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Re-Evaluation of SEFOR Doppler Experiments and Analyses with JNC and ERANOS systems

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The SEFOR (South-West Experimental Fast Oxide Reactor) static Doppler reactivity experiments have been re-evaluated. The re-evaluation was carried out on the experiments performed at power levels up to 20MW, starting from a review of raw data of the Doppler reactivity and fuel temperature. Investigations were carried out on various parameters, such as fuel thermal conductivity and gap conductance, or weighting function on the temperature distribution in the core. Experimental uncertainties on some parameters were also re-evaluated.

The re-evaluated experimental values of the Doppler constant are 3 or 5% larger than original values. The increase is mainly attributed to the update of fuel thermal conductivity correlation. The new values look more reasonable than the values recommended by Butland in that C/E values do not depend on the core type tested in the experiment.

KEYWORDS: SEFOR, Doppler reactivity, Doppler constant, static test, fuel thermal conductivity, gap conductance, fuel temperature

1. Introduction

Various experiments have been carried out to validate calculations of the Doppler reactivity, one of the key effects providing negative feedback. The SEFOR (South-West Experimental Fast Oxide Reactor) Doppler experiments [1] have unique and valuable features of measuring whole core Doppler reactivities induced in various situations, such as steady-state at power levels up to 20 MW and prompt critical transients.

SEFOR is a fast reactor fueled with mixed PuO_2-UO_2 and cooled with sodium. The experimental program was conducted by the American General Electric Company (GE) and the West German Karlsruhe Laboratory (KFK) from 1969 to 1972. The experiments have been analyzed by three different groups: GE, KFK, and Hanford Laboratory (HEDL). However, there are discrepancies of about 10% among the experimental values of the Doppler constant ($Td\rho/dT$) (see Table 1), and moreover, the experimental standard deviation was assessed to be as large as 12%. Butland [2] has investigated the differences and recommended the HEDL results, but the HEDL analysis addressed only the super-prompt experiment.

In this paper, the steady-state experiments (static tests) have been re-evaluated. In the re-evaluation, the most recent data of thermal conductivity correlation were employed. The reliability of the obtained values of the Doppler constant was investigated through comparisons with the reported values and calculations based on the current analysis systems used in Japan Nuclear Cycle Development Institute (JNC) and the French Atomic Energy Commission (CEA).

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Table 1 Reported experimental values of Doppler constant [1]

Core type	Exp. type	Tdρ/dT ($)			max./min.
		GE	HEDL	KFK*	
Core I	Static	-2.55	—	-2.42	1.13
	Transient	-2.61	-2.74	-2.55	
Core II	Static	-1.94	—	-1.90	1.08
	Transient	-1.94	-1.95	-1.81	

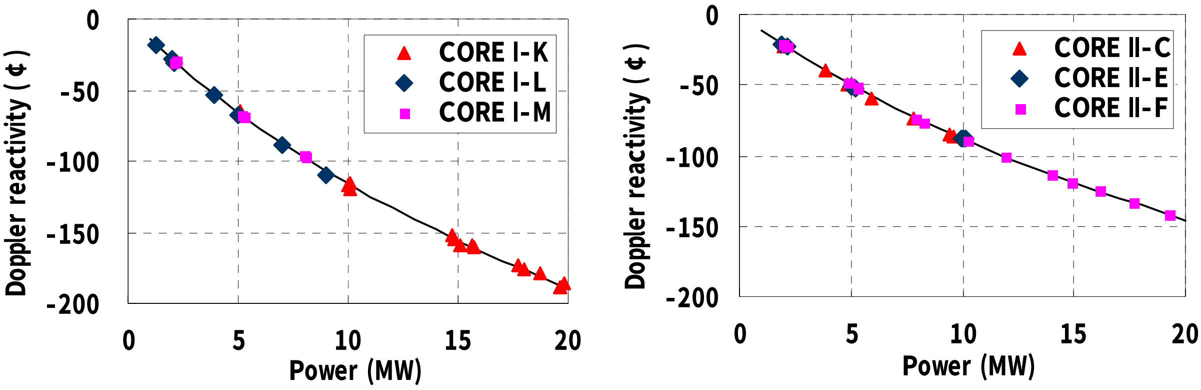
*GE ßeff value is used in this case.

