F.B.R. Core Seismic Analysis

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1. INTRODUCTION

FBR cores are composed of a great number of subassemblies of various types. These subassemblies are separated by small gaps and immersed in a fluid. During a seism, shocks may occur between subassemblies inducing a nonlinear behaviour of the core.

The two phenomena which mainly influence the response of the core are the fluid structure interaction and the impacts between subassemblies.

To study the core response, methods have been developed and validated through tests on the core mock-up RAPSODIE. The aim of this paper is to present the tests results corresponding to different levels of excitation, in air and in water, and different configurations of the core (free standing and barrel restrained). Then we will present the methods to interpret these results in pointing out the methods especially devoted to the analysis of the global fluid structure interaction (homogeneization).

2. DESCRIPTION OF THE MOCK-UP RAPSODIE

The core mock-up RAPSODIE (see fig. 1 and a detailed description in (Brochard et al., 1987) is composed by 91 fuel assemblies located at the center of the mock-up (1 central assembly and 5 rows around) and 180 neutronic shield elements, surrounding the fuel assemblies (4 rows). In order to perform tests in water the mock-up is surrounded by a stiff vessel.

The fuel assembly is composed by a cylindrical spike and an hexagonal can containing the fuel pins. The total length of the assembly is 1.5 m. There are two localized contacts between the spike and the diagrid. The weight of the assembly (20 kg) is supported at the lower contact point and at the upper one there is a small technological clearance, necessary for the introduction of the spike into the diagrid. At about 60 cm from the top of the assembly are located the pads. The distance between two adjacent hexcans is 1 mm except at the pad level where it is reduced at 0.1 mm.

The neutronic shield elements (fig. 3) are composed by steel cylinders clamped at the upper level of the diagrid.

3. BACKGROUND

During the oldest tests performed on the mock-up RAPSODIE, only the maximal values of the displacements at the top of the elements located in the central row, have been measured (Brochard et al., 1985). Studies have shown that these values were not sufficient to understand the core behaviour and that it was necessary to analyse the time history and the frequency content of the core response.

For that purpose a new set of tests have been performed in the same conditions (i.e. with measurement of the displacements time history of the elements located in the central row). Simultaneously numerical models representing the central row alone have been developed (Gauvain et al., 1982 ; Gauvain et al., 1981). We obtain good correlations in air between tests results and calculations for the time history of the displacements. These correlations mean that in air, in spite of the coupling of the motion of the different rows through the impacts, the motion of the central row taken alone was representative of the central row inside the core. In water, in addition with the shocks, the motion of the different rows are coupled through the fluid, and up to now the former assumption cannot be verified.

To have more informations about this phenomenon, a new set of tests has been realised, during which the displacement at the top of the assemblies have been measured on the whole core by an optical measurement methodology (Brochard et al., 1987). The main results of these tests will be discussed in the next paragraph.

4. TESTS ON THE MOCK-UP RAPSODIE

Excitation - Configuration of the Mock-up

The seismic excitation applied to the mock-up corresponds to the OBE and SSE of the SPX1 reactor, corrected by the scale factor of the mock-up (1/3) to keep the same maximal velocity.

The tests have been performed both in air, and in water, for two configurations:
- free standing core, which means that the motion of the external shield elements are free,
- barrel restrained core, which means that a restraint ring has been placed at the top of the external shield elements, limiting their displacement (no gap between the elements and the restraint ring).

Results

We mainly present here the influence of the fluid and of the configuration for a constant level of excitation (100 % OBE, see influence of the level of excitation in Brochard et al., 1987).

