TIME-DEPENDENT REACTOR PHYSICS IN THE FFTF UNPROTECTED
LOSS-OF-FLOW ACCIDENT

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TIME-DEPENDENT REACTOR PHYSICS IN THE FFTF UNPROTECTED LOSS-OF-FLOW ACCIDENT*

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ABSTRACT

Four reactivity models, including the SAS3A reactivity model and the adiabatic reactivity model, are compared for different states in the FFTF unprotected loss-of-flow accident. The SAS3A reactivity for this particular accident is shown to be greater than the adiabatic reactivity and sufficiently different to alter the course of the accident. Separation of the adiabatic reactivity into material and spatial components is shown to permit time-dependent reactivity worth tables which can approximate the adiabatic reactivity for use in the SAS3A point kinetics routine. It is also noted that several reactivity effects are currently ignored in SAS3A.

1. INTRODUCTION

Integrated LMFBR accident analysis code systems, such as SAS3A (1) and MELT-III, (2) have been under development for several years and attempt to model a number of phenomena, including material motion, with a high degree of sophistication. In contrast to the sophisticated manner in which they model other phenomena, they generally treat the time-dependent neutronics behavior with a point kinetics model, using a fixed power shape and space-dependent reactivity tables based on first-order perturbation theory.

This relatively crude neutronics treatment has been shown to be inaccurate by several authors (3-5) when analyzing transients during which substantial material motion occurs. Typical of these comparisons is a space-dependent kinetics calculation with the space-dependent kinetics code, FX2. (6,7) For this hypothetical core slumping in an LMFBR, the point kinetics treatment resulted in a substantial under-prediction of the reactivity due to fuel motion. (5) This calculation utilized a very simple fuel motion model and neglected the Doppler effects.

To date, however, no consistent comparison has been made between the point kinetics treatment and the multidimensional space-dependent kinetics treatment for a realistic LMFBR transient which includes detailed feedback models. As an initial effort in making such a comparison, this work presents a comparison of reactivities computed by different methods for given states

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in a hypothetical LMFBR accident which includes sodium voiding, clad motion, and fuel motion as predicted by SAS3A. The objectives of the study were to: (1) investigate the adequacy of the SAS3A point kinetics reactivity model for the FFTF loss-of-flow accident, (2) compare the reactivities predicted by three perturbation reactivity models, and (3) initiate the development of a method for including space-dependent kinetics in LMFBR accident analysis codes.

2. REACTIVITY MODELS

Excluding the SAS3A reactivity, the other three reactivities used in this study were calculated by a modified version of FX2 (called FXPERT) which uses perturbation theory techniques. The basic perturbation expression for the reactivity change between two reactor states is given by

$$\delta\rho = -\delta\lambda = \frac{1}{\bar{F}} \langle \psi_0^*, (-\delta M + \frac{1}{k_0} \delta F) \psi \rangle, \quad (1)$$

where

$$\bar{F} = \langle \psi_0^*, F\psi \rangle,$$

$\delta\rho$ denotes the reactivity change,

$\delta\lambda$ denotes the eigenvalue change,

δM denotes the change in the neutron leakage, absorption, and scattering operator,

F denotes the fission operator for the final-reactor state,

δF denotes the change in the fission operator

k_0 denotes the static k_{eff} for the initial-reactor state,

ψ_0^* denotes the adjoint flux for the initial-reactor state, and

ψ denotes the real flux for the final-reactor state.

The basic difference between the three reactivity models used in this study was in the treatment of the neutron flux and the leakage operator. Since the time-dependent neutron flux, which includes the effects of time-dependent delayed-neutron precursor distributions and flux shape adjustments due to neutron lifetime effects, could not be calculated in this study, the static or adiabatic reactivity was used as the exact reactivity. Then the flux obtained from the static eigenvalue equation,

$$(-M + \frac{1}{k} F) \psi = 0, \quad (2)$$

is used in Eq. (1) to determine the reactivity.

