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Core Size Effects on Safety Performances of LMRs

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Abstract

An oxide fuel small size core (1200 MWt) was analyzed in comparison with a large size core (3600 MWt) in order to evaluate the size effects on transient safety performances of liquid-metal reactors (LMRs). In the first part of the study, main static safety parameters (i.e., Doppler coefficient, sodium void effect, etc.) of the two cores were characterized, and the second part of the study was focused on the dynamic behavior of the cores in two representative transient events: the unprotected loss-of-flow (ULOF) and the unprotected transient overpower (UTOP). Margins to fuel melting and sodium boiling have been evaluated for these representative transients. Results show that the small core has a generally better or equivalent level of safety performances during these events.

I. INTRODUCTION

There are many core design options for the enhanced safety of LMRs. Mixed oxide is the well-established reference, but some alternatives such as mixed nitride, carbide, metal are being studied as attractive candidates for a fuel. For a power level, large cores (1500 MWe) are preferred in Europe whereas Russia and Japan work on medium sized cores (600 ~ 800 MWe). The USA developed modular cores based on lower power level (~200 MWe).

The objective of this study is to evaluate and compare the safety potential of small and large size cores in static states and during unprotected transients. The EFR[1] (European Fast Reactor) type core was taken as a reference oxide core and a small size core design, which came from the EFR concept by reducing the power level by a factor of 3, was analyzed and compared with the reference core from the safety point of view.

Analyses were carried out through the evaluations of neutronic performances, and of the static safety parameters in order to anticipate dynamic behaviors of the two cores during transient events. For the transient analysis, out of many varieties of unprotected transients,[2] two particularly important accident initiators were considered : Unprotected Loss-of-Flow (ULOF) and Unprotected Transient Over Power (UTOP). Analyses were performed with a particular emphasis on changes of sodium and fuel temperatures so that margins to sodium boiling and fuel melting can be assessed.

II. CORE DESIGN AND ANALYSIS METHODOLOGIES

As shown in Figure 1 for the EFR type reactor, the active core consists of 387 fuel assemblies with three different enrichment zones. The drive fuel height is 100cm and the equivalent core radius is 202cm. Within the active core region, there are 24 control and shutdown assemblies (CSD) and 9 diverse shutdown assemblies (DSD). The active core is surrounded radially by one row of 78 blanket assemblies. The number of fuel pins per fuel assembly is 331. The maximum burnup of fuel assemblies at the end of cycle (i.e., 5×340 efpd) reaches 170 GWd/t_{HM}. The thermal output of the core is 3600MW and the sodium inlet temperature is 395°C with an average temperature increase across the core of 150°C.

The small size core design, which came from the EFR concept by reducing the power level by a factor of 3, produces 1200MW of thermal output (see Figure 2). The dimension of the fuel pin was not changed from that of the reference core, so the exercises have been consisted to define the assembly and the geometry of the core. The drive fuel height is 80cm and the equivalent core radius is 127cm. Fuel enrichments were determined to keep the same reactivity margin at the end of cycle as that for the reference core. The cycle length of assemblies in the core was also conserved.

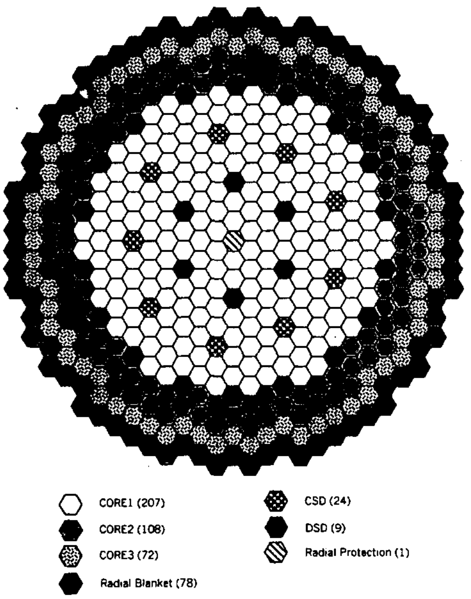

Fig.1. EFR Type Reference Core

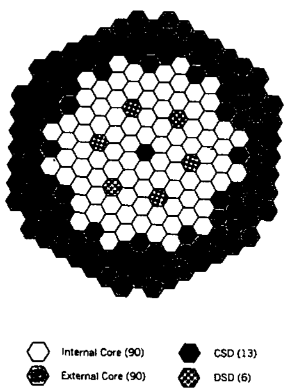

Fig. 2. 1200MWt Core

The evaluation of neutronic performances of the two cores was carried out by using the ERANOS[3] (European Reactor Analysis Optimized System). The microscopic and macroscopic cross sections were obtained by using the cell calculation code HETARED and the data set CARNAVAL IV.