2. Description of the Static Tests

The static tests were performed at power levels up to 20MW while maintaining the average core coolant temperature constant at 678K. The reactivity effects due to power changes were measured by the reflector positions, adjusted to compensate the reactivity feedback. The Doppler reactivities were then evaluated by subtracting the contribution of the fuel axial expansion. Since SEFOR was particularly designed, using segmented fuel rods and dished fuel pellets, the reactivity change due to the axial expansion is as small as 5% of the total feed back and its uncertainty little affects the Doppler reactivity evaluation.

The Doppler reactivities were measured in two core types. The first core (Core I) contains a BeO rod at the center of each fuel subassembly and the second core (Core II) contains a stainless steel rod instead, thus resulting in harder neutron spectrum in Core II. The measurements were repeated in slightly different core loadings for each core during the three-year period.

In this re-evaluation, data of the integral Doppler reactivity were taken from those after the high power operation above 17MW considering the stability of data as described in reference 1. The selected data are plotted in Fig.1 for the two cores, together with fitted lines. Table 2 summarizes data grouped into five power levels using the fitted lines. These values will be used for comparison with calculations in this paper.



Core I

Core II

Fig.1 Doppler reactivity data measured in the static tests

Table 2 Doppler reactivity data at five power levels

Power	Doppler reactivity (¢)	
(MW)	Core I	Core II
2	-28.58 ± 1.10	-21.72 ± 0.65
5	-66.12 ± 1.50	-50.04 ± 0.84
10	-116.61 ± 1.75	-88.63 ± 0.97
15	-155.69 ± 1.71	-119.44 ± 0.38
20	-190.08 ± 1.56	-145.51 ± 0.29

3. Description of Analysis

The whole core Doppler reactivity was calculated using the isothermal Doppler coefficient ($d\rho_{iso}/dT$), and the average fuel temperature properly weighted to take account of the fuel temperature distribution in the core.

3.1 Calculation of the Isothermal Doppler Coefficients

The isothermal Doppler coefficient was calculated with JNC analysis system and fitted to the well-known formula as a function of fuel temperature T as in Eq.(1).

$$\frac{d\rho_{iso}}{dT} = \frac{\alpha_D}{T^x}. \tag{1}$$

The reactivity ρ was obtained by RZ diffusion calculations with 70 group constant set JFS-3-J3.2R [3]. The mesh effect, the transport effect, the heterogeneity effects both in the subassembly and the core, and the ultra fine group effect [4] were introduced as correction factors. The effective delayed neutron fraction was calculated with Tuttle's yield data [5] and obtained as 0.00327 for core I and 0.00330 for core II.

Then the parameters α_D and x in Eq.(1) were obtained from the reactivity changes due to fuel temperature rise up to 1278K from the coolant temperature 678K (Fig.2). This temperature range corresponds to the core averaged fuel temperature range of the experiment estimated in the present analysis. Temperature in depleted UO_2 insulators which were inserted at each end of the fuel segments was changed as well. Resulting parameters are α_D=-3.26($) and x=1.022 for Core I, and α_D=-3.97($) and x=1.087 for Core II.

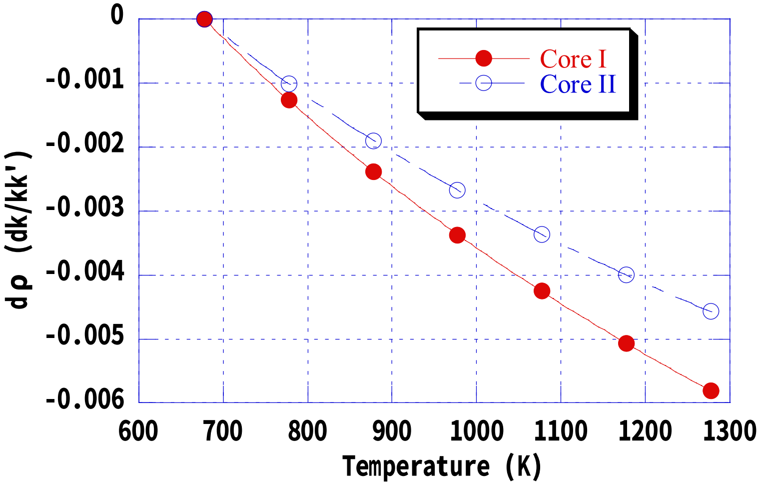


Fig.2 Evaluation of parameters in the isothermal Doppler coefficient

For comparison, the values of the Doppler constant evaluated by GE for the static test shown in Table 1, will be also applied to calculate the whole core Doppler reactivity, which values correspond to α_D since the values are evaluated under the assumption of x=1.

