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NEW ASPECTS IN THE ANALYSIS OF LOSS-OF-FLOW TRANSIENTS FOR HOMOGENEOUS AND HETEROGENEOUS LMFBR CORES*

by

A. M. Tentner, H. U. Wider
Argonne National Laboratory
9700 South Cass Avenue
Argonne, Illinois 60439

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ABSTRACT

This paper presents the results of analyses of unprotected loss-of-flow (LOF) transients which have been performed to date using the new SAS4A [1] code system. Accident histories for homogeneous and hetergeneous demo-sized cores (300 MWe) are compared and emphasis is placed on phenomena occurring after the initiation of fuel motion as described by LEVITATE [2]. LEVITATE is the SAS4A model for the analysis of fuel and cladding dynamics under loss-of-flow (LOF) conditions and is believed to be the most-sophisticated computational tool currently available for fuel-motion analysis. The results of this analysis indicate that the initiation phase of an unprotected loss-of-flow accident has a considerably lower energetics potential in a heterogeneous core than in a homogeneous core. The difference is larger than previously indicated by SAS3D [3]. Better phenomenological models implemented in SAS4A provide increased confidence in this aspect of safety evaluation of LMFBR cores.

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The homogeneous versus heterogeneous core configuration trade-off studies have been given a high priority in recent years, with the U.S. LMFBR program increasingly tilting towards the heterogeneous concept. It appears that the technical and economic performance differences between homogeneous and heterogeneous core designs are very small [4]. However, the heterogeneous concept appears to have a licensing advantange because of a much lower sodium void reactivity and consequent smaller HCDA initiation phase energetics potential.

This has been confirmed by extensive parametric calculations with the SAS3D code which uses the SLUMPY model to describe the fuel motion during a loss-of-flow accident. This model was for some time the state of the art in LOF fuel motion modeling. However, it does not include some important physical models, such as in-pin fuel motion [2] and continuous fuel flow regimes [7], which are accepted today as relevant to LOF situations.

Although the events predicted by SAS3D/SLUMPY are more energetic in homogeneous than in heterogeneous cores when conservative assumptions are used, calculations made with best estimate assumptions predict comparable and benign power levels in both homogeneous and heterogeneous cores during a loss-of-flow transient. This result reflects the fact that in homogeneous, high void reactivity cores the LOF accident sequence is sensitive to the early fuel motion [15] and, when best estimate assumptions are made, SLUMPY predicts that the early fuel motion is highly dispersive. This result, coupled with uncertainties about fuel motion modeling in SAS3D have led some researchers to suggest that there is no convincing evidence that reactors with lower sodium void coefficients offer clear advantages in HCDA situations [8], [9].

The purpose of the analysis presented in this paper is to compare the sequence of events in a homogeneous and heterogeneous LMFBR core during a loss-of-flow Transient, using the SAS4A code. The emphasis is on the use of LEVITATE, [2], a mechanistic model for the analysis of fuel and cladding dynamics under Loss-of-Flow conditions. LEVITATE has been designed to treat both the high power and near-nominal power conditions in voided assemblies of an LMFBR. Cladding and fuel motion can be treated simultaneously [10] while previous models could only treat these phenomena sequentially. LEVITATE also models several relevant phenomena, not considered in earlier models. The most important of them are the in-pin fuel motion, several pin disruption modes, continuous fuel-steel flow regimes [7], [11], fuel steel crust and plug formation [7] and a tight coupling with the sodium dynamics.

While LEVITATE results are in good agreement with TREAT LOF experimental data, the results of the old loss-of-flow model, SLUMPY, overpredict fuel dispersal [2], [13], [14]. A careful examination of the results indicates that the more realistic fuel dispersal predicted by LEVITATE is slower than the SLUMPY prediction due to increased frictional effects, fuel freezing, cladding ablation, and fuel steel mixing [2]. Another important phenomena not previously considered is the in-pin fuel motion which tends to accelerate the fuel inside the pin towards the central region when the initial failure occurs near the midplane. This leads to a slowing of the overall fuel dispersal [14].

Thus, the characteristic feature of this LOF analysis is that the early fuel dispersal predicted by LEVITATE is slower than the dispersal predicted by SLUMPY, the SAS3D LOF model. This slower fuel dispersal affects preferentially the homogeneous core, where fuel failures occur when the core is close to prompt critical and only partially voided, with a potential for accelerated voiding due to pin failures. The combination of these factors tends to lead the homogeneous core to a prompt critical condition resulting in power levels significantly higher than those reached in the heterogeneous core. It is interesting to note that not only is the fuel dispersal delayed but, when the power level at fuel failure time is high, the fuel motion can introduce small amounts of positive reactivity before significant fuel dispersal occurs.

