Fast Flux Test Facility (FFTF) Feedback Reactivity Components

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ABSTRACT

The static tests conducted during Cycle 8A (1986) of the FFTF have allowed, for the first time, the experimental determination of each of the feedback reactivities caused by the following mechanisms: fuel axial expansion, control rod repositioning, core radial expansion, and subassembly bowing. A semiempirical equation was obtained to describe each of these feedback components that depended only on the relevant reactor temperature (bowing was presented in a tabular form). The Doppler and sodium density reactivities were calculated using existing mechanistic methods. Although they could also be fitted with closed-form equations depending only on temperatures, these equations are not needed in transient analyses using whole core safety computer codes, which use mechanistic methods. The static feedback reactivity model was extended to obtain a dynamic model via the concept of "time constants." Besides being used for transient analyses in the FFTF, these feedback equations constitute a database for the validation and/or calibration of mechanistic feedback reactivity models.

I. INTRODUCTION

The design of the next generation power reactors will emphasize passive safety and enhanced engineered safety systems. True passivity can be achieved only by capitalizing on natural laws to restore the reactor's stability during an off-normal event. The most effective stabilizing mechanisms relying solely on natural laws are the feedback reactivities produced by changes in the reactor thermal state. If these feedbacks can be shown to produce a net negative reactivity, then the reactor will return to stability without the aid of self-activated engineered systems. The requirements that the coolant and fuel temperatures remain below the boiling and melting limits, respectively, during off-normal events would set specific requirements on the magnitude of the net reactivity.

The prediction of the whole-core transient behavior requires not only a good thermal-hydraulics model but also a reliable calculation of feedback reactivities. An in-depth understanding of various feedback mechanisms, their magnitude, and rate of insertion are basic requirements of a successful design for safety. Ideally, each feedback mechanism would be sufficiently understood to allow the construction of analytic models from first principles so general that they can be applied to any innovative design. It is unlikely, however, that a reactivity model can be sufficiently general to cover all special features of individual reactor design and changing operating conditions. Nevertheless, any feedback reactivity model must be validated before being applied to an innovative design.

The validation of feedback models requires a database for each feedback component. However, normally only total reactivity can be directly measured, as in the FFTF static testing program. The construction of a reactivity database requires, as a first step, the separation of feedback components from integral data. The FFTF static testing program was design with this objective in mind. This paper describes the concepts underlying the FFTF inherent safety testing program and the analysis of the data to obtain the FFTF feedback reactivity components.

II. EXPERIMENTAL CONCEPTS

It is assumed that the feedback reactivity can be broken down into the following components:

- Doppler feedback
- axial fuel expansion feedback
- sodium density feedback
- control rod repositioning feedback
- core radial expansion feedback
- subassembly bowing feedback

The separate measurement of each and every feedback component is deemed a formidable task; at the least, such undertaking would require

time and resources beyond those currently available. Operational safety in the FFTF requires that the only allowed maneuver of the reactor is the change in the basic reactor variables (power P, flow W, and inlet temperature T_i) within the following specified limits:

Power P: 0% - 100%
Flow W: 67% - 100%
Inlet T_i: 299° - 360°C

Any change in these reactor variables necessarily creates more than one feedback component, such that the reactivity measured is the total reactivity. To rely solely on mathematical tools to separate feedback components from integral data obtained by a random variation of reactor states is a formidable task. It was believed that the separation of feedback components must begin with the experiment design itself. The tests must be designed so that each measurement includes a dominant group of feedbacks, while eliminating as much as feasible the remaining components. This concept is known as the group-by-group approach of reactivity separation.