3.2 Temperature evaluation

The temperature evaluation from the local power density (LPD) heavily depends on the fuel thermal conductivity (k_f) and fuel-clad gap conductance (h_{gap}).

In the present analysis, three k_f correlations (Baily & Schmidt data used in the GE analysis, Hilbert data [6], and Inoue data [7]) were employed. Figure 3 compares them for the SEFOR standard fuel (92.6% theoretical density, oxygen-to-metal ratio 1.99). Inoue k_f has the lowest values and Hilbert k_f is between Inoue and Baily & Schmidt k_f, in the rod average temperature range of the experiment which was estimated in the present analysis.

The analytical evaluation of h_{gap} is difficult in SEFOR because of possible fuel restructuring or central void formation after a high power operation. Hence, h_{gap} was adjusted to provide agreement between calculated and measured fuel centerline temperatures as a function of LPD; this is the procedure employed in the GE analysis.

The fuel centerline temperatures were measured in the experiments by instrumented fuel assemblies (IFA) loaded at eight positions, and at different power levels for each core. Each IFA has four thermocouples (T/C's) and temperature data were taken at about 20 T/C positions (several T/C's were not used).

The LPD at each T/C location was calculated by the JNC analysis system using Tri-Z diffusion calculation. A Tri-Z model was employed to reflect local positions of T/C's correctly. Differences of fuel density and Pu concentration between IFA and the SEFOR standard fuel were taken into account to evaluate the LPD, as well as a geometrical effect of the presence of T/C on the temperature evaluation in a rod [8]. T/C's whose temperature data show a strange behavior with respect to the local power density, were excluded. The resulting number of T/C's was reduced to less than half. Moreover, temperature data at LPD above 80W/cm^3 were also excluded considering the statistical reliability of the data. Thus selected 195 temperature data are plotted in Fig.4 as temperature rise above the coolant temperature, together with a fitted line to be used in the h_{gap} adjustment.

Figure 5 compares the adjusted h_{gap} for each k_f. The h_{gap} used in the GE analysis [1], which is based on Baily & Schmidt's k_f, is also plotted. A good agreement observed between the GE analysis and the present analysis with Baily & Schmidt's k_f, indicates the present temperature evaluation is comparable to the one performed in the GE analysis.

Thus obtained three combinations of k_f and h_{gap} were used to evaluate fuel temperatures. A difference would appear in the evaluated temperatures, since the fuel specifications are different as mentioned above and the LPD at higher power levels can exceed the upper limit of the fitting range.

