



## Seismic analysis of LMFBR cores-Symphony mock-up

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### ABSTRACT

In order to validate the LMFBR seismic core design methods, an experimental program named SYMPHONY has been scheduled on large scale core mock-ups. The first step of this program consists in a 3 row mock-up which was tested on CEA shaking table for different core configurations. The test results have been analyzed with two different codes by CEA and PNC. In a second step, an even more important hexagonal mock-up will be tested.

### 1. INTRODUCTION

Fast breeder reactor cores are composed of a great number of assemblies of various types. These assemblies are separated by small gaps and immersed in a fluid. During an earthquake, shocks may occur between assemblies inducing a non linear behavior of the core. The two phenomena which mainly influence the response of the core are the fluid-structure interaction and the impacts between assemblies.

To study the dynamic core response, methods have been extensively studied during the past few years in France and in Japan. In order to proceed with the validation of these methods, CEA and PNC have developed in a common framework with EdF and Framatome an important experimental program named SYMPHONY, using dummy full scale Phenix assemblies.

### 2. EXPERIMENTS

#### 2.1. Mock-ups

Two experimental mock-ups have been designed and manufactured for the SYMPHONY program.

- The three row mock-up

This mock-up includes a central row and two adjacent rows (figure 1). The rows accommodate twenty-four or twenty-two fuel assemblies and twenty-two neutronic shield elements. All together this mock-up can be equipped with seventy fuel assemblies and sixty-six neutronic shield elements.

The diagrid is composed of two plates connected by chandelles. In these chandelles are inserted the spikes of the fuel assemblies or the neutronic shield elements. Some gap is provided for the introduction of the assemblies. The diagrid is 6.3 meter long and is bolted to the shaking table. A watertight vessel is connected to the diagrid to perform tests in water. Stiffening beams prevent lateral vibration of the vessel.

Two types of bundle configuration can be tested : free standing core and restrained core. In order to achieve the latter configuration rigid stops can be anchored to the vessel at the top level.

The total mass of this mock-up, including assemblies, is 58,000 kg.

- The hexagonal mock-up

This mock-up has exactly the same geometry (figure 2) than the RAPSODIE mock-up which has been previously tested. It is composed of ninety-one fuel assemblies (a central assembly surrounded by five crowns) and one hundred-and-eighty elements (four crowns).

The diagrid is circular and is bolted to the shaking table. The bundle is surrounded by a watertight vessel to perform tests in water. Similarly to the three row mock-up, in order to be able to test the bundle in a free standing core and restrained core configurations, removable rigid stops can be placed on the vessel at the top level.

- The fuel assembly mock-ups

Ninety 4.3-meter-high dummy fuel assemblies are available. They have exactly the PHENIX reactor assembly dimensions (figure 3). There is only one pad level (1,435 mm from the top) where the gap is 0.25 mm between two adjacent assemblies, whereas the pitch bundle is 127.2 mm. Steel cylinders located inside the hexcan are simulating the pin bundle without adding rigidity to the assembly. In order to avoid shocks during dynamic tests, water has been introduced inside the fuel assemblies to couple cylinders and hexcan. The total weight of the fuel assembly is 202 kg.

- The neutronic shield elements

One hundred-and-eighty neutronic shield elements have been specially designed for this program. They are made of steel bar which have been machined to obtain a spike at the bottom and a gap of 3.2 mm at the top (figure 4). Their rigidity have been designed to provide a stiffening effect relative to the flexibility of the fuel assemblies. Functional gap in the chandelle allows for a small rotational rigid body motion of the element.

## 2.2. Instrumentation

Almost fifty sensors have been placed on the mock-up. They mainly measure :

- assembly displacements at top and pad level,
- assembly accelerations at top level,
- strain at spike level,
- assembly-assembly impact forces,
- assembly-vessel impact forces in the restrained core configuration.

In order to optimize the digital acquisition, two sample frequencies have been chosen : 100 Hz for displacements and strains measures, and 2 kHz for accelerations and impact-forces.

## 2.3. Test program

The test program is divided in two principal phases corresponding to each mock-up. Presently only the three row mock-up have been tested. The main parts of the tests performed up-to now were :

- verification of the mock-up dynamic characteristics ;
- static and obvious dynamic tests on single assemblies to validate the finite-elements models.
- random excitation at different levels to estimate non-linearities due to shocks between assemblies.

- seismic excitation of the whole core in air and in water, at different levels with several time histories, corresponding to isolated and non-isolated reactor designs and depending on the core configuration (free-standing or restrained).

For all tests, the input accelerations were applied in the row direction.

The tests were performed at CEA SACLAY center on AZALEE 100 ton shaking table.