In accident analysis the reactivity is often approximated by using the initial-state real flux in Eq. (1) and the initial-state fission operator in the expression for F . This is commonly known as the first-order perturbation theory approximation. Another approximation that is generally made in

first-order perturbation theory for diffusion theory is to linearize the perturbed diffusion operator. That is, the change in the diffusion coefficient is given by

$$\delta D = D - D_0 = \frac{1}{3\Sigma_{tr}} - \frac{1}{3\Sigma_{tr_0}} = - \frac{\delta\Sigma_{tr}}{3\Sigma_{tr} \Sigma_{tr_0}} \quad (3)$$

and is approximated by

$$\delta D \approx - \frac{\delta\Sigma_{tr}}{3\Sigma_{tr_0}^2} \quad (4)$$

Then all cross section changes are linear in the perturbation formula, and the total reactivity can be easily separated into material components. Both the linear and the nonlinear first-order perturbation reactivity models are compared with the adiabatic reactivity model in this study.

For the nonlinear first-order perturbation reactivity model and the adiabatic reactivity model, the reactivity is separated into material contributions by retaining the fully perturbed transport cross section in the denominator of Eq. (3) for each material's leakage term. That is, Eq. (1) is rewritten as

$$\delta\rho = \sum_1 \delta\rho_1 \quad (5)$$

where $\delta\rho_1$ are the material reactivity contributions and are given by an expression identical to Eq. (1) except that δM and δF are replaced by δM_1 and δF_1 . In addition, only the numerator of Eq. (3) is separated into material components $\delta\Sigma_{tr_1}$ and the denominator remains the same for all $\delta\rho_1$.

Due to the nonlinear effects, including the flux changes in the adiabatic reactivity, this separation can be regarded as somewhat arbitrary, but it does have advantages. The most important advantage is that although the separation parallels that of the linear first-order perturbation reactivity model, for the adiabatic reactivity model the material reactivity contributions sum to the exact adiabatic total reactivity. The separation also permits the material reactivities to be further separated into spatial contributions and thus permits the generation of time-dependent material-worth tables that can be used in a reactor accident analysis code such as SAS3A. These time-dependent material worth tables, when used with the correct material changes, can be used to calculate more accurate reactivities than are presently used in the point kinetics model of SAS3A. It must be remembered that each material's reactivity is regarded as that material's contribution to the total reactivity for that particular reactor state. In any other reactor state, the same perturbation of a given material would yield a different contribution to the total reactivity.

3. ACCIDENT ANALYSIS MODEL

In order to compare the various perturbation reactivity models and the SAS3A reactivity model, it was necessary to obtain a set of reactivity worth tables (sodium void, cladding, fuel, and Doppler) that was consistent with the geometry and cross section set used in FXPRT. This was done by developing two subroutines, one to map the SAS3A geometry, including material

volume fractions and fuel temperatures, onto the FXPRT r-z geometry and the other to map the FXPRT material worths back onto the SAS3A geometry. In this mapping procedure, each SAS3A subassembly channel was represented as an annular ring in the FXPRT two-dimensional cylindrical model. Prior to generating the SAS3A time-independent reactivity tables with FXPRT, a consistent initial power and temperature distribution was reached by iterating between the SAS3A steady-state calculation and the FXPRT-calculated fission source. A ten-group cross section set generated by SDX (9) was used to obtain these worth tables and to calculate the various perturbation reactivities.

The sequence of events predicted by SAS3A for the FFTF unprotected loss-of-flow accident using the FXPRT-generated worth tables is illustrated by Table 1. In addition, the reactivity and power histories from 13 secs on are shown in Fig. 1. Both the power and reactivity dropped smoothly during the initial 13 secs of the transient. This calculation was typical of previous calculations for this accident. At the termination of the calculation, complete sodium voiding of the active core and substantial cladding and fuel melting and redistribution had occurred. The final reactivity predicted by SAS3A was -4.4% and the final power level was 83% of nominal power. The peak reactivity achieved during the calculation was just under 1% , and the peak power was nearly 25 times nominal power.