For the maximal values of the displacements we observe that:
- The level of displacement decreases from the central row to the external one, which can be related with the fact that the sum of the gaps for the external row is smaller than for the central one.
- For the free standing core, there is a decrease about 20% due to the fluid (figs. 4 and 5). Moreover, the shape of the curve is modified. In air we have a characteristic curve where the maximal displacement occurs for the external fuel assemblies (for each row), which means that the gaps at the top of the fuel assemblies are fully closed (Brochard et al., 1987). In water, the maximal displacement for the fuel assembly is rather constant which is an illustration that the gaps are not fully closed.
- The presence of a restraint ring reduces the level of displacement (about 40% in air) (figs. 6 and 7), and modifies strongly the shape of the curves. In air the maximal displacement of the fuel assembly is about the sum of the gaps and the displacements of the neutronic shield elements are very small. The decrease from the central row to the external one is less important than for the free standing core configuration.

Let's now study the frequency contents of the displacements through their response spectrum. We notice that:

- the response spectrum of the assemblies presents usually (Brochard et al., 1987 ; Brochard et al., 1985) two peaks: one corresponding to the main frequency of the excitation (in this case, it is 12 Hz) and the second peak is associated to the first eigenfrequency of the assemblies, but may be slightly different of this frequency, due to the impacts between subassemblies. In air for the fuel assemblies (resp. neutronic shield elements) this peak is at 9.0 Hz (resp. 22 Hz), and the eigenfrequency is at 8 Hz (resp. 20.5 Hz).
- The water lessens the frequency of the assemblies about 15% (fig. 8).
- The restraint ring modifies strongly the frequency contents. For the external neutronic shield elements, it is no more possible to observe a peak associated to their first eigenfrequency (fig. 9), for the free standing core, the shape of the spectra of each type of assembly is rather constant from one row to another row of the core. In the case of the restraint barrel design, there is an evolution of the shape of the spectra from the central row to the external one.

5. NUMERICAL MODELS

The main effects which influence the response of the core are:

- The impacts between subassemblies. A simple calculation shows that in air the maximal value of the displacement of one fuel assembly alone (i.e. a linear behaviour without shock) is smaller than the displacements observed in the tests. For the neutronic shield elements, this phenomenon is inversed, because their motion is imposed through the interaction between the two types of elements: the neutronic shield elements are pushed by the fuel assemblies.
- The fluid effect: we have seen that the fluid effect modifies the response of the core (modification of the frequencies, reduction of the level of displacements). The fluid couples the motion of each subassembly (Preumont et al., 1983) (inertial coupling). This aspect may be represented through an additional mass matrix. The fluid has also a local influence during the impacts between subassemblies: when two subassemblies are going to impact, the thin fluid film separating them is squeezed, inducing locally a great velocity of the fluid (Aita et al., 1985). Due to this important motion of the fluid, loses of energy occur (viscosity effect, quadratic dissipative effect) which, up to now, has not been represented in details in the numerical core models, but only through an additional local damper, acting during the impact.

Two numerical models have been developed to analyse the core behaviour: a nonlinear model which is well adapted to take into account the impacts phenomena and an homogeneous model allowing to represent the fluid effect in the global motion of the core.

Nonlinear Model

To represent the impact phenomena a nonlinear model has been developed in the computer code CORALIE (see detailed presentation in Gauvain et al., 1982). This model represents a bundle of assemblies. Each assembly is represented by its first eigenmodes. The impacts phenomena are represented by a nonlinear spring system acting only during the impact. This stiffness must take into account two aspects: the local deformation of the assembly at the shock point and the truncation effect of the modal basis. A dissipation of energy due to the impact may be represented by an additional shock damper placed in parallel with the shock stiffness.

In air, the nonlinear model used to interpret the tests represents the central row of the core (11 fuel assemblies and 8 neutronic shield elements) (Brochard et al., 1987). Each fuel assembly (resp. neutronic shield element) is represented by 4 (resp. 2) modes, and the impacts are supposed to be located at the pad level, at the top of the subassemblies and at the link between the spike and the upper part of the diagrid. This model supplied good correlations with the tests results.