By using the ERANOS, a series of calculations were carried out to determine the neutronic parameters such as the axial and radial distributions of power, reactivity coefficients (reactivity variation for a given variation of the concentration of one of core constituents), the Doppler constants, the kinetics parameters β_{eff} (delayed neutron fraction) and Λ (prompt neutron lifetime). The temperature fields, thermal feedback coefficients, and reactivity variations of the core between two different reactor operation regimes were determined by the thermal code, COREA.[4]

Finally, the dynamic behavior analyses were performed to predict the variation of the average fuel, cladding and sodium temperatures as a function of time within the core during normal operation and transients by using the nuclear plant dynamic code, DYN2B.[5] In DYN2B, peak temperatures, which were compared with safety temperature limits, are calculated with hot channel factors.

The core was assumed to be at the end of the equilibrium cycle (EOEC) in full power operation at the moment of an accident. In general, the situation at EOEC is the most unfavorable due to the increase of the sodium void reactivity with irradiation. The fuel pellet was assumed to be in contact with the cladding inner surface. This assumption is generally valid after a few at.% of irradiation. The gap conductance for closed gap between the fuel and the cladding was assumed constant and equal to 5000 W/m^2 °C for oxide fuel element.[6] In fact, the gap conductance depends on various parameters. For a loss-of-flow transient, the cladding temperature increases rapidly and tends to open the fuel/clad gap so that the conductance decreases. On the other hand, for an overpower transient, the fuel temperature increases rapidly leading to its expansion. This reinforces the fuel/clad contact and increases the conductance.

III. NEUTRONIC PERFORMANCES

Table 1 summarizes the neutronic characteristics of the two cores analyzed. Reactivity loss/cycle depends directly on plutonium enrichment. For a higher plutonium enrichment, there are less fertile isotopes which can be converted to plutonium and the reactivity loss is higher. This is the case for the 1200MWt core (increase of the enrichments due to the core size reduction). There is about 50% increase of reactivity loss/cycle compared with that of the large size core, which means that larger control rod worth is needed for the small core. The small core has a slightly larger control rod worth. The residence time for the oxide fuel EFR type core is determined to meet the design objective burnup of 20 at.%. It is noted that the two cores have almost the same maximum fuel burnup. The reduction of enrichment tends to increase the Doppler effect whereas the spectral hardening tends to decrease it. The small core is characterized by higher enrichments and also by a hard spectrum. As a result, the Doppler constant is smaller than that of 3600MWt core. There is a 30% reduction in sodium void reactivity for the small core mainly due to the increased neutron leakage.

Table 1. Neutronic Characteristics of the Cores

Core	3600MWt	1200MWt
Reactivity loss/cycle ($)	6.7	9.9
Control rod worth ($)	23.8	24.3
Maximum burnup (GWd/t_{HM})	175	180
Doppler Constant at EOEC ($)		
Fissile	- 1.9	-1.4
Fertile	- 0.4	- 0.58
Sodium void effect at EOEC ($)	+ 6.57	+ 4.64
β_{eff} ($\Delta k/k$)	0.003402	0.003366

IV. DYNAMIC BEHAVIOR DURING TRANSIENT EVENTS

IV.1. Unprotected Loss-of-Flow (ULOF)

This transient is assumed to be initiated by the trip of primary pumps but the secondary pumps are assumed to be running at rated condition. The primary pumps of the EFR type reactor coast down with a flow-halving time 10 seconds.

The power and core flow rate during the transient are shown in Figure 3. For this transient, the main reactivity effect is that of sodium density associated with the sodium overheating. The sodium temperature increase hampers the fuel cooling, and thus the overheated fuel introduces a negative Doppler feedback reactivity effect. After a few seconds, a negative reactivity due to the expansion of control rod drivelines intervenes and the net reactivity becomes negative. The power level falls and the fuel temperature decreases. The Doppler effect plays an unfavorable role at that moment when it begins to add a positive reactivity.