The three reactivity groups most essential to the group-by-group concept are shown in Table 1. The dominant fuel feedback group (Group A, Type 1 tests) can be obtained by varying the fuel temperature while keeping the coolant (and thus the structural temperature) unchanged, thereby eliminating the structural feedbacks. This is achieved by maintaining the inlet temperature the same while varying P/W at the same ratio. The Group B feedbacks (Types 2 and 3) contain dominant structural feedbacks obtained by keeping the fuel temperature constant, thereby eliminating fuel feedbacks. Type 2 tests achieve this objective by keeping both the power level and core average coolant temperature unchanged while increasing the flow rate and inlet temperature. Type 3 tests attempt to hold both the average fuel and core outlet temperature constant by varying all reactor variables (power, flow, and inlet temperature). Consistent sets of reactor variables satisfying these objectives can be obtained by calculations (i.e., using the whole-core code MELT-IIIA[1]). The Group C feedbacks (Type 4 tests) contain all feedbacks except bowing and are obtained by keeping the power and flow constant, while varying the inlet temperature. The constant P/W ratio eliminates the bowing reactivity. Achieving the required reactor maneuvers defined in Table 1 will separate the reactivity groups. At the least, the measurements will separate the fuel reactivities from the structural reactivities; furthermore, the Group C feedbacks eliminates the bowing component. A series of experiments were conducted during FFTF Cycle 8A to measure feedback reactivities.[1] These experiments were designed to separate feedback groups according to the concept of feedback separation discussed above.

III. ASSUMPTIONS IN DATA ANALYSIS

The method used to separate feedback components depends on the understanding of the mechanisms producing these feedbacks. All feedback reactivities are tied to changes in reactor temperatures (fuel and coolant). Thus, the change in fuel temperature produces two feedback components (Doppler and fuel axial expansion feedbacks); and changes in coolant temperature produce the following four structure feedback components: sodium density change, control rod repositioning, core radial expansion, and subassembly duct bowing. This assumes that at steady state, the reactor

Table 1 Group-by-Group Method of Feedback Separation

Group	Type	Purpose	Components	Procedure	Procedure Objective
A	1	Emphasize Fuel Feedback	Doppler Axial	• Vary P/W at Same Ratio • Unchanged T_i	• Keep Coolant Temp (T_o,T_i,ΔT) Unchanged • Vary Fuel Temp T_F
B	2,3	Emphasize Structure Feedback	Sodium Radial CRDL Bowing	• Calculate Combination (P, W, T_i) to Keep Fuel Temp T_F Unchanged	• Keep Fuel Temp T_F Unchanged • Vary Coolant Temp (T_o,T_i,ΔT)
C	4	Eliminate Duct Bow	Doppler Axial Sodium CRDL Radial	• Vary T_i • Keep P, W Unchanged	• Keep ΔT Unchanged • Vary Fuel Temp T_F and Coolant Temp (T_i,T_o)

structure temperature is at equilibrium with the coolant temperature. Because feedbacks are functions of temperature, a measure of success in the separation of feedback reactivity components is the ability to derive, from measured data, equations relating each component to the relevant temperatures.

The main assumptions in the data analysis are described as follows.

The Doppler and sodium density feedbacks can be calculated with acceptable uncertainties. During the past decade, extensive efforts have been made to improve the calculation of Doppler effects to within 10% in uncertainty, and it is believed that the current test program would not be able to reduce this uncertainty. The sodium density feedback is small, and its uncertainty would have little impact on the analysis of data whose magnitude is much larger than the sodium component. Furthermore, mechanisms underlying Doppler and sodium density effects are reasonably well understood; and rigorous calculational methods exist to predict these two effects. These methods have become standard calculational procedures in advanced whole-core codes, such as the MELT IIIA code and the SASSYS code.[2] The calculation of Doppler feedback is achieved by using the Doppler constant Cd and the logarithmic dependence on the fuel temperature and then by summing the contribution from all reactor channels and axial nodes within the channel as follows:

$$\rho_D = \sum_{\text{Chan. I}} \sum_{\text{Ax. J}} C_{Dij} \ln (T_{Fij}/T^o_{Fij}) \quad (1)$$

where T_{Fij} is the mass-averaged fuel temperature at axial location j in reactor Channel i. The superscript "o" denotes initial conditions.

The sodium density reactivity is calculated by summing channel-wise changes in coolant reactivity worth:

$$\rho_{Na} = \sum_{\text{Chan. I}} \sum_{\text{Ax. J}} \alpha_{ij} W_{ij} \quad (2)$$

where α_{ij} is the fractional change in sodium density at segment j in channel i, and where W_{ij} is the sodium reactivity worth.