To represent the global fluid structure interaction, we could extend the former model to the whole core and calculate the global added mass matrix. In practice such a method is not applied due to the difficulty (size of the problem to solve) to determine this matrix, which is full and couples the motion of one subassembly to the motion of all other assemblies. The projection of this matrix on the modal basis couples all modes together. We have adopted a simple modelisation of the fluid effect: we keep the former model (central row only) and we modify the eigen frequency of the assemblies (added mass effect) to adjust the lessening of 15% on the frequencies. The fluid coupling is only taken into account between two adjacent assemblies by using coupling masses deduced from experiences on a small bundle (Preumont et al., 1983 ; Preumont et al., 1986). The fluid couples the motion of the core with the motion of the vessel surrounding the core; as this vessel is very stiff, its motion is supposed to be null. Nevertheless to take into account, in a correct way, the seismic excitation, it is necessary to consider the forces on the vessel due to the pressure in the fluid. As this vessel is not represented in this model, it is necessary to modify the seismic coefficients (Martelli et al., 1987). It is to notice also that the added and coupling masses are equal for all assemblies of the same type , independently of their position in the core and uniformely distributed on the length of the assemblies.

Such model supplies acceptable agreement with test results, for maximal displacements on the central row (fig. 10) and for the time history of the central fuel assembly (fig. 11). The correlation becomes bad (especially for the time history) for external assemblies for which impacts are strong.

To represent in a more refined way, the fluid structure interaction in the global motion of the core, in keeping only a small number of D.O.F., the homogeneization method is an interesting alternative approach.

Homogeneous Model

This method consists in replacing the physical heterogeneous medium (the assemblies and the surrounding fluid) by an homogeneous equivalent medium, which macroscopic characteristics are determined from the resolution of a set of problems on the elementary cell of the bundle.

The method to derive the equations of the homogeneous medium (described in details in (Brochard et al., 1987) and (Brochard et al., 1987) consists in representing the main parameters of the problem (pressure in the fluid and displacement of the assemblies) by locally periodic functions, i.e. functions which mean variations at the scale of the unit cell are small in front of the local periodic perturbations in the cell. Then these functions are expanded in increasing power of ε (ε is the characteristic length of the cell).

The equations of the homogeneous medium may be written:

$$\mathrm{div}(A\ \overrightarrow{\mathrm{grad}}\ p) - (Y^*/c^2)\ \partial^2 p/\partial t^2 = -\ \rho_o\ \mathrm{div}\ (D\ \ddot{\vec{u}}) \qquad (1)$$

$$(M + \rho_o\ B)\ddot{\vec{u}} + K\ \vec{u} = -\ D\ \overrightarrow{\mathrm{grad}}\ p \qquad (2)$$

where:

- A,B,D are tensors depending of the macrocrospic characteristics if the medium,
- K,M are respectively the stiffness and the mass matrix of the assemblies,
- ρ_o and c are the density of the fluid and the sound velocity in the fluid,
- Y^* is the fluid area in the unit cell,
- $\vec{u}$ and p are the displacements of the assemblies and the pressure in the fluid.

This method has been applied to the geometry of the mock-up RAPSODIE (Brochard et al., 1987) and allows to represent for the frequencies the effect of lessening due to the fluid. Nevertheless, the amplitude of the shield elements motion was underestimate, because in the homogeneous medium impact phenomena are not taken into account. The modelisation of shocks in the formulation of the homogeneous medium has two aspects:

- At the boundary between two homogeneous media (one representing the fuel assembly, the second representing the neutronic shield elements), in the linear formulation we assume only the continuity of the pressure field. It is necessary to represent the mechanical interaction between the two types of elements through a unilateral link.
- Inside the medium to represent the shocks between assemblies of the same type. An approach consists in introducing in the formulation of the homogeneous medium a global modelisation of the shocks. First we need a shock criterion to know locally whether the assemblies are impacting or not. We get this condition in expanding at the first order the displacement of two adjacent assemblies and we write that their relative displacement is less than the gap between them. This condition may be expressed for a shock in the direction $\vec{n}$ ($\vec{n}$ is a unit vector):

$$\vec{n}^T \,\overline{\overline{\text{grad}}}\, \vec{u}\, \vec{n} \leqslant - j/\varepsilon \quad \text{(j is the gap between two assemblies)} \qquad (3)$$