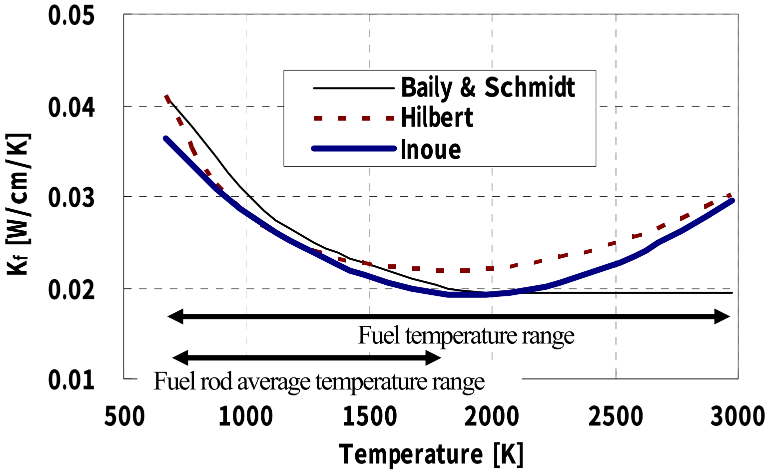


Fig.3 Comparison of fuel thermal conductivity correlations

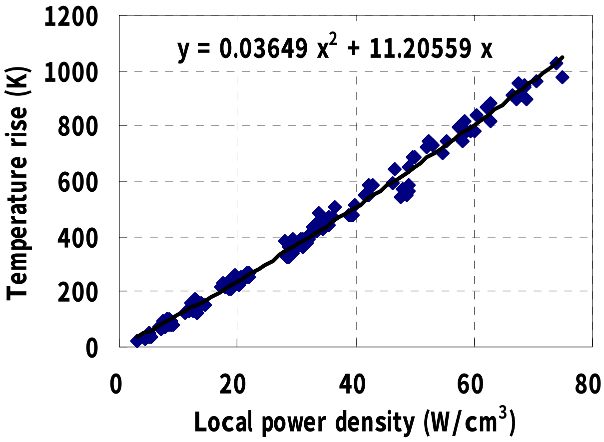


Fig.4 Selected fuel centerline temperature data

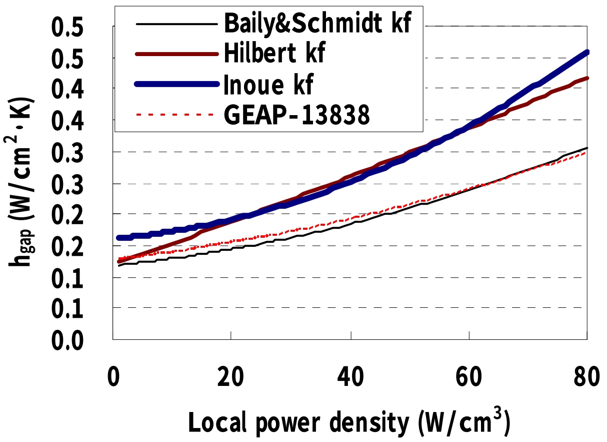


Fig.5 Comparison of adjusted gap conductance

3.3 Calculation of Whole Core Doppler Reactivity

The whole core Doppler reactivity was evaluated by the first order perturbation theory from the isothermal Doppler coefficient, considering the spatial dependence of fuel rod average temperatures. The Doppler reactivity due to the change in reactor power can be expressed as Eq.(2). The product of flux, adjoint flux, and change in cross sections is used for the weight (so called exact weight) on the fuel rod average temperatures. All the neutronic parameters were calculated by the JNC analysis system and the changes in cross sections were evaluated from the cross sections at temperatures 678K and 1278K. This choice of the temperatures little affects the Doppler reactivity because the cross-section change is considered to behave like ρ in Eq.(1) and temperature-related terms are cancelled out in the numerator and denominator of Eq.(2). The fuel rod average temperatures were evaluated from LPD for numerous axial and radial nodes throughout the core.

In addition to the above exact weight, the square of power weight (P^2 weight) used in the GE analysis (Eq.(3)) was also introduced for comparison.

$$\rho_D(Power) = C_D \cdot \frac{\int \left\{ \Delta T(r) \left(\left[\sum_g \Delta\Sigma_{a,g}(r) \cdot \phi_g(r) \cdot \phi_g^*(r) \right] - \frac{1}{k_{eff}} \left[\sum_g \chi_g(r) \cdot \phi_g^*(r) \right] \left[\sum_{g'} \Delta\nu\Sigma_{f,g'}(r) \cdot \phi_{g'}(r) \right] \right) \right\} dr}{\int \left\{ \left[\sum_g \Delta\Sigma_{a,g}(r) \cdot \phi_g(r) \cdot \phi_g^*(r) \right] - \frac{1}{k_{eff}} \left[\sum_g \chi_g(r) \cdot \phi_g^*(r) \right] \left[\sum_{g'} \Delta\nu\Sigma_{f,g'}(r) \cdot \phi_{g'}(r) \right] \right\} dr} \tag{2}$$