### 3. RESULTS AND ANALYSIS

#### 3.1. *Free standing core configuration*

- Description

In this configuration, the outermost assembly displacements are not limited by any restraining blocks. Several acceleration time histories were applied to the mock-up, corresponding to isolated and non-isolated reactor block designs. In case of non-isolated design, the main frequency of the response spectra of the input is very close to the fuel assembly frequency (3 Hz), whereas the isolated input has a lower frequency range (figure 5).

- Test result and analysis

The different tests results in the free standing core configuration were analyzed with CASTEM 2000, a CEA general purpose mechanic code. Since the non-linear dynamic calculation is based upon modal superposition, each of the 136 assemblies were represented by the first modes of an elastic beam. A 4 % modal damping were applied on each mode. Shocks which may occur between one assembly and its neighbors are modeled by damped spring systems with gap, in every directions. In case of in-water tests, the fluid-structure interaction is taken into account through an added mass.

In figure 6, the square marks represent the assembly maximum displacement measured at top level in air on the central row, versus the assembly position in the row (whereas the plus marks are the maximum displacement issued from calculation), for the non-isolated accelerogram. The highest displacements were observed in the middle of the row (45 mm), where the cumulative gaps are the more important. At each end, you can notice that the neutronic shield element displacements are much lower (15 mm) because of their relative stiffness. In figure 7 are shown a comparison of a central assembly time history displacements, issued from test and calculation. The discrepancy between calculation and test results are very small, which tends to validate the present method used for core seismic design.

#### 3.2. *Restrained core configuration*

- Description

The test configuration is the same as the free standing configuration, except for that the displacement of the outermost neutronic shield elements are limited by restraining blocks. For the tests with the restrained configuration, three acceleration time histories were used as inputs. These accelerograms, which are related to S1 (OBE) design earthquake ;

AJ: Non-isolated plant

BJ: Base isolated plant, with lower support of reactor-block

CJ: Base isolated plant, w/o lower support of reactor-block

Response spectra of these accelerograms are compared in figure 8. Note there are two dominant frequencies in the isolated spectra (BJ and CJ) which correspond to the frequencies of isolated structure and reactor-block. The maximum acceleration of these original inputs are 875, 150, and 170 gals, respectively.

- Test results

In figure 9 are compared the distribution of the maximum and minimum displacements at the top of the elements from the single row tests in water with the highest input level (+3dB for

AJ and +9.5dB for BJ and CJ). With AJ input, the neutronic shield elements and the fuel assemblies on the outer rim displace outward almost to the geometrical limit. On the other hand, the response of the fuel assemblies in the central region is rather even. The displacements of the neutronic shield are obviously smaller than those of the fuel assemblies, which can be attributed to the fact that the natural frequency of the neutronic shield is higher than that of the fuel assembly. In the tests with BJ and CJ inputs, the response displacements are smaller than those in the AJ test and the distribution is quite even.

- Comparison of test and calculation

The computer code used for the analysis of restrained configuration tests is FINAS, which is a general purpose non-linear analysis system developed by PNC. In the present analysis, a single row model was adopted corresponding to the single row tests. Here, an assembly was represented by elastic beam elements and the shock was modeled by a series connection of a linear spring-dashpot and a gap element. In order to represent a lowered natural frequency due to the clearance between the spike and the diagrid, a linear spring element was inserted at the upper end of the spike. Fluid added mass was estimated by the virtual added mass method to take into account the effect of fluid-structure interaction between the core and the vessel. Rayleigh damping was used for the beam mode damping, and a damping coefficient was directly defined for the shock damping. The response calculation was performed by the direct time integration scheme (Newmark  $\beta$ ) in which the time increment was mainly governed by the duration of shock force. Figure 10 compares the maximum and minimum displacement distribution for the test with AJ input (+3 dB) in water. The analysis result seems to reproduce the tendency that the outward displacement gradually decreases along the element and that the response of the neutronic shields are smaller than those of the fuel assemblies. In figure 12 are compared the time history traces of the displacement at the top of the central element (1E). The analysis result can be judged to be in a good accordance with the test result in the time domain also.

#### 4. CONCLUSION

The first part of the SYMPHONY program, performed on the three row mock-up allowed to compare tests results and calculations on a large scale core in a free standing and restrained core configuration. The tests were concurrently analyzed by PNC and CEA with their own design methods and computer codes in order to validate them. The physical phenomena which were particularly studied are the non linearities due to shocks between assemblies, and fluid-structure interaction. In both cases, the results of analysis were in good agreement with tests measures.

The second part of the test program, using the hexagonal mock-up, will allow to study 2D effects and fluid-structure interaction in a more representative way.

