this excess reactivity should cover burn-up reactivity loss, operation margin and uncertainty margin. However, contrary to light water reactors, control rods are the only available mean of reactivity control, boron dilution in sodium being not possible. Therefore, at the beginning of cycle, one part of control rods should be inserted into the core to balance this excess reactivity. The control rods are then withdrawn slowly during the cycle to compensate for burn-up reactivity loss. The malfunction of a control rod mechanism would lead to a so-called control rod withdrawal (CRW) accident that is considered as a typical event for unprotected transient over-power. This event could lead to the local melting of fuel assemblies and even to the global melting of the core. As a consequence, this accident must be evaluated at the core design stage to ensure good margins.

This paper proposes to use the new deterministic code APOLLO3 to optimize the model of the control rods, the transient calculation code MAT4DYN to calculate in the core response to a CRW, and the GERMINAL code to study the fuel pin thermal-mechanical behavior during incidental conditions.

This methodology is applied in a small sodium fast reactor that has an important reactivity loss and thus a high excess reactivity at start-up. The space for the implementation of control rods is limited by the space occupied by their drive mechanisms especially for small reactors. To achieve the objectives defined for Generation-IV reactors, the CRW accident becomes the limiting factor for small modular fast reactors by comparing with other requirements such as maximum fuel burn-up. Three different options are proposed and studied to obtain core designs with a favorable behavior in case of CRW accident. The first solution is to reduce calculation uncertainty, but this is a long process. The second solution is to enhance Doppler constant. The last solution is the application of new systems, such as burnable poisons, to compensate for reactivity loss. This paper investigates the required ability of such potential systems and its impact on the core design.

Keywords: ***control rod withdrawal, small modular sodium fast reactor, cycle length, burnable poisons***

1. Introduction

Sodium fast reactors (SFRs) exhibit excess reactivity at start-up to ensure continuous operation during the whole fuel cycle. This excess reactivity should cover burn-up reactivity loss, operation margin and uncertainty margin. The control rods (CRs) are almost the single system to manage the excess reactivity in SFR. One part of the control rods is inserted at the beginning of cycle to balance the excess reactivity. These control rods are withdrawn slowly over time to compensate for the burn-up reactivity loss. However, any malfunction of a control rod mechanism would lead to a control rod withdrawal (CRW) accident, which is a typical unprotected transient over-power (UTOP) that would lead to local or even global fuel melting of fuel.

Small modular sodium fast reactors (SMSFRs) usually exhibit important burn-up reactivity loss and thus high excess reactivity at start-up[1]–[3]. Nevertheless, the number of control rods in a small reactor is limited due to installation space consideration and thus high reactivity worth is stored in a single control rod. As a consequence, the limitation of the consequences of a CRW accident would be an important constraint for the cycle length of SMSFRs and thus their economical performance.

The CRW accident must be evaluated accurately at the core design stage to ensure adequate safety performances. In a SFR, all CRW accidents can be detected by two independent systems of core detection which stop the reactor by scram. The first system is the core temperature monitoring and the second is the neutron detection [4]. However, the simultaneous failure of these two systems should be considered for the inherent core safety purpose. This paper is therefore aimed at the evaluation of the consequences of an unprotected CRW accident. This paper proposes to use the new deterministic code APOLLO3 [5] to optimize the design of the control rods, the transient calculation code MAT4DYN[6] to calculate in the core response to a CRW, and the GERMINAL[7] code to study the fuel pin thermal-mechanical behavior during incidental conditions.

The Section 2 will present a typical SMSFR that is studied in this paper. This approach of CRW accident analysis will be presented in the Section 3. The CRW accident in SMSFR will be evaluated and discussed in Section 4. The sensitivity to the number of control rods, to the calculation uncertainty, and to the Doppler Effect will be studied. Combining these results, potential solutions to ensure safety of a SFR during CRW accident will be proposed: reduction on the calculation uncertainty, reinforcement of Doppler Effect and the burnable poisons to compensate for the reactivity loss.

2. Small Modular Sodium Fast Reactor

The main characteristics of the SMSFR studied in this paper, calculated with APOLLO3, are shown in Table 1. This SMSFR is a 320 MW thermal power sodium fast reactor loaded with (U,Pu)O_2 MOX fuel. Two different plutonium content zones, 42 inner core assemblies (C1) and 54 outer core assemblies (C2), are used to optimize the power distribution. The total irradiation time of the core is 1875 equivalent full power days (EFPD) to achieve a 150 GW.d/t maximal burn-up. Several dilution assemblies (DIL), composed with sodium and steel, are loaded to reduce the power peaking at the core center.

