Comparison of Reactivity Feedback Models for the FFTF Passive Safety Tests

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ABSTRACT

The FFTF Loss-of-Flow-Without-Scram Test from 50% power to natural circulation flow was analyzed with the SASSYS code using both the SASSYS reactivity feedback models and the semiempirical reactivity feedback equations for the FFTF oxide-fuel core. The experimental data for primary loop flow and reactor power were used as inputs to obtain the same fuel, sodium, and structure temperatures for both sets of reactivity feedbacks.

A detailed comparison was made for each of the reactivity feedbacks: Doppler, sodium density, control rod expansion, axial fuel expansion, radial expansion, and bowing. The major differences between the SASSYS reactivity models and the FFTF reactivity equations were in the radial expansion and bowing feedback. The sensitivity of the results to the input for the SASSYS radial expansion and bowing model was investigated.

It was not possible to unequivocably determine whether the SASSYS reactivity models or the FFTF reactivity equations gave better agreement with the experimental data because the dominant feedback, which could not be directly measured, came from the Gas Expansion Modules. Analysis of some of the other FFTF Passive Safety Tests indicates that the SASSYS reactivity models can give better agreement with the experimental data. Additional FFTF tests without the GEMs are recommended to provide more information on the structure reactivity feedbacks, which are the dominant feedbacks during a LOFWOS event for a metal-fuel core.

INTRODUCTION

One of the objectives of the FFTF Passive Safety Testing Program was to develop an understanding of reactivity feedbacks that could be used in the design and safety analyses of innovative reactors. Recently, a more urgent need has developed to better understand reactivity feedbacks in the FFTF reactor for the design and safety analyses of a new FFTF metal-fuel core.

A set of FFTF semiempirical reactivity feedback equations has been used for the analysis of the existing FFTF oxide-fuel core. However, these reactivity equations cannot be applied directly to the FFTF metal-fuel core. There is a need to develop a more fundamental understanding of the reactivity feedbacks so that models can be constructed that correctly extrapolate from the FFTF oxide-fuel core to the FFTF metal-fuel core. The SASSYS code[1] was selected because it is being used both for the safety analysis of the FFTF metal-fuel core and also for the safety analysis of the PRISM and SAFR innovative reactors. Therefore, this study will also assist in the validation of the SASSYS code for analysis of the innovative reactor designs.

The purpose of this paper is to compare the reactivity feedback models in the SASSYS code with the experimental data from one of the FFTF passive safety tests and with the FFTF semiempirical reactivity feedback equations.

ANALYSIS OF THE FFTF PASSIVE SAFETY TESTS

The FFTF passive safety tests performed in 1986 involved loss-of-flow-without-scram events at power levels up to 50% of the nominal 400 MW (thermal).[2] The main purpose of these tests was to demonstrate the effectiveness of passive shutdown devices called Gas Expansion Modules (GEMs).[3] These tests have been analyzed with the SASSYS code using both the SASSYS reactivity feedback models and the FFTF reactivity equations. The results that will be discussed are for the highest power tests (50% of full power) with the pumps tripped to natural circulation (instead of pony motor) flow.

Flow Coastdown

The pump model in the SASSYS code predicts a slightly higher primary loop flow rate than the experimental data during the flow coastdown, and therefore it was decided to use the experimental data as input for the analysis. This was achieved by trial-and-error variation of the transient pump head until the desired flow coastdown was obtained. Figure 1 compares the resulting flow coastdown curve with the experimental data for the primary loop flow.

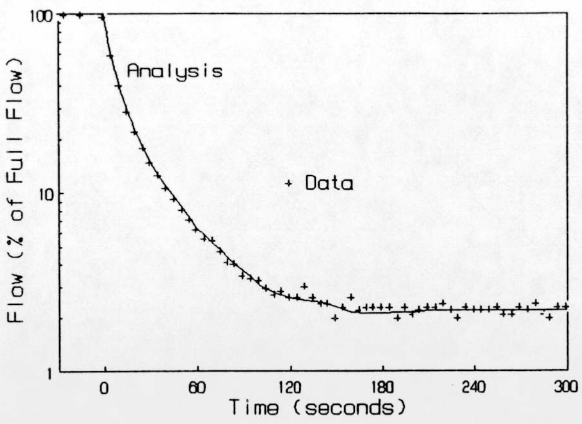

Fig. 1. Primary Loop Flow.