In heterogeneous cores, on the other hand, fuel failures occur at relatively low levels and the dispersive character of the out-of-pin fuel motion dominates the initial part of the fuel motion. In addition, at failure time the cladding is largely molten and pin disruption can occur easily, thus preventing the in pin motion from playing any significant role. Although the initial fuel dispersal is still slower than previously predicted by SLUMPY, the fact that the fuel failures occur when the core is relatively far from prompt critical and the core voiding is nearly completed leads to an energetically benign LOF accident sequence.

To illustrate these effects a comparison between the power histories of a heterogeneous and a homogeneous core during a loss-of-flow accident is presented in Fig. 1. In this analysis we considered two demonstration-sized (300 MWe) cores. The heterogeneous core consists of 156 fuel assemblies and 82 inner blanket assemblies, while the homogeneous core consists of 198 fuel assemblies. In this analysis, the assumption of no axial fuel expansion was made. Calculations including axial expansion appear to exhibit similar characteristics and will be presented in the full paper. The SAS4A/LEVITATE calculated scenario is described below:

After a pump trip at t = 0.0 sec, the core flow coasted down rapidly decaying to 30% of the initial value after about 9 sec. Continued fuel heatup and flow decay resulted in sodium boiling. In the homogeneous core, sodium boiling occurred first at 9.62 s into the transient in the channel that had the highest steady-state power-to-flow ratio. Due to the continued boiling, positive void reactivity is inserted at an increasing rate. Despite mitigating negative Doppler feedback, net reactivity increases steadily to 97 cents when the first fuel pin failure is predicted, slightly above the core midplane. The power is 85 times nominal at this time and the cladding is still solid, preventing an early disruption of the fuel pins. The high power level initially present and the subsequent rapid power increase lead to rapid fuel melting inside the pin cavity. This fuel is accelerated by fission gas pressure toward the central region and its reactivity effect temporarily exceeds the dispersive effect of the fuel motion initiated in the coolant channels. Due to the accelerated addition of sodium void reactivity caused by the pin failures and the slight fuel positive contribution (1.5 cents), the core reaches a prompt-critical condition, with a peak power of 890 times nominal. Other channels which fail during the power burst exhibit a behavior similar to that of the lead channel.

The conditions in the heterogeneous core are quite different. At the time of the first fuel pin failure, which occurs at 15.1 sec. into the transient, the power level is only 21 times nominal power and the net reactivity is 88 cents, i.e. much further from prompt critical than was the homogeneous core. The core is voided to a significant extent and the rate of positive reactivity insertion due to additional sodium voiding is rather low. Due to the low power level and the slow power increase the in-pin melting proceeds slower and the out-of-pin dispersive effects dominate. The net effect is a small negative fuel motion reactivity contribution in the lead channel. Significant fuel dispersal begins in the lead channel about 100 milliseconds after pin failure, as expected, but due to lower net reactivity at pin failure and the low rate of sodium reactivity insertion, the core never becomes prompt critical and the maximum power is 37 times nominal power.

CONCLUSIONS

Several important physical pnenomena, not included in previous loss-of-flow codes, have been identified. These phenomena, which are now incorporated in LEVITATE, the SAS4A fuel motion model, have been shown to have a significant effect on the LOF accident sequence.

The LEVITATE model predicts a slower fuel dispersal than the earlier SAS3D/SLUMPY model. This result is confirmed by data obtained in experiments simulating loss-of-flow transients with the maximum power 10-20 times nominal.

This slower fuel dispersal significantly affects the LOF accident sequence in homogeneous cores where pin failures occur at high power levels, when the core is only partially voided. The early reactivity contribution of the fuel motion can become slightly positive due to the in-pin motion. This causes the power level reached by a homogeneous core to be significantly higher than calculated for the heterogeneous core. In contrast, heterogeneous cores experience fuel failures at lower power levels, when the voiding is nearly complete and are therefore much less sensitive to the initially slow fuel dispersal. Maximum power levels calculated by SAS4A/LEVITATE during a LOF transient in a heterogeneous reactor are therefore rather low.

