

## SADI: Assembly Bow Simulation — A Calculation Method for In-Core Gaps or Interaction Forces Between Fuel Assemblies

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### ABSTRACT

A special purpose calculational method has been developed, allowing evaluation of the impact of lateral deflection of PWR fuel assemblies on in-reactor grid-to-grid gaps. The basic concepts used in this method are relatively simple. The data files originate from ex-pile measurements on fresh or spent fuel assemblies. The calculational method is applied both to core physics studies (evaluation of inter-assembly gaps in the core under hot conditions) and to handling operations (simulation of loading or unloading of a fuel assembly into a row and evaluation of interaction forces between assemblies).

### 1 INTRODUCTION

The correct positioning of fuel assemblies inside a pressurized water reactor vessel calls for the provision of inter-assembly gaps. These do not correspond to the calculated theoretical value : they vary along the assembly length with lateral deflection and are randomly distributed across the core ; they also vary during a fuel cycle according to the burnup rate and fluence gradient undergone by each assembly.

Knowledge of inter-assembly residual gaps (or interaction forces) in the reactor core is useful as input in solving several problems as :

- in-reactor handling problems (loading, unloading, shuffling), during which inter-assembly friction forces during loading or unloading may be calculated from lateral interaction forces.
- accident analyses in order to take into account friction forces between fuel assemblies.
- the determination of penalties, due to assembly bow, on the core physics safety calculation.

As a result FRAGEMA has developed a special-purpose calculational method called SADI (Simulation d'Assemblages Irradiés Déformés - In-core Assembly Bow Simulation) which evaluates the impact of fuel assembly distortion on in-core grid-to-grid gaps.

## 2 HYPOTHESES AND METHODOLOGY

The main assumptions made for this calculational method are as follows :

- assembly bow may be represented by a single parametric function,
- heatup during the cycle do not modify assembly bow.

The methodology used is illustrated in figure 1 :

- based on the cold assembly bow measurement, each (fresh or spent fuel) assembly is characterized by the parameters of the function to which it can be related ;
- the values of the parameters are combined as a function of assembly burnup ;
- based on these value files and using a MONTE CARLO method, a series of bow shape assemblies is generated ;
- the CASAC computer code (Structural analysis computer code) evaluates inter-grid gaps or interaction forces based on static analysis of the fuel assembly row ;
- interaction force or inter-grid gap distributions are characterized (histogram, arithmetical mean...) ;
- in the same way, a step by step evaluation can be made representing the cinematics of the loading or unloading force for an assembly in a given row.

## 3 DATA - CHARACTERIZATION OF AN ASSEMBLY

Data are available in two forms :

- factory manufacturing dimensional inspection printouts for fresh fuel assemblies. For the sample used, non-linear curves are of two types : bow-shaped (95 %) or S-shaped (5 %) ;
- post-irradiation examination results for irradiated fuel assemblies. The curves are the same (bow-shaped : 80 %, S-shaped : 20 %).

In both cases the first step consists in calculating the displacement, in relation to an orthogonal reference (O, X, Y), of the center of each of the grids of the analyzed assembly.

This analysis only addressed the first deformation mode (bow-shaped). In this case, in each direction, the deflection curve can be made to correspond to a curve equivalent to the equation :

$$U = A * \left( 1 - \frac{Z}{ZL} \right)^B * \left( \frac{Z}{ZL} \right)^C * \frac{1}{U_0}$$

where  $U_0 = B^B * C^C * \left( \frac{1}{B+C} \right)^{B+C}$

ZL = assembly height

A =  $U_{\max}$

Z = grid height

U = displacement along X or Y of the grid mid-point

Each of the deflection curves will be characterized by its three values A, B and C, which are assumed to be independent. Three cases arise depending on the respective values of B and C :

- B < C the curve is assymmetrical and deflection is highest in the upper part of the assembly
- B = C the curve is symmetrical
- B > C the curve is assymmetrical and deflection is highest in the lower part of the assembly.

To reduce the impact of measurement uncertainties and to assign characteristic coefficients to each assembly, the measured deflection curves are subjected to a least square fit including weighed ponderation. The three coefficients A, B and C are calculated by the LIS computer code which also performs automatic handling of data and result files.

Figure 2 shows four curves representing the results obtained by the computer code for a fresh fuel assembly in both directions (X and Y) and for an end-of-life assembly also in both directions. The experimental points corresponding to each of the grid elevations are represented by a rhombus ; the fitted curve is shown by a continuous line. Note the close correlation of the fitted curve with the experimental values.

#### 4 SIMULATION OF A ROW - MONTE CARLO METHOD

A row of assemblies exhibiting likely bows can be generated by taking a random selection of 15 assemblies from those available in the data files. However, the size of the files is insufficient to ensure a reasonable representation of physical reality. One of the solutions to this problem consists in using the MONTE-CARLO method for creating a sufficient sample.

