Proceedings of the Korean Nuclear Society Spring Meeting
Kwangju, Korea, May, 1997

Comparison of the Recriticality Risk of Fast Reactor Cores following a HCDA

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Abstract

A preliminary and parametric sensitivity study on recriticality risk of fast reactor cores after a hypothetical total core meltdown accident was performed. Only neutronic aspects of the accident were considered, independent of the accident scenario, and efforts were made to estimate the quantity of molten fuel which must be ejected out of the core to assure a sub-critical state after the accident. Two types of parameters were examined : characteristic parameters of molten core such as geometry, molten pool type (homogenized or stratified), fuel temperature, environment, and relative parameters to normal core such as core size (small or large), and fuel type (oxide, nitride, metal). The first type of parameters was found to intervene more directly in the recriticality risk than the second type of parameters.

I. INTRODUCTION

The nuclear power plants and the associated protection systems are conceived to operate in such a way that, even for a severe accident, there is no reactor core meltdown. In general, the probability of occurrence of whole core meltdown accident should be less than 10^{-7}/reactor year. In spite of low probability, it is important to understand the phenomena after a core meltdown accident to take measures and to limit the consequences of the accident at the stage of core design and conception study.

Different from thermal reactors, any rearrangement of the core geometry in a fast reactor tends to add a reactivity because a fast reactor core is not in its most reactive configuration. That is, in case of fuel melting, the core compaction would result in a super-critical state.[1] This theoretical possibility consists of an essential problem for the safety of fast reactors. In fact, it is impossible to demonstrate that this type of event can be totally ruled out. Consideration of recriticality issue has important consequences with regard to reactor containment design, definition of protection measures, and safety analysis.

For a core meltdown accident, diverse scenarios can be postulated depending upon the type of reactors and the cause of accidents (control rod withdrawal, propagation of a total instantaneous blockage of a fuel assembly, primary pumps failure without scram, etc.). Main focus of this study is only on neutronic aspects, independent of accident scenarios, and consideration was given only one situation at the end of the primary excursion after a total core meltdown accident. However, unchanged radial structures, i.e., the radial blankets and the radial shielding assemblies of the accidental configuration, were assumed to keep their normal positions. To examine the sensitivity of diverse parameters which have an influence on the reactivity, efforts were made to estimate the quantity of molten fuel that should be ejected to avoid a secondary excursion, assuming that the molten fuel can be ejected under the pressure of fission products and vapors of molten fuel and sodium.[2]

The parameters considered are molten pool type, fuel temperature, environment and also two essential parameters of the core in its normal configuration : core size and fuel type. A large sized EFR[3] (European Fast Reactor) type core and a small sized PRISM[4] (Power Reactor Inherently Safe Module) type core were studied. As for the fuel type, taking the mixed oxide fuel as the reference, a nitride fuel for EFR type core and a metal fuel for PRISM type core were considered.

The calculations were carried out with the ERANOS[5] (European Reactor ANalysis Optimized System) code, based on diffusion theory for the two dimensional cylindrical geometry (RZ) and with 25 energy groups.

II. CORE DESCRIPTION

The main characteristics of EFR and PRISM type cores are summarized in Table 1 and fuel characteristics are presented in Table 2.

Table 1. Principal Characteristics of the Cores Studied

CORE	EFR		PRISM	
Fuel Type	Oxide	Nitride	Oxide	Metal
Fuel Vol.% (%)	34.59	37.32	31.93	25.72
Steel Vol.% (%)	28.21	28.21	28.73	28.73
Sodium Vol.% (%)	32.14	32.14	34.53	45.55
S/A Pitch (cm)	18.80		13.82	
No. of Fissile Pins	331		217	
No. of Fuel S/As	376		76	
No. of Absorber S/As (Inner Core/Outer Core)	15 / 18		3 / 6	
Fissile Height (cm)	100		101	
Core Radius (cm)	199		67	