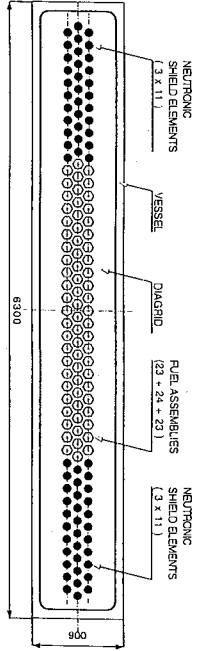
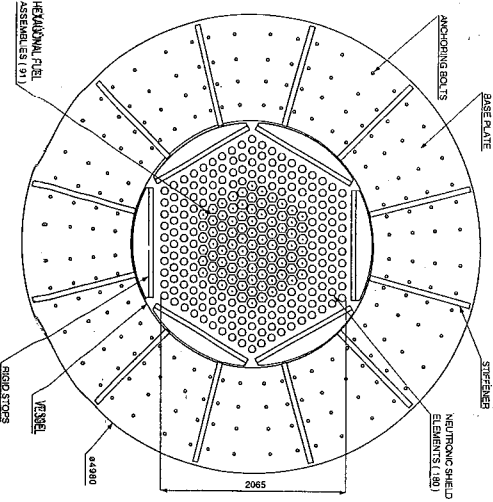


