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Dynamic Behavior of Oxide and Nitride LMR Cores during Unprotected Transients

Byung Chan Na and Dohee Hahn

Korea Atomic Energy Research Institute
150, Dukjin-dong , Yusong, Teajon, Korea, 305-353

Abstract

A comparative transient analyses were performed for oxide and nitride cores of a large (3600 MWt), pool-type, liquid-metal-cooled reactor (LMR). The study was focused on three representative accident initiators with failure to scram : the unprotected loss-of-flow (ULOF), the unprotected transient overpower (UTOP), and the unprotected fast transient overpower (UFTOP). The margins to fuel melting and sodium boiling have been evaluated for these representative transients. The results show that there is an increase in safety margin with nitride core which maintains the physical dimensions of the oxide core.

I. INTRODUCTION

The objective of this study is to evaluate and compare the safety potential of nitride fast reactor core with that of an oxide core during unprotected transients. For this, it is necessary to simulate the core in the nuclear steam supply system and to analyze the dynamic behavior of this whole system during accidental transients. These transient analyses therefore consider the reactor, the pools, the pumps, the IHX, and other components of the cooling system that can have an impact on the progression of an event. It is essential to adequately represent the various reactivity feedback effect mechanisms including Doppler effect, sodium density changes, radial expansion of the grid plate, fuel expansion, and control rod driveline expansion.

In this study, the EFR[1] (European Fast Reactor) type core was taken as the reference oxide core and the nitride core, which has the same physical dimension as that of the reference core, was also analyzed. In the EFR type reactor, the active core comprises 387 fuel assemblies with three different enrichment zones. Within the active core region there are 24 control and shutdown assemblies and 9 diverse shutdown assemblies. 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, that is, after 5×340 efpd (equivalent full power day), 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 nitride core design came from the EFR concept by replacing the mixed oxide with the mixed nitride. The geometry of the fuel pin was not changed, but the smear density became 85% of the theoretical density in order to accommodate the irradiation swelling of the nitride. The cycle length of assemblies in the reactor was conserved. The three enrichment zones and the enrichment ratios between the different zones were also conserved.

Out of the wide range of unprotected transients,[2] three particularly significant accident initiators were considered : Unprotected Loss-of-Flow (ULOF), Unprotected Transient Over Power (UTOP), and Unprotected Fast Transient Over Power (UFTOP). As is shown in the initiator names, a total failure is assumed for the plant protection system during the accidents. Analyses were performed with a particular interest in changes of sodium and fuel temperatures so that margins to sodium boiling and fuel melting can be assessed.

II. MATERIAL PROPERTIES OF OXIDE AND NITRIDE FUELS

Table 1 summarizes the thermo-physical properties of the oxide and the nitride fuels. The irradiation performance of oxide fuels has been well demonstrated up to 25 at.%. A high melting temperature compensate for a mediocre thermal conductivity which restricts its linear power to lower than 500W/cm.[3] Therefore, the temperature gradient in the fuel pellet is important and the margin to melting is about 800°C. The neutron spectrum in an oxide core is softer than that in a metal fueled core, which results in a large negative Doppler constant.

The nitride fuel[4] has a good thermal conductivity (almost 6 times the oxide fuel) and a relatively high melting temperature, which allows a high linear power with a large margin to melting. Stored heat in the fuel is considerably reduced due to a low fuel temperature during normal operation. Its high density and harder spectrum allow a higher breeding gain than that in the case of the oxide fuel. These properties of the nitride fuel seem to comply with recent LMR safety requirements. That is, there is a possibility that the nitride fuel could avoid sodium boiling and fuel failure in various accidental situations.