The control rod architecture contains two redundant, diverse and independent groups (named hereafter CSD and DSD) to minimize both failure frequencies and consequences. Similarly to the control rod utilization strategy proposed for ASTRID[8], both CSD and DSD are used in a same way to manage power level, compensate for burnup reactivity swing and adjust power distribution. This strategy shares reactivity control on the highest number of control rods and thus reduces the stored worth in one single control rod to reduce CRW accidents effects.

Various core configurations, as shown in Figure 1 and Table 2, are investigated in this paper, in which the number of control rods varies from 6 to 12. The installation space for the control rod drive mechanism (CRDM) is very limited. The surface fraction of control rod in Table 2 is defined as the ratio between the number of control rods and the number of fuel assemblies. In the previous French SFR design, this fraction varies from 6.4 % to 7.9 %. The reactivity worth in Table 2 is calculated for total insertion of all control rods, which is used to shut the reactor down and keep it subcritical in any state. The shutdown ability should cover various effects: reservation to compensate for burn-up reactivity swing (3180 pcm for 375 EFPD per cycle scenario), uncertainty margin (400 pcm), operation margin (300 pcm), Doppler Effect from nominal state to isothermal state (800 pcm), neptunium effect after shutdown (120 pcm) and fuel handling error margin (3200 pcm). Therefore, the total insertion of all control rods should lead to more than 8000 pcm reactivity worth.

Core Power	320 MWth
Fuel Irradiation Time	375×5 EFPD
Core Fuel Assembly Number (C1|C2)	42 | 54
Plutonium content (C1|C2)	22.3 % | 27.2 %
Fuel Zone Volume	1.27 m^3
Blanket Zone Volume	0.45 m^3
Average Power Density	250 $MWth/m^3$
Maximal Linear Power Density	420 W/cm
Maximal Burn-up	150 GWd/t
Maximal Flux	3.3×10^{15} $n/cm^2/s$
Void Effect	-563 pcm (-1.47 $)
Doppler constant	-762 pcm (-1.99 $)
Reactivity Loss	-8.5 pcm/EFPD

Table 1: Main characteristics of SMSFR

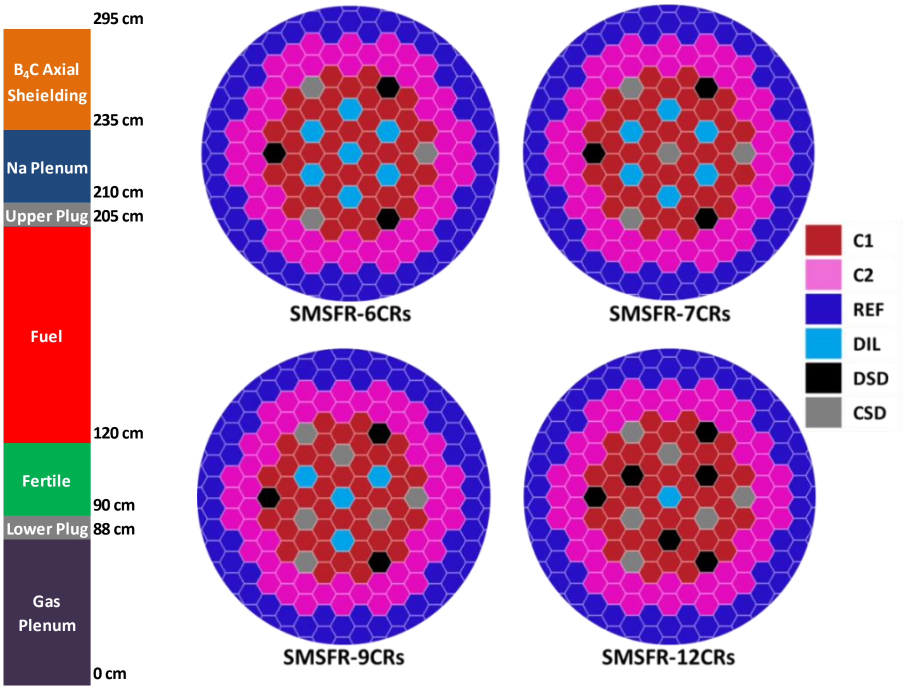

Figure 1: Axial layout of fuel assembly (left) and radial layout of core (right)