Fig. 1



SYMPHONY HEXAGONAL BUNDLE  
TOP VIEW

Fig. 2

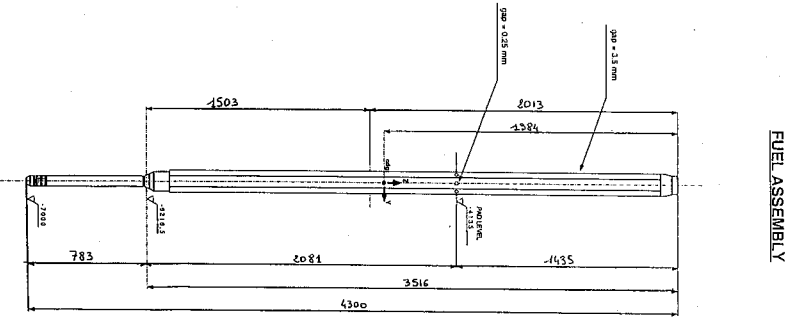


Fig. 3

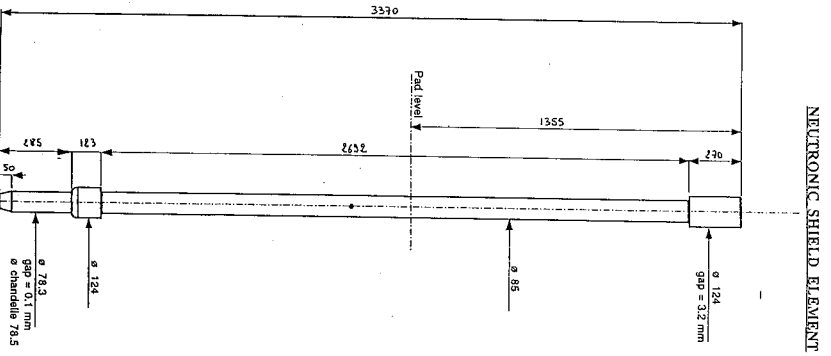


Fig. 4

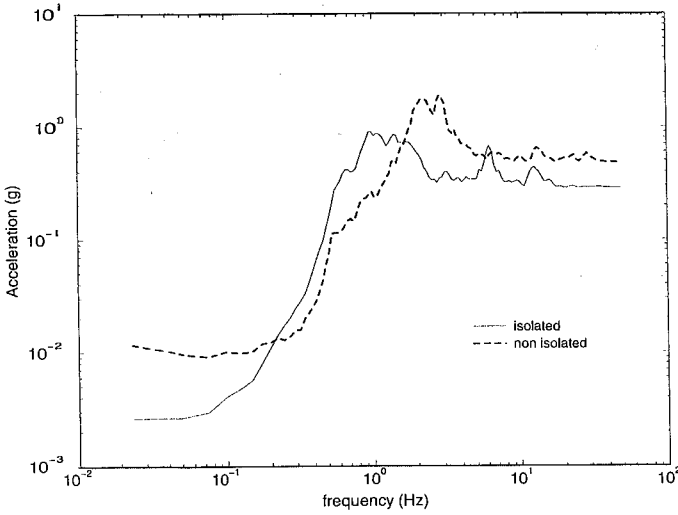


Fig. 5 - Comparison of Response Spectra for Free Standing Core Tests

Fig. 6 - Distribution of Maximum/minimum Displacements

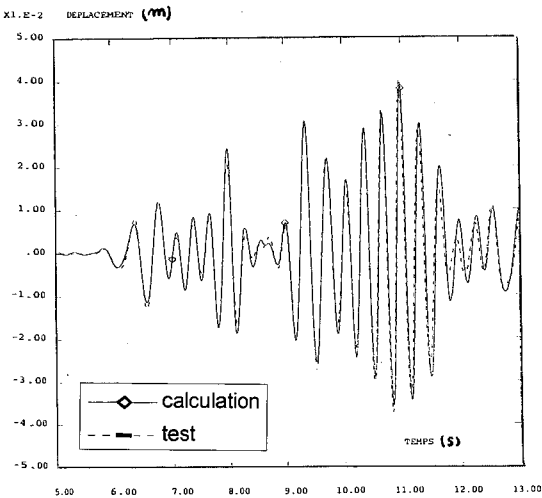
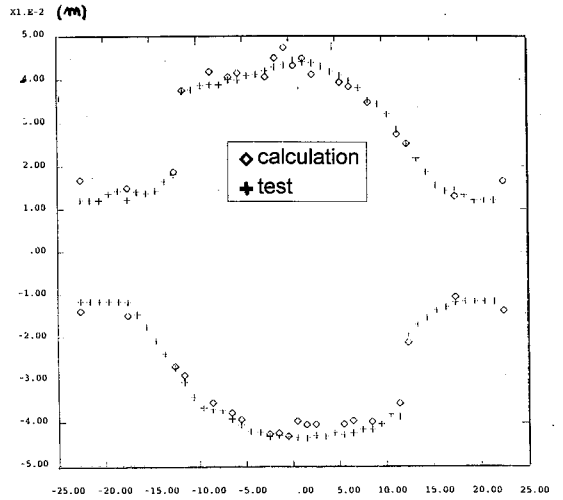


Fig. 7 - Comparison of Test and Analysis : 3 rows, in air, Central element

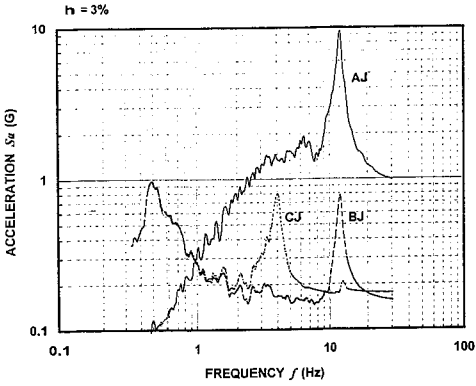


Fig. 8 - Comparison of Response Spectra of Restrained Core Tests

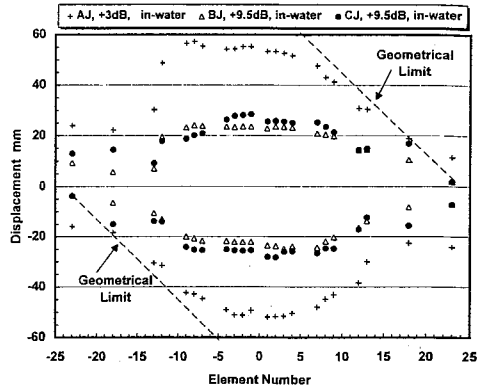


Fig. 9 - Distribution of Maximum/minimum Displacements

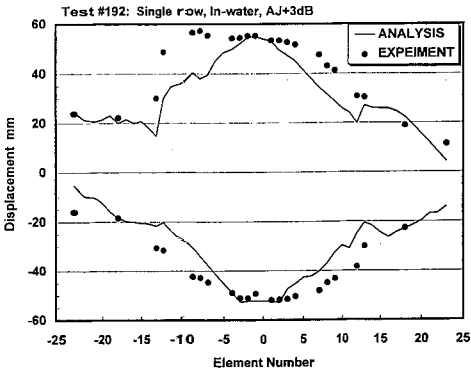


Fig. 10 - Comparison of Test and Analysis : Single row, AJ+3dB, In-water

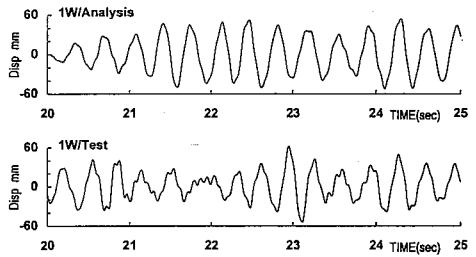


Fig. 11 - Comparison of Test and Analysis : Single row, AJ+3dB, in-water, Central element

