Seismic behaviour of LMFBR Reactor cores
The SYMPHONY Program.

Daniel BROC

CEA CEN Saclay
DRN/DMT/SEMT/EMSI
91 191 Gif/Yvette France

ABSTRACT

As part of a comprehensive program on the seismic behaviour of the LMFBR reactor cores, the SYMPHONY experimental program, performed at the CEA Saclay, is carried out from 1993 up to now. LMFBR reactor cores are composed of fuel assemblies and neutronic shields, immersed in sodium (the primary collant) or water (for the experimental tests). The main objective of the seismic studies is to evaluate the assembly motions, with consequences on the reactivity and the control rod insertability, and to verify the structural integrity of the assemblies under the impact forces. The experimental program has reached his objectives. Tests have been performed in a satisfying way. Instrumentation allowed to collect displacements, accelerations, and shock forces. All those results constitute a comprehensive base of valuable and reliable data. The interpretation of the tests is based on beam models, taking into account the Fluid Structure Interaction, and the shocks between the assemblies. Theoretical results are in a quite good agreemment with the experimental ones. The interpretation of the hexagonal tests in water pointed out very strong coupling between the assemblies and lead to the developement of a specific Fluid Structure Interaction, taking into account not only inertial effects, but dissipative effects also.

1 INTRODUCTION

LMFBR reactor cores are composed of fuel assemblies (FA) at the center and neutronic shields (NS) at the periphery, disposed in an hexagonal geometry, and immersed in sodium (the primary coolant) or water (for the experimental tests). The main consequences of a seismic sollicitation applied to a LMFBR reactor core, are:
- the motion of the assemblies that could limit the insertion of the control rods,
- the relative displacement of the assembies, that could, by a varation of the core diameter, lead to reactivity fluctuations,
- the streses and impact forces with consequences on the integrity of the structures.

The basical physical phenomena is the dynamic behaviour of the assemblies. Interactions may be very strong, with shocks between the assemblies, and fluid structure interaction. The Research and Developpement activities have experimental and theoretical aspects. One of the objective is to built a seismic behaviour model for the core. The current models consider the central assembly row of the core. In the next sections, the SYMPHONY program is first discribed. Then, the experimental results and the interpretations are given for the different tests. Endly, a balance of the program is presented, that point out the contribution of the program to the understanding of the seismic behaviour of the LMFBR reactor cores.

2 THE SYMPHONY PROGRAM

The definition of the SYMPHONY program use the results of a previous experimental and theoretical program, named RAPSODIE, performed at a reduce scale, with 271 assemblies of about 1.5 meters tall (91 FA and 180 NS) embedded in a diagrid. The main limits of this program are the size of the structure and the dynamic characteristics of the assemblies, that do not correspond to a real reactor core.

The SYMPHONY mock up use assemblies full scale of the PHENIX reactor, and 1/3 diameter scale of SUPER-PHENIX (about 4 meters tall). The dynamic characteristics of the assemblies correspond to a real reactor core, particularly the insertion in the diagrid. The experimental part includes single assembly tests of the FA and the NS (Figures A-1 and A-2), one or three row tests (Figure A-6), and hexagonal configuration tests (Figure A-9). All tests are performed in air and in water. The characteristics of the water (mainly the density) are assumed to be close to the primary coolant (sodium). Some experiment will be performed in a restrained configuration, corresponding to some LMFBR reactors, where the movements of the outermost assemblies are limited by restraining blocks. The sollicitation applied to the mock-ups are seismic reference movements or white noise excitations.

3 METHODOLOGIC TOOLS

The interpretation of the tests use the classical tools of the vibratory mechanics. Due to the geometry of the assemblies, beams models are used. Row tests or hexagonal tests are described by calculations based upon modal superposition, with the first modes of the assemblies. Shocks wich may occur between the assemblies are modeled by damped spring systems with gaps. A modal superposition calculation can consider shocks interactions, as external forces, when the shocks occur.