	SMSFR-6CRs	SMSFR-7CRs	SMSFR-9CRs	SMSFR-12CRs
Surface fraction of CR (%)	6.25	7.30	9.38	12.50
Absorber	B_4C in 48 % ^{10}B	B_4C in 48 % ^{10}B	Nat. B_4C	Nat. B_4C
Reactivity worth (pcm)	8584	10412	9291	11879

Table 2: Core configurations of SMSFR with different number of control rods

3. Methodologies

The withdrawal speed of control rods is limited by the mechanism speed, which is 4 mm per second in SFR. Therefore, the transient time of a CRW is about 50 s for a 20 cm insertion for a beginning of cycle configuration. The power transient can thus be represented by the variation of the total power and of the local variation in a specific region. The linear heat rating at the end of a CRW accident in region *i* ($Plin_{CRW}^{i}$) is obtained by the following equation:

$$Plin_{CRW}^{i} = Plin_{0}^{i} \times (1 + k_i' \Delta\rho_{CRW}) \times (1 + b_0 \, \Delta\rho_{CRW}) \tag{1}$$

where $Plin_0^i$ is the linear heat rating at normal operation state. $\Delta\rho_{CRW}$ is the reactivity worth of withdrawn control rod. Difference after the static calculations, k_i' represents the relative variation of the local power per unit of inserted reactivity and thus $1 + k_i' \Delta\rho_{CRW}$ is the variation of power in region *i* while b$_0$ represents the relative variation of the total power per unit of inserted reactivity and thus $1 + b_0 \, \Delta\rho_{CRW}$is the variation of total power of the core.

Accurate and high performance neutronic simulation is the key for the correct evaluation of a CRW accident. The withdrawal of control rod would raise local or global increase of power. APOLLO3 is chosen for the neutronic simulation in this work because of its high level confidence to simulate the control rods in sodium fast reactor[9].

The reactivity worth of all insertion of control rods and withdrawn control rods are calculated by APOLLO3. APOLLO3 calculates the initial linear power of core i.e. $Plin_0^i$ at normal state and its variation in a CRW state and thus the k_i'. The 2-D distribution of k_i' in SMSFR-12CRs with the control rod in 32/30 withdrawals from 20 cm insertion is presented in Figure 2. The value of the k_i' decreases with the distance from the extracted rod.

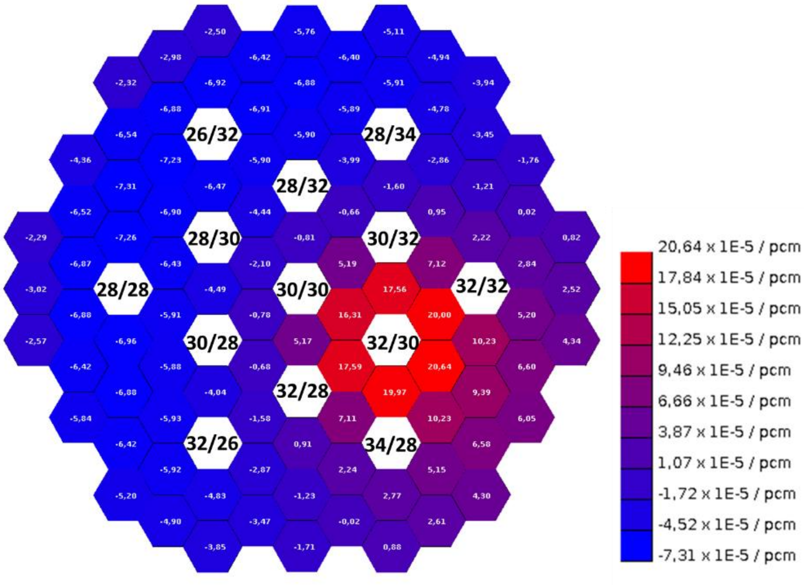

Figure 2: Relative variation of the local power per unit of inserted reactivity

MAT4DYN is a mono-channel code with point kinetics developed at CEA at beginning of the 2000s [6]. The axial profiles of core power and Doppler constant used in MAT4DYN are calculated by APOLLO3. The variation of total core power is calculated by MAT4DYN and thus the parameter b_0.The b_0 depend on the core configuration, which is presented in Table 3. The b_0 value decreases with the number of control rods because the expansion of non-withdrawn control rods brings negative reactivity in the core.