Table 2. Principal Characteristics of Fuels Considered

CORE	EFR		PRISM	
Fuel Type	Oxide	Nitride	Oxide	Metal
Fissile Theoretical Density (g/cm^3)	11.46	14.25	11.46	16.45
Fertile Theoretical Density (g/cm^3)	10.95	14.32	10.95	15.89
Porosity	0.955	0.85	0.955	1.00
Fuel Filling Ratio	0.83	0.80	0.83	0.70
Enrichment of Inner Core (%)	15.27	13.59	21.79	17.99
Enrichment of Outer Core (%)	19.33	17.20	27.24	22.49

III. PARAMETERS CONSIDERED

III.1 Molten Mixture Composition

The criticality of the molten core depends on (1) Presence of steel in the molten mixture, (2) Enrichment of the molten fuel, and (3) Presence of absorber in the molten materials. And the values of the parameters have been chosen from conservative hypotheses and within reasonable variation ranges of these parameters.

(1) Presence of Steel in the Molten Mixture

Just after a core meltdown accident, the core becomes a homogeneous mixture pool of molten materials. Afterwards, due to the density differences of molten materials, there will be a stratification among them. To treat this effect, two models were considered as follows :

- Homogeneous model : homogeneous mixture of fuel and steel
- Stratified model : Stratification of molten materials, i.e., the molten fuel surmounted by steel

(2) Enrichment of the Molten Fuel

The criticality of the molten fuel depends on the enrichment of PuO_2 in the fuel. Five different enrichments were considered for the two cores and for each type of fuel. The enrichment values chosen are those at the beginning of cycle. This choice is conservative from the safety viewpoint because the enrichments decrease with irradiation.

- Case 1 : Enrichment of the outer core,
- Case 2 : Average enrichment of the inner and the outer cores,
- Case 3 : Enrichment of the inner core,
- Case 4 : Enrichment resulted from the mixture of the inner core and the upper axial blanket,
- Case 5 : Enrichment resulted from the mixture of the inner core and all axial blankets.

For the case 1, all of the molten fuels of the inner and outer cores are assumed to have the same enrichment that the outer core has. This hypothesis is not realistic, however, this is the most severe case. If the molten fuel does not become critical after a total core meltdown accident for this case, the sub-criticality for all other cases can be guaranteed. The case 2 is more realistic than the case 1. The cases 4 and 5 have been chosen from the accident scenario. Because the temperature of the upper part of the core is higher than that of the lower part, the upper part of the core will melt first in case of a total core meltdown accident.

(3) Presence of Absorber (B_4C) in the Molten Materials

To study the effect of the presence of absorber material in the molten pool, two complementary cases, in which the absorber B_4C was added to the mixture of the case 5, were considered. The volume fractions of materials in the absorber assembly for the EFR type core are 30% B_4C, 28% steel 39% sodium, and 2% void.

- Case 6 : Case 5 + B_4C of shutdown S/As in the inner core,
- Case 7 : Case 5 + B_4C of all shutdown S/As.

III.2 Other Hypotheses

The fuel temperatures were assumed to be 1227°C for the oxide and the nitride fuels, and 843°C for the metal fuel. Nevertheless, in order to analyze the temperature effect on reactivity, the oxide fuel temperature of 3000°C was treated for the case 1 of EFR.

The fuel was assumed to have densities in normal operation. But to consider the fuel density change during the accident, one more case was analyzed with the fuel density of 8.33 g/cm^3 (corresponding to the fuel at 3327°C) compared with the normal case of 10.55 g/cm^3.

During the accident, the sodium will be vaporized due to the fuel temperature increase. But in this study, all sodium was assumed to remain in liquid phase. Its density is 0.95 g/cm^3 at 470°C. This choice is conservative from the safety viewpoint because the liquid sodium is a better reflector than sodium vapor. This effect has been studied on one case by decreasing sodium density by a factor of 10.

IV. RESULTS AND DISCUSSIONS

IV.1 Results for the EFR type Core

Special attention has been given to the volume of molten materials which must be ejected to avoid the secondary excursion of power. This volume is the difference between the reference volume (molten core volume) and the calculated critical volume. The reference volume depends on models (homogeneous or stratified) and on cases : fuel, fuel + fertile, fuel + fertile + absorber. To simplify the analysis, R_{min} was defined to be the ratio of the maximum volume to be ejected to the reference volume $(V_{ref}-V_{crit})/V_{ref}$. The main results are presented in Table 3.