Reactor Power

The most straightforward calculation is to allow the SASSYS code to determine the power from the set of reactivity feedbacks. However, the precise magnitude and timing of the GEM reactivity were not known. Therefore, in order to simplify the comparisons, it was decided to use the experimental data for the total reactor power as input for the analysis. The advantages of using the experimental reactor power are that the same core temperatures would be used to calculate the reactivity feedbacks for both the SASSYS reactivity models and the FFTF reactivity equations and that they can be compared on a consistent basis.

The total reactor power consisted of the data for prompt fission power combined with calculations for the decay power, which could not be measured. The decay power calculations, which were performed using 32 decay heat groups, take into account the change in fission power during the experiment. Figure 2 compares the reactor power used for the analysis with the data for the total reactor power.

Comparison of Coolant Temperatures

Having established the power and flow for the analysis of the transient, the predicted temperatures can be compared with the experimental data. The reactor core included two Posttest Irradiation Open Test Assemblies (PIOTAs) that contained fast-response thermocouples to measure the coolant temperatures

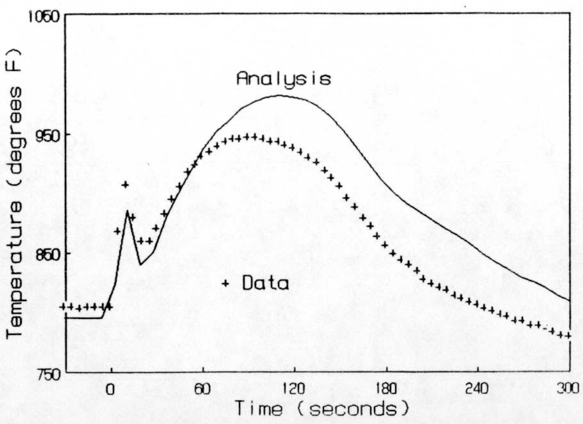

Fig. 2. Total Reactor Power.

~10 in. above the top of the fuel pins. These two PIOTA assemblies, which were located in Row 2 and the outer Row 6 of fuel assemblies in the core, were modelled individually along with three other calculational channels representing the three orifice and fuel enrichment zones. Figure 3 compares the calculated coolant temperatures with the thermocouple data for the Row 2 PIOTA assembly. The agreement is very good. The difference between the analysis and the data at later times is probably due to not accounting for assembly-to-assembly radial heat transfer, which extracts heat from the assembly. Figure 4 compares the calculated coolant temperatures with the thermocouple data for the Row 6 PIOTA assembly. The lack of agreement at later times can definitely be attributed to radial heat loss to the relatively cold reflector assemblies in Row 7.

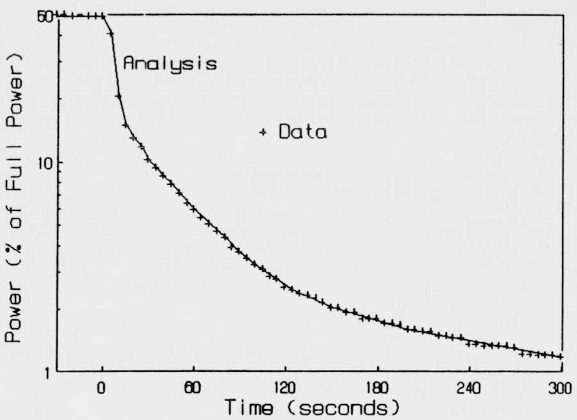

Fig. 3. Row 2 PIOTA T/C Response.

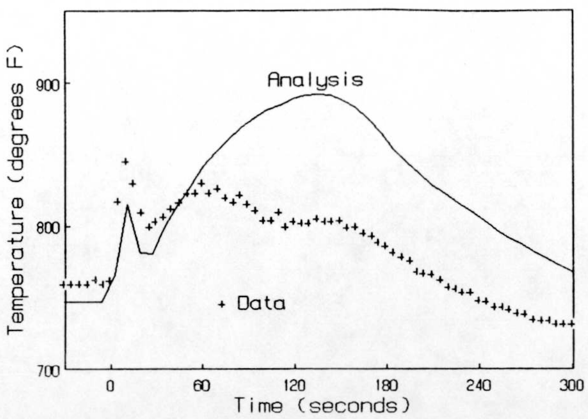

Fig. 4. Row 6 PIOTA T/C Response.

The overall agreement in the temperatures is good except at later times when the heat losses are not accounted for. Since the reactivity models respond primarily to core-averaged temperatures, this internal redistribution of heat will have only a small effect on the reactivity feedbacks. The agreement in the temperature histories suggests that the SASSYS code modelling forms a suitable basis for evaluation of the reactivity feedbacks.