Each assembly is therefore characterized by three coefficients A, B and C. For each irradiation (beginning of life, end of cycle 1, end of cycle 2 and end of cycle 3) we have N deflection curve measurements and therefore N measurements of each coefficient. The SIMUL computer code calculates the corresponding histogram. It assigns a characteristic value to each of the histogram categories (the median of the category) and a series of "MONTE CARLO" integers. It then generates a table of random numbers which, when compared with the MONTE CARLO series, indicate the category and therefore the corresponding value of the histogram. Each A, B and C triplet is then recombined to obtain a bowed fuel assembly. Each generated assembly is inserted into its location in the row. The computer code then evaluates the residual gaps and indicates any interference. Figure 3 shows the middle row of a PWR 900 MWe reactor at end of cycle and hot condition, generated by SIMUL. It consists of two assemblies at the end of cycle 1, six at the end of cycle 2 and seven at the end of cycle 3. Note the numerous interferences between the assemblies and between the peripheral assemblies and the core baffle.

The MONTE CARLO method provides sufficiently representative distribution of all the possible combinations.

#### **5 CALCULATION OF INTERACTIONS BETWEEN ASSEMBLIES**

The SIMUL computer code provides the deformations of assemblies which will make up the row. Given the interactions between fuel assemblies during loading into the reactor core, the deflection curves will be modified. Calculation of the new deformations and accordingly of inter-grid gaps or interactions is carried out by the CASAC computer program /1/ and more specifically by the "non-linear static calculation" option. The input parameter is loading, i.e the sets of initial forces applied to each assembly and the boundary conditions. Knowing the deflection curve for each assembly, the next step is to calculate the sets of forces which, when applied to unbowed assemblies, would provide the same grid mid-point displacements. This is performed (using the CASAC program for imposed-displacement linear static analysis) for each assembly to calculate all the sets of forces applied to the row. The assembly row model exhibits non-linearities due to inter-assembly gaps (figure 4). Figure 5 shows the shape (resembling wire) of the figure 3 assembly deflection curves after assembly insertion into the row.

The CASAC program provides the position in the row and the magnitude of inter-grid gaps or interactions. The HISTO program then calculates the corresponding histograms and the various statistical parameters characterizing gap and interaction distributions.

## 6 EXAMPLES - RESULTS

We generated 4 series of 3 rows of 15 17 x 17 standard assemblies representative of the middle rows of a reactor core under hot conditions in both directions at the beginning and end of the cycle. By way of illustration, figure 6 shows a histogram of the inter-grid gaps at the grid 6 location, at the beginning of the cycle in the X direction. The average value of the inter-assembly gap increased from 1.02 mm to 1.51 mm and there are 7 contacts between grids (14 assemblies affected) for the 45 assemblies analysed. These results are presented in figure 7. The overall results (for all directions) for the residual inter-assembly gaps at the mid-grid location after balancing of the rows are illustrated in the table of figure 8. The interaction forces between the grids across the core are also shown. The average gap increases by about 25 % between the beginning and end of the cycle. There is therefore more interaction between assemblies and accordingly the average interaction force increases by about 50 %. For handling problems, we simulated the loading of the central assembly into the reactor vessel (under cold conditions at the beginning of the cycle). All the other assemblies are assumed to be in position. Figure 9 shows the different stages of assembly loading into the middle row. The main difference between the model used here and that in figure 5 concerns the boundary conditions : the top nozzles are free to move whereas in the hot row the positioning of the upper internals has locked the top nozzles in their nominal position.

Interaction points and forces vary with the level to which the fuel assembly is inserted into the reactor core. Figure 10 shows trend in the compressive force exerted by the core on the assembly as a function of its insertion into the core. The calculation made no allowance for the force absorbed by the lower core plate alignment pins, which explains the break in the curve at the last point.

## 7 CONCLUSIONS

This method makes it possible to calculate distributions of interaction forces and gaps between assemblies in the case of mode 1 deflection curves (bow-shaped curves). It provides an efficient tool for understanding the effect of the fuel assembly deformations under irradiation, on the gaps and interaction forces under hot conditions, and on the fuel assembly loading under cold conditions.

## 8 REFERENCE

- /1/ J.C. LEROUX, "CASAC : A Code Computing the LOCA and Seismic Loading on PWR Fuel Assemblies".  
Transactions of the 7th conference, Paper C6/1.