The high power levels predicted for a loss-of-flow in a homogeneous high void reactivity core appear to be particularly undesirable when the licensing process is considered. Even if the calculated energetics are such that the events can be contained by the pressure vessel, the lack of high power fuel motion experimental data will render the results difficult to use in licensing [16].

This difference between heterogeneous and homogeneous core behavior reinforces the safety/licensing advantage for HCDAs of the heterogeneous core.

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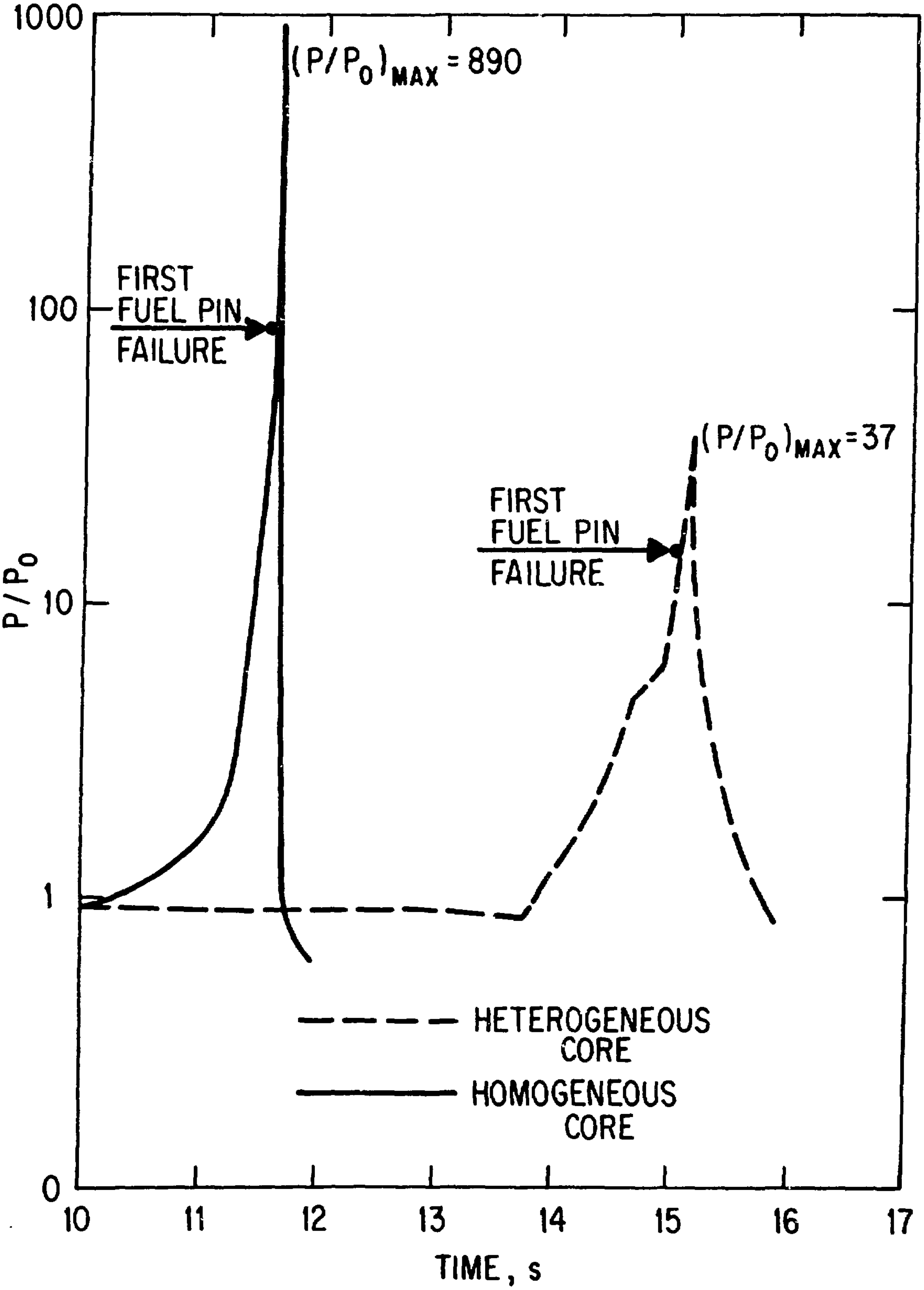

Fig. 1. Power History During a Loss-of-Flow Transient in Homogeneous and Heterogeneous Cores