COMPARISON OF REACTIVITY FEEDBACKS

FFTF Reactivity Feedback Equations

The FFTF reactivity equations used in the original analysis of this experiment[4] are shown in Table 1. Except for bowing, each component of a reactivity feedback is characterized by a coefficient and, when appropriate, a time constant. The bowing reactivity feedback is characterized by a table of reactivity as a function of power-to-flow ratio based on calculations using the NUBOW-3D three-dimensional structural analysis code. This table was tested against the FFTF Cycle 8A static feedback experiments and was shown to give good agreement for power-to-flow ratios less than 1.0, the range of this experiment.

Doppler and Sodium Density

Figure 5 compares the reactivity feedbacks due to Doppler and sodium density calculated by the SASSYS reactivity models and the FFTF reactivity equations. The SASSYS Doppler and sodium density feedbacks were obtained by

Table 1 FFTF Reactivity Feedback Equations

Feedback	Temperature	Coefficient (Δk/°F)	Time Constant (s)
Doppler	Fuel	-0.0053	
Axial Expansion	Fuel	-1.0 E-6	
Control Rod	Fuel	-2.6 E-7	
Expansion	Coolant Inlet	+1.2 E-6	
	Outlet Plenum	-4.6 E-6	22
	Outlet Plenum	+3.1 E-6	1000
Sodium Density	Coolant Inlet	-1.3 E-7	
	Coolant Average	-3.7 E-7	
	Coolant Outlet	-2.8 E-7	
Radial Expansion	Coolant Inlet	-1.2 E-5	120
Bowing	Coolant Core ΔT	Table	180

Power-to-Flow Ratio	Reactivity (¢)
0.0	3.95
0.25	-4.11
0.50	-10.39
0.75	-17.83
1.00	-29.38
1.25	-37.15
1.50	-39.20
1.75	-43.50
2.00	-49.75

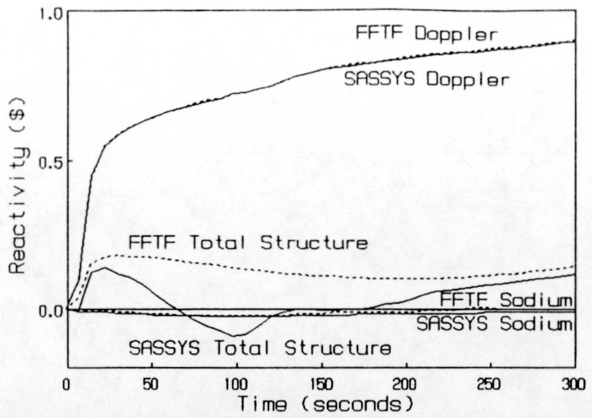

Fig. 5. Reactivities.

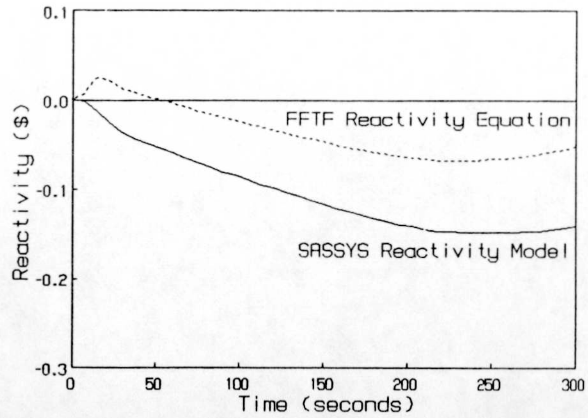

Fig. 6. Control Rod Expansion Feedback.

summing the contributions from each radial and axial node in the core, whereas the FFTF equations used the core-averaged fuel and sodium temperatures. The agreement is very good because the FFTF reactivity equations were developed from fuel and coolant temperature and reactivity worth distributions from the multichannel MELT-III code. Also shown in Figure 5 is the difference in the reactivity feedbacks due to the total structure (control rod expansion, fuel and cladding axial expansion, core radial expansion, and bowing). The main difference between the SASSYS reactivity models and the FFTF reactivity equations occurs in the structure reactivity feedbacks.

Control Rod Expansion

Figure 6 compares the reactivity feedback due to control rod expansion using the SASSYS model and the FFTF equation. As indicated in Table 1, the FFTF equation has four components: control rod driveline expansion, reactor vessel expansion, bottom support plate expansion, and axial fuel expansion. The SASSYS model treats only the first three components but the component corresponding to axial fuel expansion has been added to the reactivity feedback due to axial fuel expansion.