Feedback reactivities are functions of temperatures only. The objective of the analysis is to derive semiempirical equations for the reactivity components, with the functional dependence described by reactivity coefficients C's and by relevant temperatures, as follows:

A. Axial Fuel Expansion

A linear relationship is assumed as follows:

$$\rho_A = C_A (T_F - T^o_F) \quad (3)$$

where T_F is the fuel temperature.

B. Core Radial Expansion

This feedback is assumed to have two components: a uniform radial core expansion, determined by a change in inlet temperature, and a flowering effect caused by the difference between the changes in inlet and outlet temperatures:

$$\rho_R = C_{R1} (\Delta T_i) + C_{R2} (\Delta T_o - \Delta T_i) \quad (4$$

where

$$\Delta T_i = T_i - T^o_i = \text{change in coolant inlet temperature}$$

$$\Delta T_o = T_o - T^o_o = \text{change in coolant inlet temperature}$$

Due to the above-core yoke design, the flowering effect in FFTF is minimal and the second term in Equation (4) should have only a small contribution.

C. Control Rod Repositioning

The repositioning of the control rod is the net effect of the mechanisms of fuel expansion into the control rod environment (which depends on fuel temperature), combined lower pin, control material, and lower vessel expansion (which depends on inlet temperature), expansion of control rod driveline (which depends on plenum temperature), and downward expansion of the upper portion of the reactor vessel (which also depends on plenum temperature):

$$\rho_{CR} = C_{CR1} (T_F - T^o_F) + C_{CR2} (T_i - T^o_i) \quad (5)$$
$$+ C_{CR3} (T_p - T^o_p) + C_{CR4} (T_p - T^o_p)$$

The separation of the last two terms is made in anticipation of the extension of the static results to a dynamic model, when these components have different time constants, although both are assumed to depend on plenum temperature. The relative magnitudes between the constants C_{CR3} and C_{CR4} are guided by independent calculations to estimate the effects of the driveline and reactor vessel expansion.

D. Bowing

Bowing is assumed to depend only on the Power-to-Flow (P/F) ratio. This ratio can be shown to be proportional to the ratio

$\Delta T/\Delta T_{max}$, where $\Delta T = T_o - T_i$ and ΔT_{max} occurs at full reactor power:

$$\rho_B = f\ (\Delta T/\Delta T_{max}) \qquad (6)$$

IV. ANALYSIS PROCEDURES

The procedure for data analysis is guided by the experimental concepts (Section 2) and the assumption with regard to the Doppler and sodium density reactivities (Section 3). The following steps are carried out in the analysis.

A. MELT-IIIA Calculations

This code was first used to determine the reactor temperature distribution (fuel and coolant) for each reactor state. This detailed temperature field was then used to calculate the Doppler and sodium density reactivities according to well-established procedures (Equations 1 and 2).

B. Type 1 Test Data

The data of Type 1 tests (fuel feedbacks) were first analyzed, beginning with the verification that in these tests, the change in coolant temperature (inlet and outlet) was negligible, so that these data contained dominant fuel feedbacks. Since the Doppler reactivity has been eliminated by mechanistic calculations, the feedback due to axial fuel expansion can be extracted. The accuracy of the axial fuel expansion reactivity obtained by this procedure depends on the accuracy of the calculated Doppler effect. For oxide fuel, the Doppler reactivity is large and this procedure could lead to a large percentage uncertainty in fuel expansion reactivity. Nevertheless, because the fuel expansion reactivity is small and Doppler reactivity is large in oxide fuel, the effect of a large percentage uncertainty in fuel expansion reactivity is not any more severe than that of a smaller uncertainty in Doppler reactivity. For metal fuel, the Doppler reactivity is smaller, and a similar procedure would yield a smaller uncertainty in the fuel expansion reactivity.

A semiempirical equation [in the form of Equation (3)] to describe the fuel axial expansion effect can be obtained from data using this procedure. An important requirement is that the results calculated by this equation, when added to the calculated Doppler reactivity must recover the experimental data of Group A (Type 1 tests), which represent the total fuel feedback. Note that Equations (1) and (3) represent generic models, while the Group A data are measured at specific reactor states.