Table 1. Physical Characteristics of Oxide and Nitride Fuels

Fuel Type	Oxide	Nitride
Nominal Composition	$(U,Pu_{0.25})O_2$	$(U,Pu_{0.2})N$
Theoretical Density (g/cm^3)	10.5	14.3
Thermal Conductivity at 1000°C (W/m K)	2.62	14.66
Specific Heat at 1000°C (J/kg K)	322.6	232.5
Expansion Coefficient at 1000°C (10^{-6}/K)	9.72	8.78
Melting Temperature (°C)	2750	2440

III. ANALYSIS MODELING AND ASSUMPTIONS

The transient analysis, which predicts the variation of the fuel, cladding and sodium temperatures as a function of time during normal operation or transients, was performed by using the nuclear plant dynamics code DYN2B.[5]

With regard to the core description, a grouping of assemblies was done, and for every grouping, only an average pin is modeled, using a two-dimensional (RZ) spatial representation. The reactivity was obtained from the detailed reactivity balance equation established with thermal feedback coefficients and the temperature variations in the core. The point reactor kinetics model was used.

The necessary neutronic parameters were determined by a series of neutronic calculations using the ERANOS[6] (European Reactor Analysis Optimized System) computer code and the thermal feedback coefficients were obtained by using the thermal calculation code COREA.[7]

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 closed to the cladding inner surface. This assumption is generally valid after a few at.% of irradiation. The thermal exchange coefficient between the fuel and the cladding was considered constant and assumed to be equal across the core (5000 W/m^2 °C for oxide fuel element and 7000 W/m^2 °C for nitride fuel element[8]). The primary pump of the EFR type reactor was assumed to coastdown with the flow-halving time of 10seconds.

IV. RESULTS AND DISCUSSIONS

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 power and core flow rate during the transient are shown in Figure 1. In this transient, the main effect is the sodium overheating associated with the positive sodium density reactivity. The sodium temperature increase degrades the cooling capability of the fuel, and thus the fuel is overheated leading to 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 a equilibrium state with a reduced power level and a cooling by natural convection.

Similar phenomena occur for both of the cores, however, the different magnitudes of feedback effects result in different safety margins during the transient. For the oxide 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 reactivity, respectively. The sodium reaches its boiling temperature (see Fig. 2).

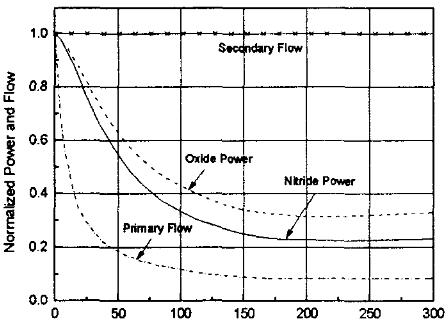

Fig. 1. Power and Flow Variations during the ULOF

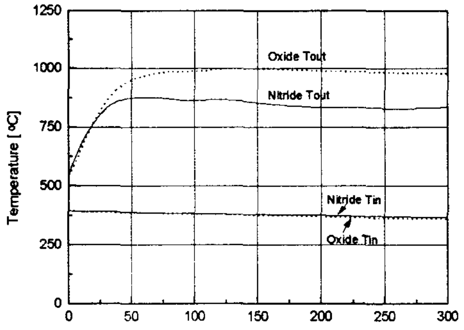

Fig. 2. Sodium Temperature Variations during the ULOF

The nitride core shows more favorable behavior even if its positive sodium density effect is as important as in the oxide core. In fact, the peculiar of the nitride fuel is to have a Doppler constant equivalent to that of the oxide, but to be *cold* in the nominal regime. The latter characteristic, combined with the fact that the formula of the Doppler effect takes part in the initial fuel temperature, explains that the same increase of temperature gives a much larger effect on reactivity in the case of the nitride. At the same time, the same decrease of power results in a reduced temperature variation which adds a much reduced positive Doppler reactivity, i.e., the nitride core is less opposed to the power reduction. These two situations are successively met in the ULOF transient.