When there is no shock (criterion not verified) the linear formulation of the medium is still available (eqs. 1 and 2). During a shock eq. 1 is not modified, but in eq. 2 describing the dynamic behaviour of the assemblies, we must add in the right handside a force representing a mean value of the impact force. As in the nonlinear model, this force is deduced in modelling the impact through a nonlinear shock stiffness system. The implementation of this shock model is in progress in the computer code CASTEM 2000.

As a preliminary study to the nonlinear analysis of RAPSODIE, we have made a modal analysis in a plan orthogonal to the axis of the mock-up. This analysis describes in fact the behaviour of the mock-up at low level of excitation, i.e. when the impacts between assemblies are negligible. The assemblies are modelled by a mass and a stiffness representing the characteristics of their first eigenmode.

The results show two types of modes:

- Modes corresponding to a global motion of one type of elements, the other elements having small displacements. These modes may be excited by a seism (fig. 12).
- Modes corresponding to local opposite phase motion of some elements (fig. 13). These modes cannot be directly excited by a seism but have a great importance for the study of impacts.

These two types of modes will be used in the RAPSODIE nonlinear analysis at high level of excitation, when the impacts have a great influence on the response.

6. CONCLUSION

Tests performed on the core mock-up RAPSODIE have shown the great influence of the fluid and of the impacts, on the core response. Theoretical models have been developed. The nonlinear model (central row alone) represents correctly the in air behaviour (impacts) but uses a simplified modelisation of the fluid (lessening of frequency through added mass, coupling masses between only adjacent subassemblies, modification of the seismic coefficients) which does not allow to represent in a realistic way the in water core behaviour. The homogeneous model, in which the impacts will be represented, will allow to make global calculations of the core. Results of this last model could be used as an input for a local nonlinear model of a small bundle of assemblies.

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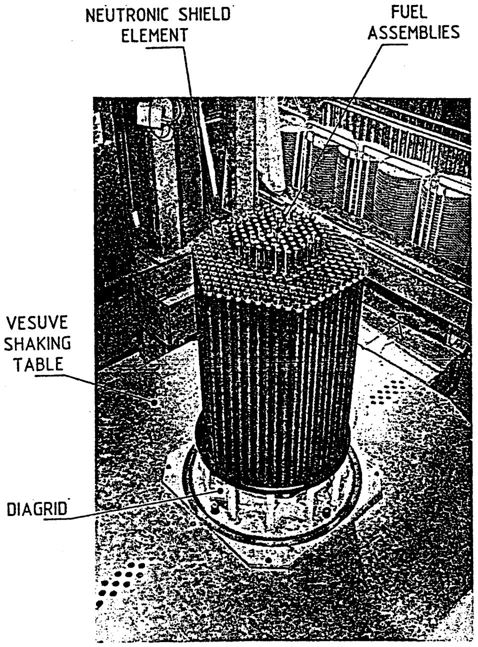