Table 3. Results of the EFR Type Core with Oxide Fuel

	Homogenization					Stratification				
Case	H_{crit} (cm)	V_{crit} (m^3)	V_{ref} (m^3)	R_{min} (%)	k_∞	H_{crit} (cm)	V_{crit} (m^3)	V_{ref} (m^3)	R_{min} (%)	k_∞
1	20.0	2.50	6.02	58.4	1.60	12.6	1.58	3.98	60.3	1.82
2	25.0	3.12	6.02	48.1	1.48	14.6	1.83	3.98	54.1	1.71
3	30.9	3.87	6.02	35.7	1.38	17.3	2.16	3.98	45.7	1.61
4	44.0	5.51	6.98	21.0	1.25	21.9	2.74	4.64	40.8	1.47
5	109.4	13.70	8.59	-	1.08	33.4	4.18	5.73	27.1	1.29
6	-	-	8.89	-	0.69	33.3	4.17	5.73	27.3	1.29
7	-	-	9.26	-	0.51	33.3	4.17	5.73	27.3	1.29

The R_{min} decreases from 58.4% for the case 1 (enrichment of the outer core) to 35.7% for the case 4 (enrichment of the inner core). Addition of the axial fertile zones reduce sensibly the ratio R_{min}.

The hypothesis of homogeneous mixture, fuel + steel, is favorable in so far as it allows a rapid reduction of the ratio R_{min} with the enrichment. For the homogeneous model of the case 5, which corresponds to the meltdown of fuel and axial blankets, the criticality condition is never met.

Conversely, for the stratified model of the case 5, the sub-criticality supposes the ejection of 27.1% of the reference volume.

For the homogeneous mixture, the infinite multiplication factors k_∞ are 0.6948 and 0.5153 for the cases 6 and 7, respectively, so that the criticality cannot be achieved. In the stratified model, the presence of absorber over the steel does not influence on the calculated critical height.

Even though the fuel temperature and the density are linked together physically, these were treated separately for the analysis in order to quantify the importance of each parameter from the neutronics viewpoint.

IV. 2 Influence of different parameters

The influences of fuel temperature and density, sodium density, core radius were also studied. The corresponding calculations have been performed only for the case 1. The reference critical heights for this case were found to be 20.0 cm and 12.6 cm for the homogeneous and stratified models, respectively.

First case considered an increase of the fuel temperature from 1227°C to 3000°C. Because the Doppler effect acts mainly on the capture rate of ^{238}U, there is an increase of the critical height of 3% for the homogeneous case and less than 1% for the stratified case.

A reduction of the fuel density from 10.55 g/cm^3 to 8.33 g/cm^3 results in an increase of the critical height of 34.4% for the homogeneous mixture and of 23.3% when there is a stratification.

In case of the core meltdown accident, the sodium would be in gas phase. For liquid-metal cooled reactor that operates in low pressure, the density of the sodium vapor would be 2000 times less than that of the liquid sodium. The computer code cannot treat the medium of such a low density. Nevertheless, the sensitivity has been studied by a reduction of a factor of 10 of the liquid sodium density and for the case of the homogeneous mixture. This sodium density reduction leads to an increase of the critical height of 28.4%.

It is interesting to determine the critical height when the molten fuel was assumed to spread on the core catcher, which has a radius of 4 meters for Super-Phenix. The critical height decreases slightly : - 8% for the case of the homogeneous mixture and - 2% for the stratified case. On the other hand, the critical volumes with the core catcher radius were estimated to be 9.21 m^3 and 6.25 m^3 for homogeneous and stratified case, respectively. These volumes exceed the total volumes of the molten cores (6.02 m^3 and 3.98 m^3 for homogeneous and stratified case, respectively). The recriticality can thus be avoided if there is an uniform spreading of molten fuel under the core catcher.