At the beginning of the transient, the fuel temperature increases as the sodium temperature arise, and the nitride fuel can have a larger negative feedback reactivity. Afterwards, the fuel temperature decreases under the effect of the power reduction. The magnitude of the fuel temperature decrease is smaller in the case of nitride (140°C compared to 265°C in the case of oxide) and there is a reduced effect on reactivity which is favorable at this moment. As shown in Figure 2, the sodium outlet temperature is higher for oxide core by about 125°C.

IV.2. UTOP (Unprotected Transient Over Power)

This transient represents an inadvertent withdrawal of all control rods with a speed of 1mm/second (maximum value permitted for EFR). The ramp reactivity insertion rate is + 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 as shown in Figures 3 and 4. The Doppler feedback effect gives a negative reactivity, which is opposite to the inserted reactivity. On the whole, the net reactivity attains a certain level (~ +10pcm) and 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.

For the oxide core, the beginning of fuel melting occurs at 78 seconds. At this moment, the inserted reactivity is +625pcm and the power increase rate is 70MWt/second. On the other hand, the nitride core shows more rapid increase of the power (126 MWt/second). This is due to the thermal properties of the nitride fuel which provide a smaller Doppler feedback effect: for the same variation of power, less fuel temperature variation is associated and there is less Doppler feedback in spite of the equivalent Doppler constant. The total inserted reactivity at the moment of nitride fuel melting is +824pcm compared with +625pcm for the oxide fuel, which allows a delayed melting (103 seconds) compared with the oxide fuel (78 seconds).

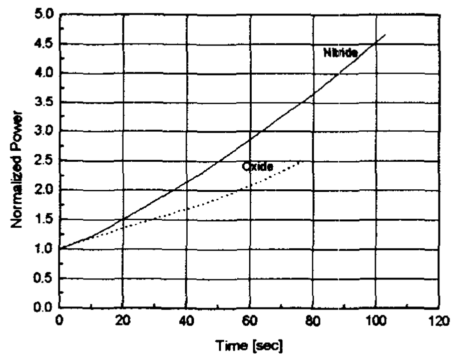

Fig. 3. Power Variations during the UTOP

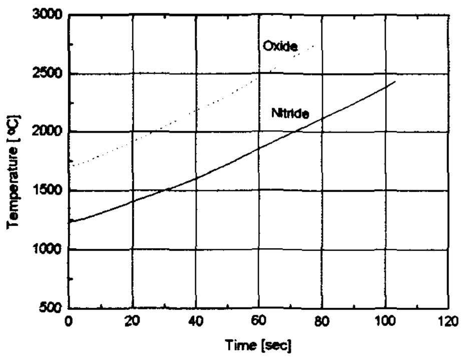

Fig. 4. Peak Fuel Temperature Variations during the UTOP

IV.4. UFTOP (Unprotected Fast Transient Over Power)

This case has been chosen as an envelope case of eventual situations due to a gas passage in the core. The step reactivity insertion of 400pcm was assumed to be maintained for 150ms. This reactivity insertion rate corresponds to approximately 1/5 portion of sodium voiding in the EFR type core.

This transient is characterized by its rapid progress and an insertion of reactivity slightly higher than 1$. The reactivity introduced by the initiators classified as design basis accidents is relatively low (<1$). Thus this transient was studied only to compare dynamic behavior of the two cores subject to a rapid and large insertion of reactivity. The core will become prompt critical before feedback effects play a role to decrease the total reactivity under 1$. Therefore, as shown in Figure 5, the power increases very rapidly to a maximum value, and then decreases corresponding to a total positive reactivity of about 10pcm which results from mainly a large negative Doppler feedback reactivity. The average fuel temperature are presented in Figure 6.