$$\rho_D(Power) = C_D \cdot \frac{\int \left\{ \Delta T(r) P^2(r) \right\} dr}{\int P^2(r) dr} \tag{3}$$

where,

$\Delta T(r)$: change of fuel rod averaged temperature from zero power (T_0(r)=678K) (4)

$$= \overline{T(r)^{1-x}} - \overline{T_0(r)^{1-x}} \quad (\mathit{for}\ x \neq 1), \quad = \overline{\ln T(r)} - \overline{\ln T_0(r)} \quad (\mathit{for}\ x = 1)$$

$$C_D = \frac{\alpha_D}{1-x} \quad (\mathit{for}\ x \neq 1), \quad = \alpha_D \quad (\mathit{for}\ x = 1)$$

$\Delta\Sigma_{a,g}(r), \Delta\nu\Sigma_{f,g}(r)$: change in cross section due to temperature change (absorption, ν-fission)

$\phi_g(r), \phi_g^*(r), \chi_g(r), P(r)$: flux, adjoint flux, fission spectrum, and local power

the variables ‘r’ and the subscript ‘g’ denote mesh position and energy group, respectively.

4. Results

4.1 C/E for Doppler Reactivity

Table 3 shows C/E values for the Doppler reactivities. The isothermal Doppler coefficient by JNC calculation described in Section 3.1 was used together with Inoue k_f and the exact weight. Almost the same tendency is observed in Core I and Core II; quite a good agreement at higher powers and an overestimation at lower powers.

The corresponding uncertainties are tabulated in Table 4, showing that the drift of C/E values at the lower powers remains within the uncertainties.

The contribution of h_{gap} to the uncertainty was evaluated by the product of the average deviation of temperature data from the fitted line in Fig.4, and the ratio of the temperature rise in the fuel-clad gap to the total temperature rise for a core averaged value of LPD. This evaluation assumes that the average deviation for the total temperature rise would be applied for the temperature rise in the fuel-clad gap. The average deviation was obtained from the data below the maximum value of LPD evaluated for each power. However, at powers higher than 10MW, the average deviation for 10MW was applied instead since the maximum LPD at 10MW reaches 80W/ cm^3 that is the upper limit of LPD in the temperature data used in the h_{gap} adjustment. At 2MW, the average deviation is 20% and the ratio is 40%, thus leading to the uncertainty due to h_{gap} of 8%. At 20MW, they are both 13%, leading to the uncertainty of 2%. In addition to this evaluation, a difference in h_{gap} between the present and the GE analysis shown in Fig.5 was taken into account.

The contribution of k_f to the uncertainty was evaluated as the maximum difference observed by changing k_f from Inoue's to Hilbert's, or changing the fuel density from the standard value to 97% theoretical density (value considering possible densification of the fuel after a high power operation).

When compared with GE evaluation [9], the uncertainty at 20MW is reduced by half. A major contributor is a reduction in the uncertainty due to k_f, from 8% to 2%.

Table 3 C/E for Doppler reactivity with Inoue k_f and exact weight

Core type	Power (MW)				
	2	5	10	15	20
Core I	1.10	1.07	1.03	1.02	1.01
Core II	1.13	1.09	1.04	1.02	1.01

Table 4 Experimental uncertainty of Doppler reactivity

Source of uncertainty	Power (MW)				
	2	5	10	15	20
h_{gap}	8%	4%	3%	3%	3%
k_f	2%	4%	3%	2%	2%
Reactivity			3%		
Power			4%		
Sum	9%	8%	7%	6%	6%

4.2 Comparison with original result

Table 5 compares C/E values for the Doppler reactivitiy at 20MW with the various parameter combinations mentioned in Section 3, that is, two cases for the Doppler coefficients; based on the GE values and JNC values, two cases for the weight on temperature distribution; P^2 weight and the exact weight, and three cases for the fuel thermal conductivity correlations.

A temperature change in the insulators was ignored to calculate the isothermal Doppler coefficient and the denominator of Eq.(2) or (3), following the GE analysis.