Axial Fuel Expansion

Figure 7 compares the reactivity feedback due to axial fuel expansion using the SASSYS model and the FFTF equation. The feedback using the SASSYS model is higher than that using the FFTF equation by about the same difference as in Figure 6 for the reactivity feedback due to control rod expansion. Therefore, the combination of control rod expansion and axial fuel expansion would give good agreement between the SASSYS models and the FFTF equations.

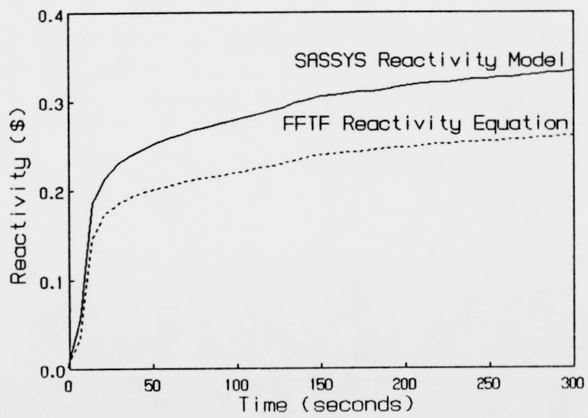

Fig. 7. Axial Fuel Expansion Feedback.

Radial Expansion and Bowing

Figure 8 compares the reactivity feedback due to radial expansion and bowing using the SASSYS model[5] and the FFTF equations. Comparison of Figure 8 with Figure 5 indicates that the differences in the total structure feedback is due almost entirely to the differences in the radial expansion and bowing.

The SASSYS model uses the as-fabricated dimensions of the assembly ducts and the core restraint system together with the appropriate temperatures to predict the bowing reactivity feedback for both steady-state and transient conditions. This model is able to give good agreement with the steady-state bowing reactivity for power-to-flow ratios less than 1.1, which is the range of this experiment. This

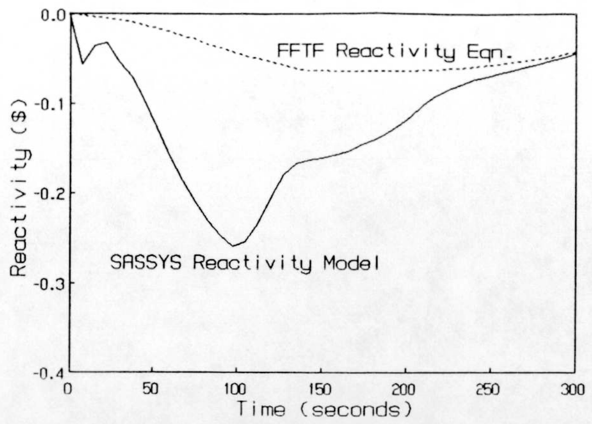

Fig. 8. Radial Expansion and Bowing Feedback.

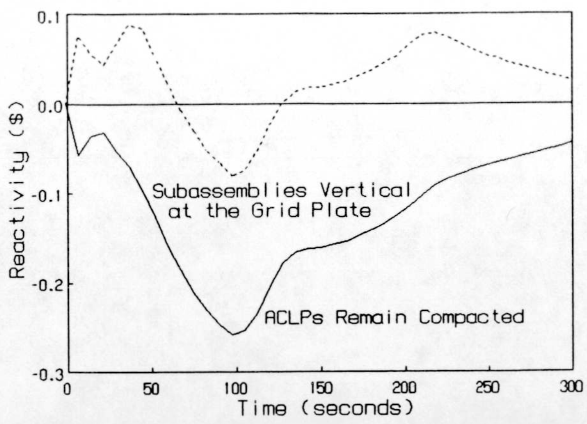

Fig. 9. Sensitivity of SASSYS Radial Expansion and Bowing Feedback.

agreement requires that the assumption be made that the above-core load pads for the core assemblies remain compacted at low power-to-flow ratios. The differences between the FFTF model and the SASSYS model lie in the transient behavior. The SASSYS model calculates the transient axial shape of the average fuel assembly in the outer row of the core based upon the geometry, while the FFTF model applies the bowing reactivity with a specified time constant. The SASSYS model reflects the temperature history in the core, as can be seen by comparing Figure 8 and Figure 3, while the reactivity from the FFTF model is heavily damped because of the 180-s time constant applied. At long times, the two models agree.

Figure 9 shows the expected radial expansion and bowing reactivity from the SASSYS model compared to an alternative calculation where the assemblies are vertical at the grid plate at low power-to-flow ratios. As noted above, this assumption is inconsistent with the steady-state bowing curve, but it is still appropriate to confirm this modelling decision by transient analysis. The feedback has a similar characteristic shape, but shifted up by 0.2$. More importantly, the initial reactivity is positive, caused by the initially vertical assemblies being pushed inwards, taking up the space available. This behavior is not characteristic of observation, and thus the assumption of core compaction appears further justified.