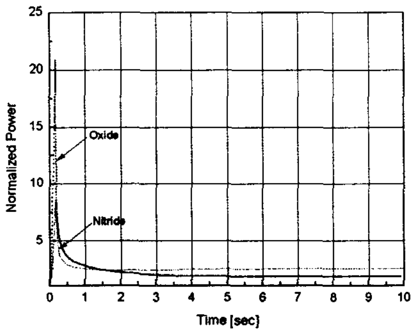

Fig. 5. Power Variations during the UFTOP

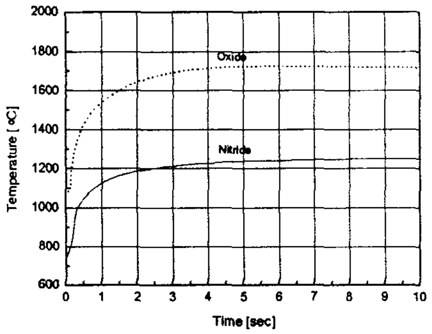

Fig. 6. Average Fuel Temperature Variations during the UFTOP

During the power excursion, the fuel becomes almost adiabatic. In this case, the Doppler effect is the only feedback effect which can intervene effectively. The fuel expansion is not effective because of the closed gap between the fuel and the cladding. The other parameters which intervene are the core kinetics parameters, i.e., β_{eff} and neutron lifetime, and the thermal inertia of the fuel.

For the oxide core, the power at peak is 21 times of the nominal power (76300MWt at 0.16seconds). The peak fuel temperature is 2466°C at 6.4seconds and thus the margin to melting is small.

For the nitride core, the power at peak is equivalent to 8.5 times of the nominal power (30600MWt at 0.15seconds). Compared with the oxide case, this small increase comes from principally the large Doppler feedback at the beginning of the transient. In fact, the thermal inertia of the nitride fuel is 15% less than that of the oxide fuel. This results in a more rapid fuel temperature increase in the case of the nitride fuel than in the oxide fuel.

Moreover, effect on reactivity for a given variation of the fuel temperature is sensibly large for the nitride fuel because of the low operation temperature of the nitride fuel. These two effects are favorable for the Doppler feedback effect.

During the thermal equilibrium, high thermal conductivity of the nitride fuel tends to inverse the situation : the power is stabilized at 9120MWt for the nitride core compared with 7000MWt for the oxide fueled one. In spite of a large power increase, the fuel temperature increase from the initial state of the nitride core is smaller than that of the oxide core(510°C compared with 656°C). Therefore, the nitride core is favorable on two aspects : more efficient Doppler feedback effect during the transient and a substantial margin to melting after the transient.

VI. SUMMARY AND CONCLUSIONS

In an accidental situation due to either an ULOF or an UTOP event, the two effects are systematically favorable; axial fuel expansion and differential expansion of the control rod drivelines. In general, the first effect is small (~-0.3pcm/°C), and the second is larger but delayed and variable because it depends on control rod insertion position which changes during the cycle. The Doppler effect, essentially favorable effect in UTOPs, is favorable at the beginning of ULOF but becomes unfavorable afterwards. Finally, the sodium density effect is always unfavorable, particularly in ULOFs. In general, if a core has smaller sodium density effect and larger Doppler and expansion effects, the risk will be less.

In addition to feedback effects, the thermal properties of fuel play an important role in the dynamic behavior of cores. This aspect is well illustrated in this comparative study on oxide/nitride fuels. The differences shown during the transients are directly linked to physical characteristics of the nitride fuel, even though the sodium void reactivity and the Doppler constant of the nitride core are very similar to those of the oxide fueled reference core.

In the ULOF event, the nitride core is characterized by a larger Doppler feedback effect when it is necessary (at the beginning of the transient) and a smaller Doppler effect when it is unfavorable (after 10seconds). And thus the margin to sodium boiling is larger for the nitride core.

For the UTOP event, the nitride fuel temperature increase is sensibly less pronounced due to the high thermal conductivity than for the oxide fuel. This means on the one hand a less effective Doppler feedback effect so that the power increases rapidly, on the other hand high margin to melting.

In conclusion, the nitride fueled core shows better performance than the oxide fueled one under selected unprotected accidents, which is mainly based upon high thermal conductivity and corresponding thermal feedback effects.

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