Table 1. FFTF Loss-of-Flow Accident Sequence of Events

Channel	Number of Subassemblies - Radial Ring	Average Days of Burnup	Time (sec) of Initiation of			
			Sodium Boiling	Cladding Melting	Cladding Motion	Fuel Motion
1	1-1, 2-2	143	14.35	16.48	17.42	19.60
2	3-2, 2-3	10	13.26	15.46	16.36	19.44
3	7-3	181	16.55	18.90	19.66	19.68
4	5-4	230	18.57	19.77		
5	7-4	110	18.88			
6	3-4	10	18.88			
7	12-5	152	18.74			
8	6-5	10	14.43	16.67	17.69	19.61
9	19-6	226	16.32	19.56		19.76
10	9-6	10	15.65	18.79	19.63	19.67

During the SAS3A calculation, eleven restart files were saved for continuing the calculation. These restart files also provided reactor states to be mapped onto the FXPRT geometry so that the three perturbation reactivity models and the SAS3A reactivity model could be compared.

Fig. 1. SAS3A Power and Reactivity for Loss-of-Flow Accident

4. REACTIVITY RESULTS

The FXPRT reactivity calculations were performed twice for the perturbation reactivity models. Following the first set of calculations, it was noted that the transformation from SAS3A to FXPRT included material motion effects not normally included as a reactivity effect in SAS3A. These included: axial sodium voiding below the lower blanket and above the upper blanket, cladding and structural axial expansion, blanket material axial expansion and motion, and apparent loss of cladding during cladding motion.

For the second calculation of the perturbation reactivities, the transformation was altered so as to neglect these effects. The total reactivities predicted by the four reactivity models in this second calculation are shown in Table II and in Fig. 2. If the SAS3A reactivity model were consistent, then the SAS3A reactivity and the linear first-order reactivity should be identical. As can be seen from the table, the SAS3A reactivity is consistently less than the linear first-order reactivity. The SAS3A reactivity components at 19.65 sec are compared with the linear first-order reactivity components in Table III. Although the individual material components are in better agreement in the second perturbation calculation, the total reactivity differs more. At the bottom of the last column is the percentage difference between the SAS3A total reactivity and the linear first-order total reactivity. The other entries in that column indicate the amount that each material reactivity contributes to that percentage difference.

Table II. Total Reactivities Predicted by the Models

Time into Transient (sec)	Used by SAS3A (\$)	First-order with Linear D (\$)	First-order with Non-linear D (\$)	Adiabatic (\$)
13.75	-0.1295	-0.1006	-0.1075	-0.1034
15.46	0.0772	0.1326	0.0692	0.1060
16.34	-0.0230	0.0596	0.0407	0.0243
17.17	-0.1632	-0.0469	-0.2656	-0.1306
17.87	0.1423	0.2610	0.1783	0.1071
18.43	-0.1834	-0.0596	-0.7081	-0.2603
19.06	-0.1709	-0.0403	-0.7626	-0.2634
19.49	0.2172	0.3943	0.4234	0.1293
19.65	0.9173	1.2309	1.1400	0.6446
19.76	0.9075	1.1506	2.1218	0.4486
19.83	-2.3936	-2.6044	-8.3144	-2.9022

The difference that exists in the fuel reactivities may be attributed primarily to the Doppler reactivity treatment in the two models. In SAS3A, the Doppler coefficient is treated as $T(dk/dt) = \text{constant}$, with a sodium-out variance of the constant. In FXPRT, the cross sections are interpolated from four cross section sets generated at different temperatures. Removing sodium should have no effect on the linear first-order Doppler

Fig. 2. SAS3A and FXPRT Reactivities for Loss-of-Flow Accident

reactivity since only the steady-state flux is used in the perturbation formula. A minor SAS3A input error for the channels 6-10 sodium-out Doppler coefficients probably also contributes slightly to this difference.

Table III. SAS3A and FXPERT Linear First-Order Material Reactivities at $t = 19.65$ sec

Material	Reactivity (\$)	<u>Linear First-Order Reactivity</u>		<u>SAS-First-Order</u>
		1st Calculation (\$)	2nd Calculation (\$)	1st-Order Total (%)
Coolant	-0.1226	-0.3493	-0.1998	6.3
Steel	0.9236	1.1087	1.0662	-11.6
Fuel	0.1164	0.3633	0.3645	-20.2
Reflector	---	-0.0416	---	---
Total	0.9173	1.0811	1.2309	-25.5

The steel reactivity difference is due to the loss of cladding when cladding motion occurs. This effect was corrected in the transformation routine, but still occurs in the SAS3A calculation. It arises from assuming an average clad density for all cladding in a channel when the first clad node begins clad motion. Since other nodes in the channel are in varying stages of thermal expansion, mass appears to be lost if the molten clad density is used.