FIG.1
RAPSODIE MOCK-UP

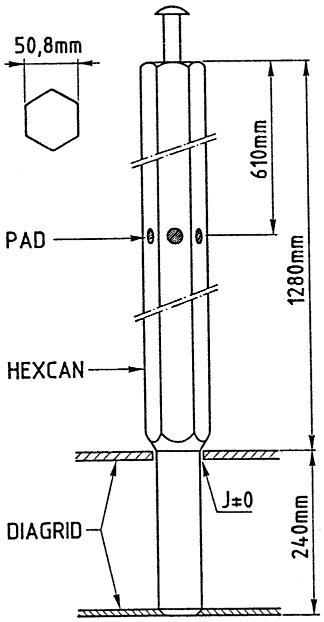

FIG. 2
FUEL ASSEMBLY

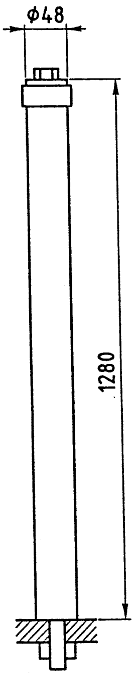

FIG. 3
NEUTRONIC SHIELD ELEMENT

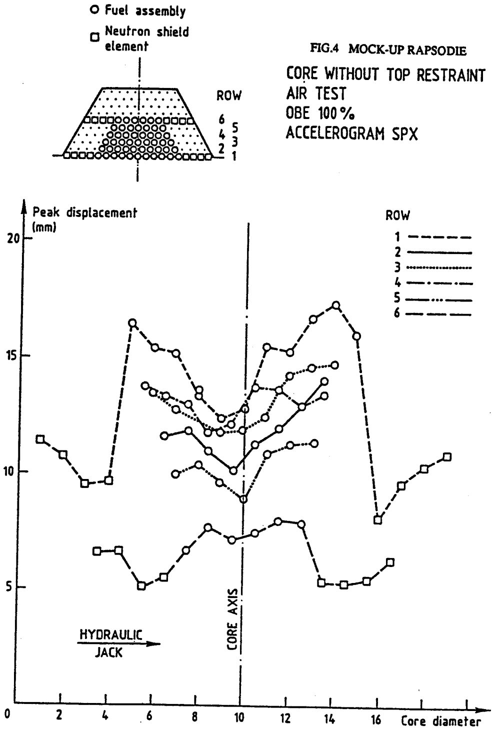

FIG.4 MOCK-UP RAPSODIE

CORE WITHOUT TOP RESTRAINT
AIR TEST
OBE 100%
ACCELEROGRAM SPX

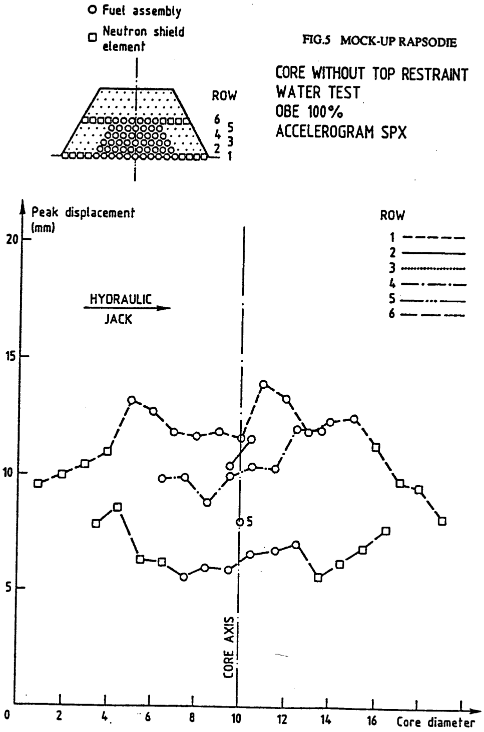

FIG.5 MOCK-UP RAPSODIE

CORE WITHOUT TOP RESTRAINT
WATER TEST
OBE 100%
ACCELEROGRAM SPX