In this small core, the k_i', as shown in Figure 2 is much smaller than the b_0. For this SMSFR, the local variation is about 10 % of total variation. In small SFR, the withdrawal or insertion of one control rod would impact the flux distribution in the entire core. Conversely, the movement of one control rod would impact only its neighboring fuel assemblies in large SFR in which the local variation would be more important.

SMSFR-6CRs	SMSFR-7CRs	SMSFR-9CRs	SMSFR-12CRs
2.41×10^{-3}	2.35×10^{-3}	2.17×10^{-3}	2.03×10^{-3}

Table 3: Relative variation of the total power per unit of inserted reactivity (pcm^{-1})

The fusion linear heat rating criteria, $Plin^{i}_{fus}$, is calculated by the GERMINAL code using the neutronic input coming from APOLLO3 post processing. The fusion linear heat rating depends on the position and the burn-up. Finally, $Plin^{i}_{CRW}$ is compared with $Plin^{i}_{fus}$ to evaluate the performance of core in CRW accident with integration of calculation uncertainty.

4. Results and discussions

4.1. Evaluation of CRW accident in SMSFR

In this section the uncertainty on the fusion linear heat rating is 40 W/cm (coming from the GERMINAL calculations) and the uncertainty of CRW linear heat rating is 5% (coming from APOLLO3 calculations). The sensitivity to the uncertainty will be discussed in the Section 4.2. The CRW accident is analyzed at beginning of equilibrium cycle (BOEC). The position of control rod would impact the transient of power in CRW accident. Therefore, the CRW accidents in the previous four core configurations are classified into seven cases according to the withdrawn control rod position. The allowed reserved worth in control rods and the allowed cycle length are summarized in Table 4.

To ensure that the linear heat rating is smaller than the fusion threshold during a CRW accident of SMSFR-6CRs, the maximal insertion depth of control rods is 14.0 cm corresponding to a total around 642 pcm (all rod banks *i.e.* 107 per control rod). In addition, to compensate for reactivity swing, the excess reactivity in control rods at BOEC should cover the uncertainty margin on core reactivity (400 pcm) and the operation margin (300 pcm). The SMSFR-6CRs design is not able to achieve the expected margin at BOEC neither to compensate for reactivity swing.

For SMSFR-7CRs core, the withdrawal of 30/30 control rod increases more significantly the power than that of 34/28. The control rods in different position lead to different local power variation in CRW accidents and thus their allowed "stocked" worth are different. The reactivity worth "stocked" per control rod varies from 90 pcm to 120 pcm for these four core configurations. This means that the position of control rods could be optimized to reduce their effects in CRW accident but its benefit would not be very significant.

As shown in Table 1, the reactivity loss for SMSFR is -8.5 pcm/EFPD. Therefore, the control rod system is only able to compensate safely for the reactivity loss during 35 EFPD in SMSFR-9CRs core and 76 EFPD CRs in SMSFR-12 CRs core.

Core	Case	Withdrawn CR position	Maximal reserved worth in CRs (pcm)	Mean worth (pcm/CR)	Allowed cycle length (EFPD)
SMSFR-6CRs	Case1	34/28	642	107	--
SMSFR-7CRs	Case2	30/30	630	90	9
	Case3	34/28	794	113	
SMSFR-9CRs	Case4	34/28	1073	119	35
	Case5	32/30	927	103	
SMSFR-12CRs	Case6	34/28	1446	120	76
	Case7	32/30	1347	112	
	Case8	32/28	1368	114	

Table 4: Core configurations of SMSFR with different number of control rods

These results prove that even with important number of control rods, the allowed cycle length is very limited in SMSFR because of CRW accidents. The short cycle length means high refuel frequency which would limit the economic performance of small reactors and complicate their operation in remote regions. To achieve the long cycles and safety performances considering the CRW accident, two predetermined targets for small SFR, three directions are discussed in the following: the reduction on the calculation uncertainty, the reinforcement of Doppler Effect and the application of new system such as burnable poison.