The coolant reactivity difference arises from the use of an average coolant density in SAS3A to determine the initial total coolant worth of a coolant node. Since the coolant has an axial temperature profile at steady state, there is also an axial coolant density variation. Thus, a given SAS3A node in the transformation to FXPERT may have more or less total coolant worth than it does in SAS3A. Averaging processes that occur in mapping between the SAS3A geometry and the FXPERT geometry also contribute to the reactivity differences for all three materials.

The total reactivities for the three perturbation models are compared in Table II. The reactivities, in order of increasing size at each time point, and consistently nonlinear first-order, adiabatic, and linear first-order. The nonlinear diffusion coefficient treatment in the first-order perturbation model underpredicts the reactivity considerably throughout the transient. This is similar to previous results. (10)

However, the relation of the adiabatic reactivity to the linear first-order reactivity is quite different than the results reported in other studies. (3-5) Table IV gives an indication of why this occurs. Although the fission, scattering, and removal contributions to the adiabatic reactivity are larger than their contributions to the first-order reactivities, the adiabatic leakage term is larger in magnitude and with opposite sign. It thus dominates to make the adiabatic reactivity less than the linear first-order reactivity. The nonlinear first-order reactivity has an even more negative leakage component. This is due to removal of considerable material including sodium, cladding, and fuel from the upper part of several subassemblies. This material density decrease results in a small transport

cross section in these regions which, according to Eq. (3), causes a large leakage component. The linear first-order reactivity, using Eq. (4) for the leakage component, does not have this small transport cross section in the denominator. The adiabatic reactivity model accurately accounts for this material motion through its use of the final-state flux.

Table IV. Reactivity Components of the EXPERT Perturbation Models at $t = 19.65$ sec

Component	Linear First-Order (\$)	Nonlinear First-Order (\$)	Adiabatic (\$)
Fission	3.5547	3.5547	3.5565
Scattering and removal	0.8171	0.8171	1.1808
Leakage	-3.1409	-5.5118	-4.0926
Total	1.2309	-1.1400	0.6447

5. CONCLUSIONS

This investigation has produced many interesting results and has raised several questions requiring further research. First, the SAS3A total reactivity is greater than the adiabatic total reactivity at each point examined in this transient. The differences are substantial and sufficient to alter the predicted course of the accident. The SAS3A reactivity cannot be considered conservative, since the lower adiabatic reactivity could have resulted in higher reactivity ramp rates just as easily as more incoherent fuel slumping. Since the first-order reactivity model has been shown to underpredict the adiabatic reactivity model in other studies, (3-5) it is probably only coincidental that the first-order and the SAS3A reactivity models over-predicted the adiabatic model in this study. This would not be expected in all cases.

The SAS3A reactivity model has been shown to neglect a number of material motion effects. Some of these appear to be important, and improvements to the models should be considered. For FFTF studies, the short axial reflectors (~14.5 cm long and treated as blanket material in SAS3A) requires consideration of sodium-void reactivity effects below and above them. For the longer axial blankets of commercial plants, the sodium-void effects may be negligible, however. The reasons for the differences between the SAS3A reactivities and the linear first-order reactivities for fuel and steel should be resolved further. In particular, the clad motion model should be revised to conserve clad mass, so that a consistent comparison can be undertaken. Steel axial expansion effects can be easily included in the SAS3A reactivity model, but they probably have a minor effect on the total reactivity.

This study has also demonstrated, although it is not explicitly presented in this paper, the feasibility of separating the adiabatic reactivity into material and spatial components. The method considered here is quite similar to that proposed in an earlier paper by Meneley, *et al.* (6) Thus,

time-dependent reactivity worth tables, regenerated at various times in a transient with a module similar to FXPERT, could be used to obtain close-to-exact adiabatic reactivities for use in the SAS3A point kinetics routine.

Finally, the variation of the leakage term in the three perturbation reactivity models and its effect on the total reactivity indicates that it may be necessary to consider transport effects in accident analysis codes such as SAS3A. Preliminary investigations by one of the authors (J. E. C.) seem to indicate, however, that a diffusion theory treatment remains valid for typical LMFBR cores where quite substantial material motion has occurred.

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