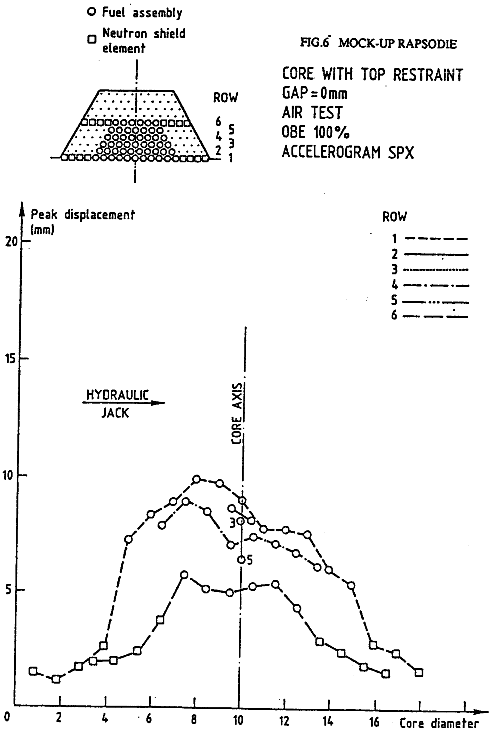

FIG.6 MOCK-UP RAPSODIE

CORE WITH TOP RESTRAINT
GAP = 0mm
AIR TEST
OBE 100%
ACCELEROGRAM SPX

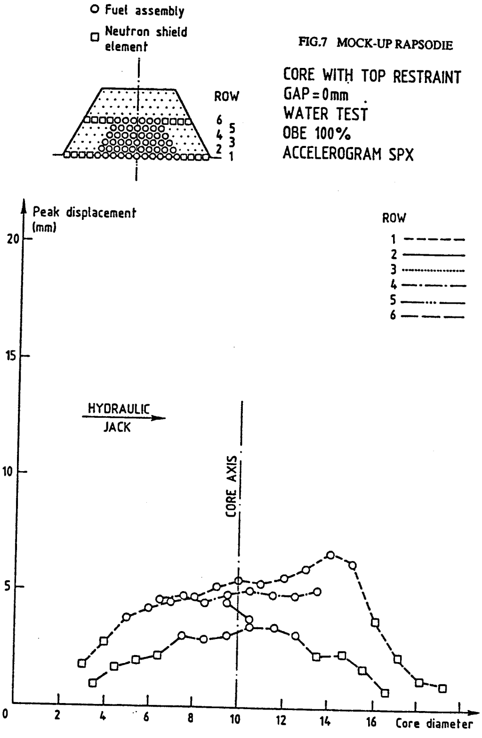

FIG.7 MOCK-UP RAPSODIE

CORE WITH TOP RESTRAINT
GAP = 0mm
WATER TEST
OBE 100%
ACCELEROGRAM SPX

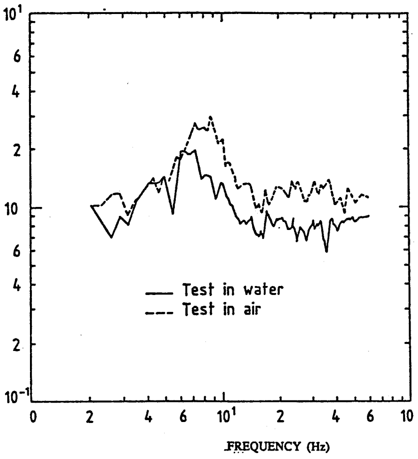

Fig. 8 - Mock-up RAPSODIE ratio of response spectrum of the central fuel ASS versus the excitation spectrum (100 % OBE)