IV.3 Results for the PRISM type Core

The previous parametric studies showed that the enrichment influences directly on the criticality of the molten core. Knowing that the enrichment depends first of all on the core size, it is interesting to make a comparison between the results obtained for EFR type (3600 MWth) and those for PRISM (425 MWth). The axial compaction of the core presents the same results for the two cores in so far as their heights are almost identical.

Because of small size of the core, the fuel is clearly more enriched in PRISM than in EFR. Apart from this enrichment/core size effect, there is an another effect due to the different proportion [fuel/(fuel+steel)] in PRISM and EFR (higher volume fraction of steel for PRISM).

The results show that the critical heights are almost the same as that for EFR and that the ratios

R_{min} are also close to the values for EFR. But the differences are more significant at low enrichments and for the stratified case, as shown in Figure 1.

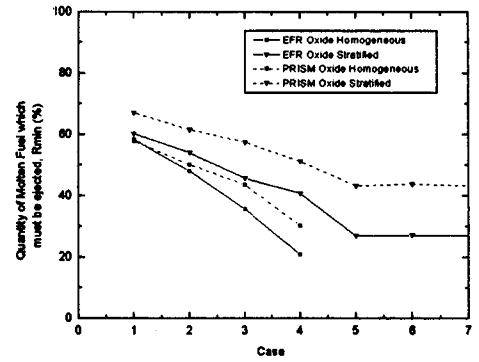

Fig. 1. EFR Oxide Core vs. PRISM Oxide core

IV.4 Results for the Alternative Fuels

In the previous parametric results, not only the enrichment but also the fuel density were found to have a great influence on the criticality of the molten core. Knowing that these two parameters are linked together and depend on the fuel type, it is interesting to compare the results obtained with the oxide fuel, nitride fuel, and metal fuel which is the reference of the PRISM design. The comparisons are presented in Figures 2 and 3.

The combination of a more dense fuel associated with a lower enrichment leads to a similar result for enrichment of the outer core or little different for the low enrichments compared with two cases of reference.

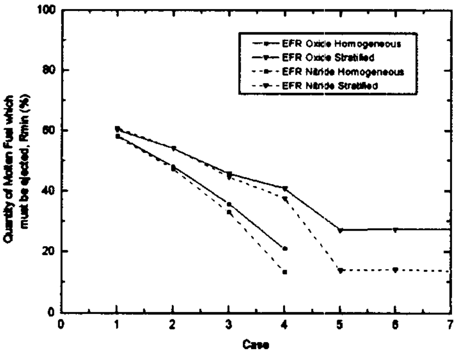

Fig. 2. EFR Oxide Core vs. EFR Nitride Core

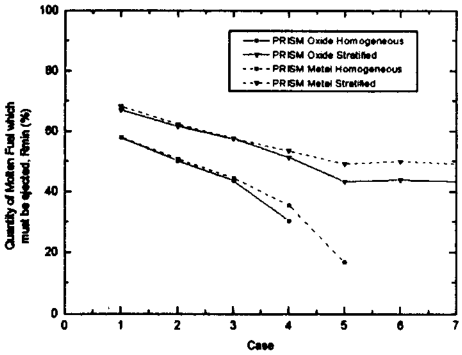

Fig. 3. PRISM Oxide Core vs. PRISM Metal Core

V. CONCLUSIONS

The present study has permitted to understand the influence of different parameters on the recriticality risk in case of total core meltdown accident. Two types of parameters were examined :

- Characteristic parameters of the molten core such as geometry (radial spreading, homogeneous or stratified models), temperature, density, and enrichment of molten fuel, and environment (sodium reflector).
- Relative parameters of normal core such as core size or fuel nature.

This study shows that the second type of parameters intervenes less directly in the analysis of recriticality than the first type. For this reason, the analysis of recriticality needs above all a better understanding of accidental scenarios. It is important to perform the analysis with reasonable hypotheses and to take into account all aspects of the question : neutronics, as well as hydrodynamics and thermodynamics. Then, it will be possible to reflect the results of recriticality analysis at the stage of initial core concept studies.

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