C. Type 4 Test Data

Having obtained the fuel feedback components, Type 4 data, with bowing reactivity absent, were next analyzed. First, the change in the P/W ratio were verified to be negligible, implying negligible bowing reactivity. The total fuel feedback (Doppler + axial fuel expansion) could be calculated quite accurately from equations derived in the previous step (models verified by experimental data of Type 1 tests). The small sodium density reactivity can also be calculated mechanistically [Equation (2)]. Then, the sum of core radial expansion and control rod repositioning reactivities can be unfolded from Type 4 test data.

Since the sum of these reactivities was dominant by experiment design, the uncertainty involved in this procedure is reasonably small. However, there was insufficient information to separate these two components from data alone. Thus, the relevant temperatures were calculated or determined from direct measurements from the Type 4 reactor states, and Equations (4) and (5) were used to determine the reactivity coefficients from data using a regression type of analysis.

D. Types 2 and 3 Test Data

Types 2 and 3 test data were analyzed next. First, from the reactor variables (P,W,T_i) of the test states, the MELT-IIIA code was used to verify that the change in fuel temperature between these states was negligible, implying negligible fuel feedback contributions. Thus, these data contained dominant structural feedbacks. However, because the fuel temperatures were not exactly constant between reactor states, the small fuel feedback contribution was eliminated by code calculations of Doppler effect, and by using the fuel axial expansion reactivity [Equation (3)] obtained from Step B. The sodium density component also was obtained by calculations. When the radial expansion and control rod repositioning reactivities were eliminated using Equations (4) and (5), the bowing reactivity could be backed out.

E. Reactivity Components

The above analysis steps (A through D) separate the following reactivity components: axial fuel expansion, core radial expansion, control rod repositioning, and bowing. To obtain a self-contained set of reactivity equations, the Doppler and sodium density reactivities obtained from code calculations were also fitted by closed-form expressions with the Doppler reactivity depending on the

logarithm of fuel temperatures and the sodium reactivity depending on the coolant inlet, outlet, and average temperatures. However, transient analyses normally use mechanistic models for Doppler and sodium density reactivities [Equations (1) and (2)], not these semiempirical relationships. The equations of the feedback components are presented in the next section.

V. RESULTS

The total reactivity, measured in dk as the sum of individual components, can be written in terms of various temperature changes, as follows:

$$\rho = \sum_i \rho_i \qquad (7)$$

$$= -0.00535 \ln (T_F/T_F^o) \qquad \text{Doppler}$$

$$- 1.3\text{ E-}7\ \Delta T_i - 3.7\text{ E-}7\ \Delta T_c - 2.8\text{ E-}7\ \Delta T_o \qquad \text{Sodium Density}$$

$$- 9.5\text{ E-}6\ \Delta T_i - 1.0\text{ E-}6\ (\Delta T_o - \Delta T_i) \qquad \text{Core Radial Expansion}$$

$$- 3.3\text{ E-}7\ \Delta T_F + 1.1\text{ E-}6\ \Delta T_i - 6.5\text{ E-}6\ \Delta T_p + 4.4\text{ E-}6\ \Delta T_p \qquad \text{Control Rod Repositioning}$$

$$- 1.0\text{ E-}6\ \Delta T_F \qquad \text{Fuel Axial Expansion}$$

$$+ \rho_B \quad \text{(see Table 2)} \qquad \text{Bowing}$$

where all temperatures are in K and where $T_c = 0.5\ (T_i + T_o)$.

Table 2 Bowing Reactivities for Cycle 8A

P/W	Reactivity (¢)*
0	19.0
0.1	17.2
0.2	16.5
0.3	16.65
0.4	17.0
0.5	16.8
0.6	16.1
0.7	15.1
0.8	13.6
0.9	11.4
1.0	8.5

*Arbitrary reference of 10¢ at P/W = 0.94

Equation (7) was compared with the measured total reactivities of various test types (1, 2, 3, and 4). Since Equation (7) is general, its application to these special-purpose tests constitutes a severe test of validity. Type 1 tests emphasized fuel feedbacks. When applied to these tests, Equation (7) should be able to produce dominant fuel feedbacks. For Types 2 and 3 tests, it should be able to minimize fuel feedbacks and emphasize structural effects. Likewise, under Type 4 test conditions, it should yield negligible bowing reactivity.