The insight afforded by the results from the SASSYS model suggests that reasonable results for the FFTF model could be obtained if a much smaller time constant were used. This was confirmed by decreasing the time constant for the FFTF model from 180 s to 1 s, as shown in Figure 10. However, this approach would not be successful for rapid transients where a quasi-steady-state approach is not justified.

Net Reactivity and GEM Reactivity

If the reactivity from the nine GEM assemblies were known accurately, the total reactivity feedbacks from the SASSYS reactivity models and the FFTF reactivity equations could be used to calculate the net reactivity. As the pressure in the inlet plenum decreases during the flow coastdown, the trapped gas in the upper part of the GEM assemblies expands. The decreasing liquid level in the GEMS determines the GEM reactivity feedback.

Figure 11 shows the experimental data for the net reactivity and the GEM reactivity calculated by the IANUS code assuming that the total GEM worth was either 1.46$ (pretest estimate) or 1.62$ (posttest estimate). Using the net reactivity data, the total reactivity feedbacks from the SASSYS reactivity models and the FFTF reactivity equations were used to calculate the GEM reactivity required to agree with the net reactivity data. These two curves are also shown in Figure 10. Continuing analysis of all of the Passive Safety Tests indicates that the most reasonable value of the total GEM worth for this test is about 1.5$. The GEM reactivity is injected over a very short time (30 s) and then would be expected to remain relatively constant. It would appear that the SASSYS models are more capable of producing this behavior than the FFTF equations, although the difference is not large.

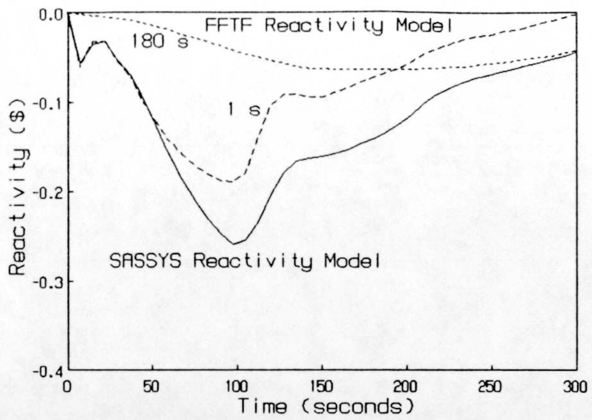

Fig. 10. Sensitivity of FFTF Equation Radial Expansion and Bowing Feedback.

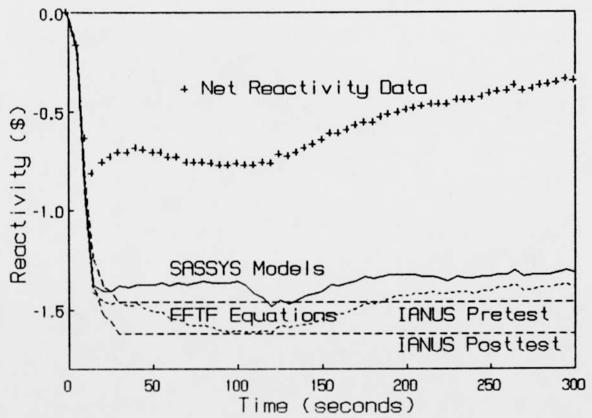

Fig. 11. Net and GEM Reactivity.

SUMMARY

For the analysis of this one FFTF Passive Safety Test, it was possible to get reasonable agreement with the experimental data using either the SASSYS reactivity models or the FFTF reactivity equations. Since the dominant reactivity feedback was the GEM reactivity, which could not be measured, the uncertainty in the GEM reactivity did not allow a detailed separation of reactivity feedbacks. However, the analysis of one other Passive Safety Test, the Flow Transient Test,[6] did indicate that the SASSYS reactivity models can give agreement with the experimental data for that test. There are indications that here also the SASSYS model is more satisfactory.

The structural reactivity feedback due to radial expansion and bowing is particularly important in the safety analysis of the proposed FFTF metal-fuel core because it is the dominant mechanism that can provide early negative reactivity feedback leading to neutronic shutdown. Results shown here support the use of the SASSYS model for this purpose. Additional FFTF loss-of-flow experiments without the GEMs, which can provide valuable data on the structure reactivity feedbacks, are recommended. It is hoped that these experiments will be performed when the FFTF is converted to a metal-fuel core.

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