4.2. Sensitivity to uncertainty

The $Plin^i_{CRW}$ is compared to $Plin^i_{fus}$ to evaluate the performance of core in CRW accident. Their following uncertainties are divided into two terms,

- $\sigma_{Plin^i_{CRW}}$: uncertainty of linear heat rating in CRW accident that is given from APOLLO3 and MAT4DYN calculation,
- $\sigma^2_{Plin_{fus}}$: uncertainty of fusion linear heat rating that is given by GERMINAL calculation,

should be integrated in the evaluation. In this paper, the limited linear power density $Plin^i_{lim}$ confidence is set at 95 % (i.e. 1.645 σ) while a group of pins are considered.

$$Plin^i_{lim} - Plin^i_{fus} = Plin^i_{margin} = \mu_N \sigma_{Plin^i_{CRW}} + 1.645\sqrt{\kappa_N^2 \sigma^2_{Plin^i_{CRW}} + \sigma^2_{Plin^i_{fus}}} \quad (2)$$

A section of assembly, with 127 fuel pins and 5 cm height, is considered as a evaluated region of which the corrected coefficient μ_{127}= 2.5469 and κ_{127}=0.4849 to ensure the safety performance of independent [pins. For current simulation ability, the uncertainty of fusion linear heat rating is 40 W/cm and the uncertainty of CRW linear power density is 5%. If the linear heat rating in CRW accident is 500 W/cm, the margin between the maximal linear heat rating in CRW accident and the fusion linear heat rating should be set to 132.4 W/cm in order to cover the calculation uncertainty.

In the evaluation of the CRW accident, the uncertainty on the CRW linear heat rating and fusion linear heat rating is adjusted at different levels to study their impact on the maximal reserved worth in a single control rod for Case 7. As shown in Figure 3, the maximal reactivity stocked in control rods varies significantly with these two uncertainties.

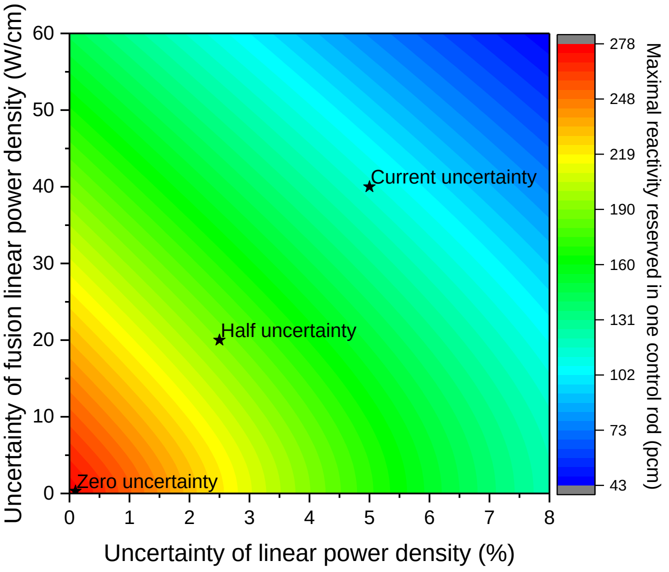

Figure 3: Sensitivity of maximal reactivity reserved in one control rod to calculation uncertainty

With current uncertainty level, the maximal reactivity allowed "stocked" in one operational control rod is around 112 pcm. In a core with 12 operational control rods, the allowed excess reactivity is about 1350 pcm which should cover 700 pcm margin and the burn-up reactivity loss. As the burn-up reactivity loss is -8.5 pcm/EFPD, the maximal length of one cycle is 76 EFPD. This reduced cycle length would be acceptable for experimental SFR, but is not applicable for commercial SMSFR especially if used in remote region.

The MAT4DYN is mono-channel with point kinetics method that is pertinently used in this paper to quantify the impact of CRW accident on the design of SMSFR. The new multi-physics methodology for the calculation of CRW accident, for instance the coupling APOLLO3 and CATHARE3[10], is one way to reduce the calculation uncertainty. If the uncertainty of fusion linear heat rating is 20 W/cm and the uncertainty of CRW linear power is 2.5 %, the maximal reactivity allowed in one control rod is 190 pcm. In a core with 12 control rods, the maximal cycle length is 186 EFPD which would limit the economic performance of SMSFR. Even all the uncertainty is reduced to zero, the maximal stocked reactivity can compensate for 2636 pcm burn-up reactivity per cycle (310 EFPD), and control 700 pcm margin.