Finally, the positive (sodium density and Doppler) and the negative (expansion of the control rod drivelines) feedback effects equilibrate so that the net reactivity becomes zero. The reactor reaches an equilibrium state with a reduced power level and a cooling by natural convection.

Similar phenomena occur for both of the cores, however, different magnitudes of feedback effects result in different safety margins during the transient. For the reference core, the strong positive sodium density feedback effect and the strong negative Doppler constant play an unfavorable role : when the sodium temperature reaches its maximum value (140 seconds), these two effects add 210 pcm and 139 pcm of positive reactivities, respectively.

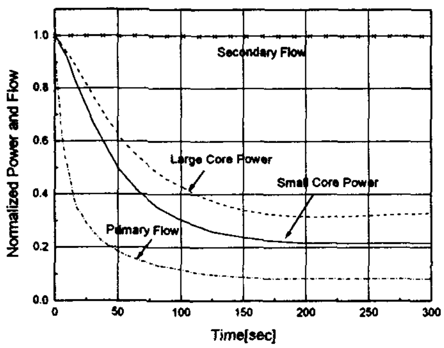

Fig. 3. Power and Flow Variations during the USLOF

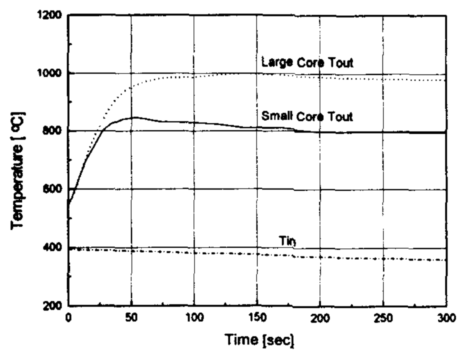

Fig. 4. Sodium Temperature Variations during the USLOF

For the ULOF transient, there is a difference of 156°C between the peak core outlet sodium temperatures as shown in Figure 4, and the superior safety performance of the small core comes mainly from the smaller sodium void effect.

IV.2. Unprotected Transient Over Power (UTOP)

This transient represents an inadvertent withdrawal of all control rods with a speed of 1mm/second which is the maximum value permitted for EFR. This is equivalent to the ramp reactivity insertion rate of + 8pcm/second, which is anticipated for EFR at 10cm of the control rod insertion from the top of the core.

The positive reactivity insertion results in an immediate increase of the power and the fuel temperature. The Doppler feedback effect gives a negative reactivity, however, the net reactivity reaches ~ +10pcm which is maintained during the transient. Because of this constant positive reactivity, there is a linear increase of power and temperatures. Calculation was terminated when fuel begins to melt, and the results are summarized in Table 2.

For the reference core, the beginning of fuel melting occurs at 78 seconds. At this moment, the inserted reactivity is +625pcm. The small core shows the behavior generally equivalent to that of the reference core, but its smaller Doppler effect results in a reduced net reactivity at the beginning of fuel melting. The peak coolant temperature rise in the small core is less than that in the reference core, and the normalized power is similar for both cores at the moment of fuel melting.

Table 2. Results of the UTOP event at the moment of the beginning of the fuel melting

Core	3600MWt	1200MWt
Time (sec)	78	64
Net Feedback effects (pcm)	-583	-480
Total inserted reactivity (pcm)	+625	+512
Net reactivity (pcm)	+42	+32
Peak Coolant Temperature Rise (°C)	207	179
Average Fuel Temperature (°C)	2079	2076
P/Pn	2.5	2.4

V. CONCLUSIONS

The reduction of core size, and hence the power level is often considered as a means to enhance the safety of LMRs. When the same type of fuel is used, the reduced core size has an effect in dynamic behavior of the core by the reduction of the sodium void reactivity feedback. In the ULOF transient, the reduction of the sodium void effect works and the risk of sodium boiling is reduced compared with the large reference core.

In the UTOP event, the small core shows a dynamic behavior equivalent to that of the reference core because the smaller Doppler effect could be compensated by the reduced sodium void feedback in the small core.

In conclusion, the small core has a better or equivalent level of safety performances during ULOF and UTOP events mainly due to its smaller sodium void effect.

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