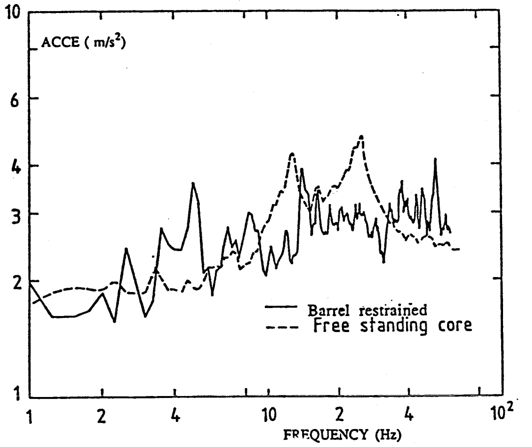

Fig. 9 - Response spectrum of external neutronic shield element

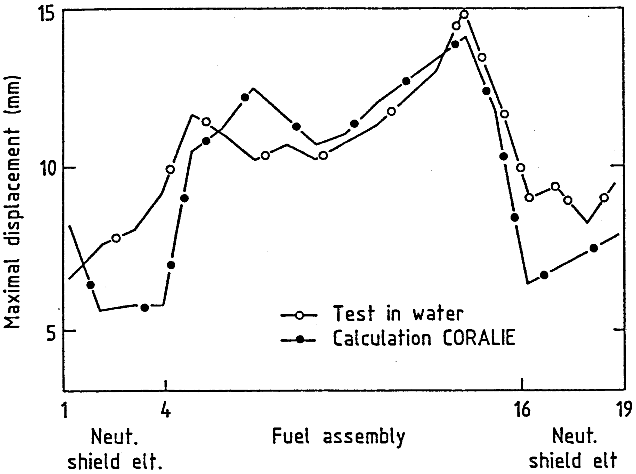

Fig. 10 - Mock-up RAPSODIE (100 % OBE in water)

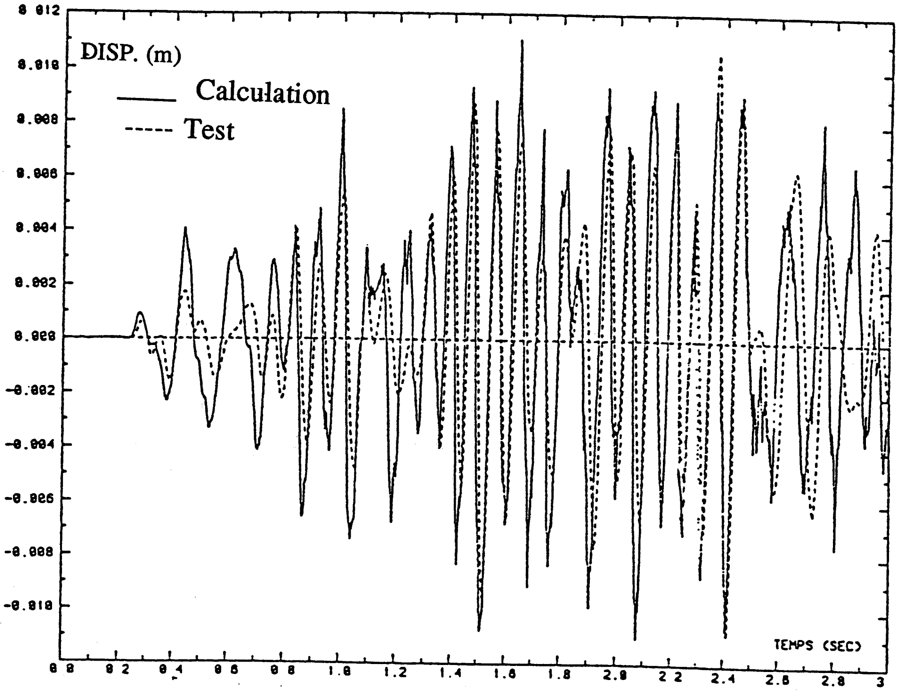

FIG. 11 Mock-up RAPSODIE (100% OBE in water)
Displacement of the central fuel assembly

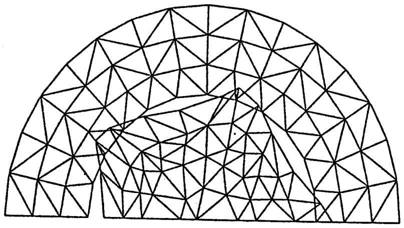

FIG. 13 _ Mock-up RAPSODIE
Homogeneous model

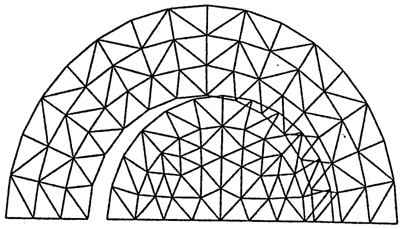

FIG. 12 _ Mock-up RAPSODIE
Homogeneous model