The improvement on the simulation accuracy will reduce the required margin for the evaluation of CRW accident and thus increase the allowed cycle length. However, this would require important efforts for decades.

4.3. Sensitivity to the Doppler Effect

The Doppler constant is one key reactivity feedback coefficient for reactors. The enhancement of this effect would not only improve the safety performance in CRW accidents but also in other unprotected power transients. Important efforts have been made to enhance the Doppler effect. For example, the addition of moderator pins in fuel assemblies would increase the absorption rate in the resonance region, which enlarges the Doppler effects of reactor.

To investigate the sensitivity, the Doppler feedback coefficient is artificially increased in SMSFR-12CRs core while other parameters are unvaried in a first approximation. As presented in Figure 4, the relative variation of the total power per unit of inserted reactivity, i.e. b_0 in equation (1), decreases with the Doppler constant. Therefore, the adding of Doppler effect will reduce the linear heat rating in CRW accident and thus increase the allowed reserved reactivity in one control rod.

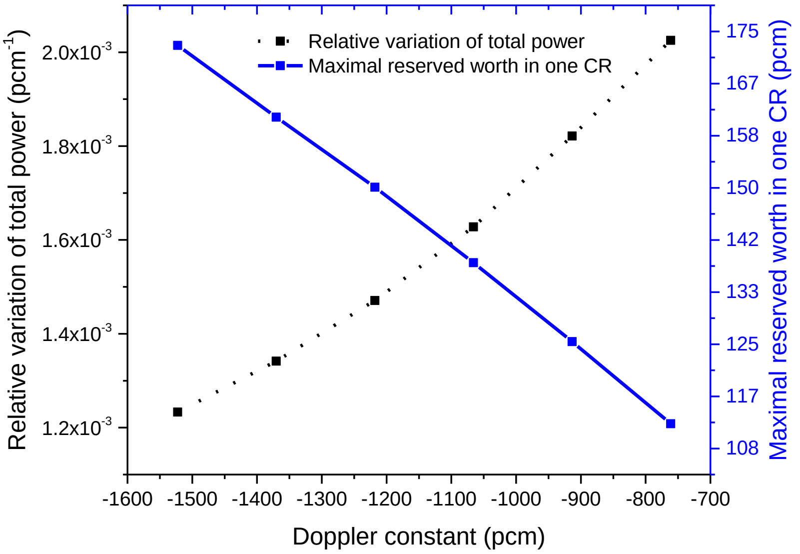

Figure 4: Sensitivity of maximal reactivity reserved in one control rod to Doppler constant

In the reference core with 12 operational control rods, as shown in Figure 4, the Doppler constant is -762 pcm, which enable the cycle length of 76 EFPD. If the Doppler effect is reinforced to -1500 pcm, the maximal allowed reactivity in one control rod would be 170 pcm which could compensate reactivity loss for 158 EFPD and cover 700 pcm operational margin.

The reinforced Doppler effect will improve safety performance of reactor in unprotected transients. The research works on the small SFR with reinforced Doppler effect are being done in CEA[11]. However, the target cycle length is unsatisfied even with double Doppler effects. Furthermore, the large addition of moderator in fuel region will reinforce the Doppler effect and at same time increase burn-up reactivity loss. Therefore, independent systems such as burnable poison in pressurized water reactors (PWRs), would be required for SMSFR to compensate for burn-up reactivity loss.

4.4. Expected ability of burnable poisons

Burnable poisons are materials with an initial absorption capacity that should be significantly reduced under neutron irradiation. For instance, in PWRs, burnable poisons are routinely used in thermal reactors in the form of gadolinium-containing pins in order to decrease the initial boric acid concentration in the primary circuit, the reactivity compensation needed, and the relative power of fresh fuel assemblies.[12], [13].This section is aimed at investigating the required compensation ability of potential alternative system in SMSFR. Such a new system would occupy some positions reserved for the control rods and thus this section is focused on the SMSFR-9CRs core, where 3 control-rods assemblies can be replaced by burnable poisons assemblies.