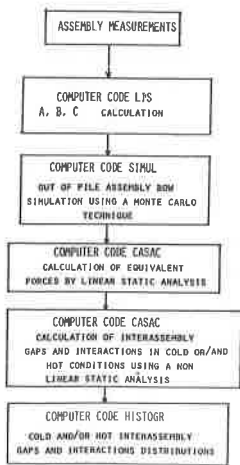


FIGURE 1 - SADI FLOW CHART

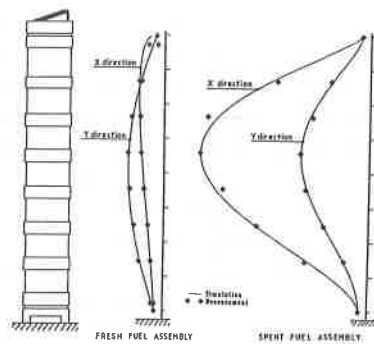


FIGURE 2 - EXAMPLES OF FITTED ASSEMBLY BOW

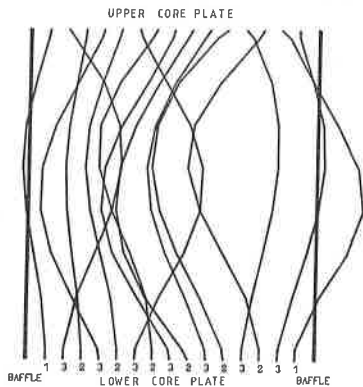


FIGURE 3 - SIMULATED ROW OF FIFTEEN 17 X 17 STD ASSEMBLIES PRIOR TO BALANCING

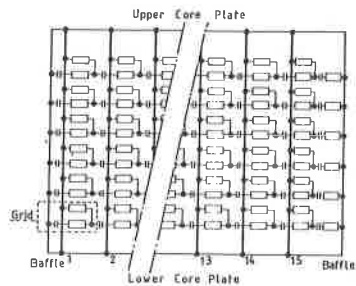


FIGURE 4 - STRUCTURAL MODELIZATION OF A ROW OF FIFTEEN FUEL ASSEMBLIES

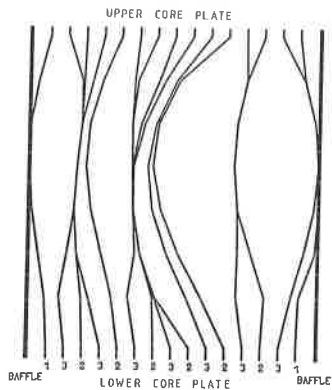


FIGURE 5 - SIMULATED ROW OF FIFTEEN 17 X 17 STD ASSEMBLIES AFTER BALANCING

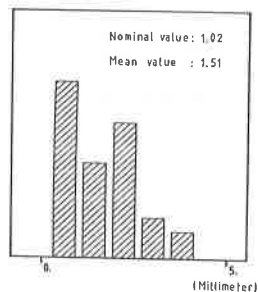


FIGURE 6 - HISTOGRAM OF A GAP SAMPLE (X DIRECTION, GRID 6 ELEVATION, BEGINNING OF CYCLE)

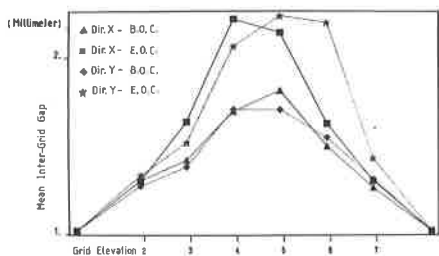


FIGURE 7 - TRENDS IN MEAN INTER-GRID GAP

CORE DIMENSION	CORE ASSEMBLY DATE		CORE ASSEMBLY DATE (MONTH)
	GRID 4 SEPARATION	GRID 6 SEPARATION	
Beginning of Core	4.54	3.28	67.1
End of Core	3.46	2.24	68.9

FIGURE 8 - DISTRIBUTION OF INTER-ASSEMBLY GAPS AND INTERACTION FORCES (UNDER HOT CONDITIONS IN REACTOR, BASED ON 4 SERIES OF 3 ROWS OF FIFTEEN 17 X 17 STD FUEL ASSEMBLIES)

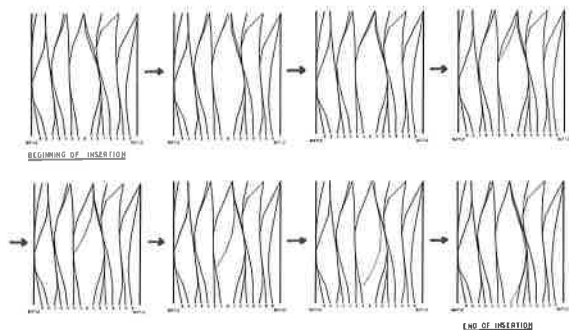


FIGURE 9 - INSERTION STAGE OF ASSEMBLY LOADING INTO MIDDLE ROW

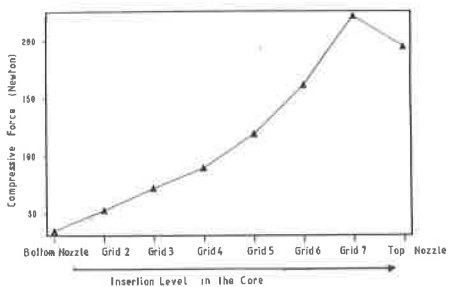


FIGURE 10 - COMPRESSIVE FORCE EXERTED BY THE CORE ON THE ASSEMBLY