Reactivity Equation (7) depends on temperature. Because the test states are defined in terms of the reactor variables (P, W, T_i), a whole-core code is needed to map the space (P, W, T_i) into the space $\underline{T}$. The MELT-IIIA code was used for this purpose. For each reactor state defined by the set of variables (P, W, T_i), the MELT-IIIA code calculated the fuel, core coolant, and plenum temperatures, which were then used in Equation (7) to obtain the total reactivity.

Table 3 shows the comparison between Equation (7) and Type 1 (dominant fuel feedbacks) test results. The deviation, defined as

$$\Delta = (\text{Equation} - \text{Data})/\text{Data} \qquad (8)$$

ranged between 2% and 14.4%, with most data points within 10%.

Table 4 shows the comparison of Types 2 and 3 (dominant structural feedbacks) test results. A relatively large percentage deviation is associated with small reactivities, usually on the order of a few cents. For reactivities on the order of 10 cents, the deviations are within 10%.

The comparison for Type 4 (negligible bowing) test data are shown in Table 5. The deviations range between 0.084% and 12.1%, with most data falling within 5%.

Table 3 Comparison of New Reactivity Model with Type 1 Data

Reactivities (¢)		Deviation
Calculated	Measured	(%)
19.8	17.7	12.2
37.0	35.3	4.74
-18.4	-19.5	-5.21
-39.4	-34.5	14.4
18.5	16.3	13.5
35.7	32.4	10.2
-17.9	-16.4	9.63
-34.9	-31.5	11.0
14.9	13.6	9.41
27.6	25.7	7.37
-15.7	-14.3	9.32
-28.4	-26.7	6.61
11.3	10.2	10.6
20.8	20.1	3.31
-9.97	-9.56	4.33
-20.00	-19.6	2.0

Table 4 Comparison of New Reactivity Model with Types 2 and 3 Data

Reactivities (¢)		Deviation
Calculated	Measured	(%)
-1.51	-2.92	-46.50
-3.34	-4.07	-17.90
-3.28	-3.30	-0.711
-2.49	-3.28	-24.00
-2.71	-3.33	-18.50
-0.829	-0.860	-3.66
-1.49	-2.28	-34.80
-1.67	-2.02	-17.30
4.83	5.49	-12.10
10.30	11.6	-11.70
15.1	16.7	-9.66
4.28	4.86	-11.90
9.66	10.4	-7.52
15.5	16.8	-7.71
3.02	3.16	-4.48
6.60	7.27	-9.22
11.10	12.30	-9.71
1.67	1.61	3.76
3.42	3.95	-13.30
6.19	7.10	-12.80

VI. A SEMIEMPIRICAL DYNAMIC REACTIVITY MODEL

Equation (7) describes static reactivity, applicable for steady state conditions. A transient analysis requires the separation between the prompt and delayed effects of reactivity feedbacks. Equation (7) can be considered as the limiting case of a dynamic

Table 5 Comparison of New Reactivity Model with Type 4 Data

Reactivities (¢)		Deviation
Calculated	Measured	(%)
9.94	10.7	-6.97
25.0	25.5	-1.94
13.2	13.1	1.41
12.2	11.8	3.37
-24.3	-23.4	3.63
25.7	24.6	4.17
-24.5	-24.3	0.79
-9.96	-9.92	0.454
16.1	15.8	1.98
16.69	16.70	-0.21
15.8	15.4	3.11
-16.4	-14.7	11.10
16.3	15.5	5.25
-16.3	-15.0	8.99
-15.2	-14.5	5.10
9.11	9.37	-2.75
9.14	9.50	-3.83
9.64	9.43	2.22
-10.5	-9.87	6.07
10.2	9.98	2.18
-24.5	-22.6	8.23
-9.83	-8.77	12.10
-9.01	-8.72	3.35
11.30	11.0	2.73
5.81	6.28	-7.46
-5.84	-5.21	12.0
-29.2	-29.2	0.08
-6.47	-5.32	21.7
-11.10	-11.20	-0.873

reactivity model, as the reactor in transient reaches the asymptotic state:

$$\Delta\rho(T) = \lim_{t \to \infty} \Delta\rho(T,t) \qquad (9)$$

Thus a semiempirical dynamic reactivity model can be constructed, based on Equation (7), by accounting for the rate of insertion of various reactivity components. A mechanistic model of reactivity feedbacks would automatically account for insertion rates by describing the details of the heating process governed by fluid flow and heat transport. The most convenient way to extend a semiempirical static model to a dynamic model is to introduce transfer functions for various feedback components. These transfer functions are characterized by appropriate "time constants" for delayed mechanisms and operate on the relevant temperatures. In this way the following semiempirical dynamic feedback model can be obtained:

$$\Delta\rho(T,t) = \qquad (10)$$

$$- 0.00535 \ln\left(\frac{T_F(t)}{T_F^o}\right) \qquad \text{Doppler}$$

$$- 1.3\ \text{E-7}\ \theta_i(t) - 3.7\ \text{E-7}\ \theta_c(t) - 2.8\ \text{E-7}\ \theta_o(t) \qquad \text{Sodium Density}$$

$$- \frac{9.5\ \text{E-6}}{T_R^i} \int_o^t [\theta_i(t')] e^{-(t-t')/T_R^i}\, dt' \qquad \text{Core Radial Expansion}$$

$$- \frac{1.0\ \text{E-6}}{T_R^o} \int_o^t [\theta_o(t') - \theta_i(t')] e^{-(t-t')/T_R^o}\, dt'$$

$$- 3.3\ \text{E-7}\ \theta_F(t) + 1.1\ \text{E-6}\ \theta_i(t) \qquad \text{Control Rod Repositioning}$$

$$- \frac{6.5\ \text{E-6}}{T_{CR}^1} \int_o^t [\theta_p(t')] e^{-(t-t')/T_{CR}^1}\, dt' + \frac{4.4\ \text{E-6}}{T_{CR}^2} \int_o^t [\theta_p(t')] e^{-(t-t')/T_{CR}^2}\, dt'$$

$$- 1.0\ \text{E-6}\ \theta_F(t) \qquad \text{Fuel Axial Expansion}$$

$$+ \Delta\rho_B[x(t)] \quad \text{(see Table 2)} \qquad \text{Bowing}$$

Since the reactivity in Equation (10) is expressed in dk, the bowing feedback in Table 2 has to be converted to the correct unit. Furthermore, the following variable is used in conjunction with Table 2:

$$x = \frac{\Delta T(t)}{\Delta T_{max}} \propto \frac{P}{W} \qquad (11)$$

where

$$\Delta T(t) = T_o^o + \frac{1}{T_B} \int_o^t \theta_o(t') e^{-(t-t')/T_B}\, dt' - T_i$$

ΔT_{max} = temperature rise across core at full power conditions

In Equation (10) θ describes the temperature change; and the subscripts i, o, c, p, and F denote inlet, outlet, average core, plenum, and fuel, respectively.

It is clear that this dynamic model assumes prompt fuel (Doppler and axial expansion) and sodium density effects. The combined expansion of the lower fuel pin, control material, and lower vessel is also assumed to be prompt. The remaining mechanisms have delayed effects, with appropriate time constants, defined as follows:

T_R^i = time constant for grid plate support expansion

T_R^o = time constant for core flowering effect

T_{CR}^1 = time constant for control rod driveline expansion

T_{CR}^2 = time constant for reactor vessel expansion

T_B = time constant for duct bowing effect

It should be noted that the rate of reactivity insertion depends on the response of various reactor components to the thermal-fluid dynamics in the reactor, and the time constants are at best simplified concepts to describe a complex situation.

The current estimates of the time constants are shown in Table 6:

Table 6 Estimated Time Constants

Time Constant	Current Estimate (s)
T_R^i	50 - 180
T_R^o	1.6
T_{CR}^1	22
T_{CR}^2	100
T_B	60 - 180

These estimates will continue to be updated as new information becomes available.

VII. SUMMARY

The Cycle 8A static tests results have led to a significant improvement in the understanding of LMR feedback reactivities. Although the question of uncertainty of each feedback component has not been completely resolved, the test results have increased the confidence in the calculation of the fuel feedback group and of the structure feedback group, in as much as Equation (7) has been verified by group data. This fact alone supports the claim that understanding of the feedback components themselves has improved.

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