Without the modification of core characteristics, such as reinforced Doppler Effect, the allowed reactivity stored in the operation control rods is 1000 pcm in SMSFR-9CRs which should control the 700 pcm reactivity margin. Therefore, the control rods are able to compensate only for 300 pcm burn-up reactivity loss. As shown in Figure 5, the allowed cycle length increases with the compensation ability of burnable poisons. To realize the target cycle length, i.e. 375 EFPD, the burn-up reactivity loss is 3188 pcm/cycle. Therefore, the independent reactivity control system should compensate for 2888 pcm reactivity loss.

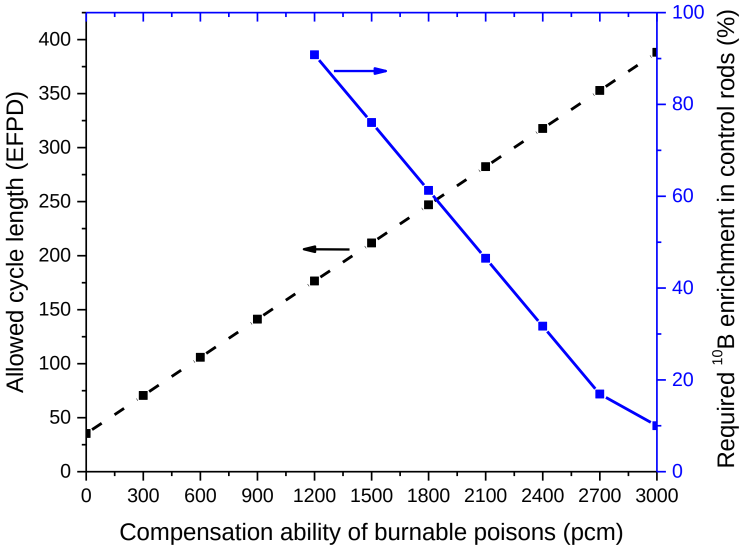

Figure 5: Variation of cycle length and required ^{10}B enrichment in B_4C with the compensation ability of burnable poison

As the absorption cross-section decrease with incident neutron energy, the absorption rate of most absorber would be not enough to realize burnable poison objective in SFR. According to our preliminary, the coupling between absorbers and moderators would be a solution[14]. Detailed designs of burnable poison in SMSFR are currently under investigation

The application of an alternative system to compensate for reactivity loss will lessen the requirement on the control rods. Boron carbide (B_4C) with different ^{10}B enrichment is used as absorber. As shown in Figure 5, the required ^{10}B enrichment decreases with the compensation ability of burnable poisons. The maximal ^{10}B enrichment used in SFR is about 90 %[15]. If higher enrichment is required, the only solution is to increase the number of control rods or the insertion depth of control rods. Moreover, the operating life of control rods with B_4C in high ^{10}B enrichment is very limited because of the swelling and melting issues. However, with a low ^{10}B enrichment, various alternative control rods designs have been studied to improve and economical safety performance of control rods[16]. Consequently, the application of burnable poison would reduce the difficulty on the control rods design and increase the application range of alternative designs.

5. Conclusions

Excess initial reactivity should be limited to avoid CRW accident in SFR. The high burn-up reactivity loss in small reactor limits their allowed cycle length. The short cycle length means high refuel frequency which would limit the economic performance of small reactors and complicate their operation. To achieve the objectives defined for Generation-IV reactors, the CRW accident becomes the constraint factor for small modular fast reactors by comparing with other requirements.

In this paper, various core layouts are investigated. The reactivity reserved in the complete control system increases with the number of control rods. However, the reactivity stored in a single control rod does not vary significantly in different core configurations.

The allowed core excess reactivity to avoid fuel melting in CRW accident is sensible to the uncertainty of calculation and Doppler effect. The improvement on the calculation accuracy would reduce the required safety margin to the fusion linear power density and therefore increase the allowed reserved reactivity. A new multi-physics methodology for core transient analysis, by coupling APOLLO3 and CATHARE3, is under development, which could improve CRW simulation accuracy.

The enforcement of the Doppler Effect would enhance core safety performance in unprotected power transient. A core with enhanced Doppler Effect is being investigated in CEA[11].

The application of new solutions, for instance the use of burnable poisons, to compensate for reactivity could be also a way to reduce core surplus reactivity and thus increase the allowed cycle length. Moreover, burnable poisons are able to reduce the requirement on the control rod design. The design of such new systems is being investigated in small modular sodium fast reactor.

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