When the same parameters as in the GE analysis are used (P^2 weight and Baily & Schmidt k_f), quite a good result is obtained for both cores, which indicates the present evaluation is comparable to the GE analysis. Note that the power distribution and h_{gap} were based on the present re-evaluation. The use of the exact weight little changes the C/E values, which result is also consistent with the GE analysis. The Effect of the k_f changes from Baily & Schmidt's to Hilbert's or Inoue's are 2-4%. The Doppler coefficients based on the JNC analysis give reasonable results with the updated k_f.

Table 5 Comparison of C/E for Doppler reactivity with various parameter combinations

Core type		Core I			Core II		
Parameter	k_f	Baily & Schmidt	Hilbert	Inoue	Baily & Schmidt	Hilbert	Inoue
dρ/dT (GE)	P^2 weight	1.02	0.99	0.98	1.01	0.98	0.97
	Exact weight	1.01	0.98	0.98	0.99	0.96	0.95
dρ/dT (JNC)	P^2 weight	1.06	1.03	1.02	1.06	1.04	1.03
	Exact weight	1.05	1.02	1.01	1.04	1.02	1.01

4.3 C/E for Doppler constant

It is common in whole core Doppler reactivity analyses to assume the Doppler reactivity coefficient obeys the 1/T law, and the isothermal Doppler constant ($Td\rho_{iso}/dT$) is presented in a benchmark problem. Then the original values of the Doppler constant evaluated by GE were adjusted by E/C biasing, using the C/E values in Table 5 evaluated with the GE reactivity coefficients, the exact weight, and Inoue k_f. This biasing results in 2 or 5% increase in the original values. It should be noted that the C/E values used in the biasing strongly depend on the JNC calculation because major parameters in Eq.(2) are based on the JNC analysis system. The Doppler constants thus adjusted should be close to the Doppler constants calculated by the JNC system. This procedure is justified since the C/E values evaluated by the JNC analysis are 1.0 without the assumption.

The resulting Doppler constants divided by βeff (Tdρ/dT/βeff) for Core I and II are -2.61$ and -2.03$, respectively. When compared with the recommended HEDL result, the value is 5% smaller for Core I and 4 % larger for Core II.

5. Comparison with Calculations by JNC and CEA

The reliability of the re-evaluated Doppler constants was investigated through a comparison with the HEDL values recommended by Butland, and calculations based on the current analysis systems used in JNC and CEA.

CEA calculations were performed with the ERANOS code system [10]. The main features of the calculation scheme are as follows. JEF-2.2 nuclear data libraries are used, with fine (1968 energy groups) and broad structure (33 groups). The cell calculations are performed with the ECCO module, using a 2D heterogeneous model of the fuel subassemblies and a fine energy mesh (1968 groups); nuclear data are condensed in 33 groups for the core calculations, performed then in S8 transport with the BISTRO finite difference Sn transport module (P1 scattering anisotropy) in a RZ core geometry. Calculations are performed for various fuel temperatures tabulated in the libraries (293 K, 573 K, 973 K, 1473 K, 2973 K). The βeff values computed with ERANOS are 0.00338 for core I and 0.00339 for core II.

In both analyses, the reactivity due to temperature change from 677K to 1365K was used to obtain the Doppler constants, referring the benchmark problem [11].

Table 6 compares C/E values for the Doppler constants based on each analysis system. The C/E dependence on the core type is significantly reduced in the both analyses when the experimental values based on the present evaluation are used. This indicates that the present evaluation is more reasonable since only difference between the two cores is a slight change in neutron spectrum.

Table 6 Comparison of C/E for Doppler constant

Origin of experimental value	Core type	JNC cal.	CEA cal.
HEDL evaluation	Core I	0.97	0.96
	Core II	1.06	1.04
Present evaluation	Core I	1.01	1.01
	Core II	1.02	1.00

6. Conclusion

A re-evaluation of the SEFOR static tests has been carried out. The re-evaluated Doppler constant is 3 or 5% larger than the original GE evaluation. The increase is mainly due to the update on the fuel thermal conductivity correlation.

The new values look more reasonable than the recommended HEDL evaluation in that now the C/E values do not depend on the core type. In addition, the experimental uncertainty is significantly reduced from 12% to 6%, and this is of the utmost importance according to current accuracy requirements.

Independent re-evaluation by other researchers is welcomed for the results to be widely accepted.

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