Fluid Structure Interaction is taken into account with inertial effects, leading, for the assemblies, to lower frequencies in water than in air. For the one assembly tests, and for the row tests, a global added mass is considered, without coupling terms between the assemblies: for the interactions with the fluids, the structure is considered as a single DOF system, with a global uniform movement of the assemblies. For the hexagonal tests in water, this global FSI method does not take into account all the complexity of the physical phenomena, as the non uniform movements of the bundle. For the interpretation of those tests, a complete FSI model is built, taking into account, also, the dissipative effects due to the fluid.

4 ASSEMBLY TESTS RESULTS

Fuel Assemblies (FA) and Neutronic Shields (NS) are presented in Figures A-1 and A-2. Theoretical results (beam results) are in good agreement with the experimental ones. The general shape is similar for the first and second modes of the FA and the NS (Figure A-3). The first bending frequency in air is 3.05 Hz for the FA (Figure A-4). Due to gaps in their fixation in the diagrid, leading to shocks, NS have a non linear behaviour, and lower displacements than FA. The first frequency in air depends on the amplitude, from 3 Hz to 5 Hz. The transfert fonction, obtained with withe noise tests, shows, for the NS, a equivalent damping, especially for small displacements, and for the tests in water (Figure A-5). The transfert fonction shows, for the FA, a lower frequency in water than in air, corresponding to an added mass of 24% (Figure A-4).

5 ROW TETS RESULTS

Figure A-6 show the geometry of the one or three rows tests. The central row contains 24 FA at the center and 22 (2 x 11) NS at the extremities. The lateral rows contain 23 FA and 22 NS. Some tests are performed with a row of only 24 FA. The different tests results in the free standing core configuration were analysed with CASTEM 2000, computer code developed at the CEA Saclay (/14/). Fuel assemblies displacements and impacts forces can be quite well predicted by the models: about 45 mm and 5 000 N for the tests in air and in water The relative displacements of the assemblies are more difficult to describe.

In the 24 FA tests, all assemblies are moving in phase. The first frequency in air is the same as the single frequency assembly. In the water tests, the added mass value is lower than for an one assembly test (8%), due to the row geometry (Figure A-7).

For the complete row tests, the NS limit the displacement of the peripherical FA. Figure A-8 represent the assembly maximum displacements at the top level in air on the central row, versus the assembly position in the row (experimental and theoretical results). The highest displacements are observed for the central FA (45 mm), where the cumulative gaps are the more important, and the interaction with the NS negligible. The displacements of the NS are much lower (15 mm) due to their relative stiffness. The one or three rows tests give very similar results. The adjacent row do not change the behaviour of the central row.

6 HEXAGONAL TEST RESULTS

Fuel assemblies displacements and impacts forces are well predicted by the theoretical models only for the tests in air (about 40 mm for the FA, 20 mm for the NS, and 5 000 N for the shocks). For the hexagonal tests in water, very strong coupling between the assemblies by the fluid leads to much lower displacements than for the tests in air, particularly for the low displacements (Figures A-9, A-10, A-11, et A-12).

Table 1 presents the results of white noise tests on the hexagonal structure, with different levels (0 dB, -3 dB, and -6 dB). For the tests performed with FA only, displacements in air or in water are close (about 45 mm for the 0 dB test). The tests in a complete core configuration (FA and NS) present interesting results. For the tests in air, the displacements of the NS are low (about 20 mm for the 0 dB test), but the displacements for the FA are about 40 mm (close to the tests with only FA). The tests in water show very low displacements for both FA and NS (13 mm for the 0 dB test).

		0 dB	-3 dB	-6 dB
FA only	Air	46	24	13
	Water	45	29	16
Complete Core Air	FA	40	23	–
	NS	20	15	–
Complete Core Water	FA	13	8	4
	NS	13	8	–

Table 1 : SYMPHONY hexagonal tests, White noise results: displacements (in milimeter), for the FA and the NS.

Theoretical interpretations, based on the global added mass notion, are not able to explain these results. Therefore, we propose, in a next section, a model for the dynamic behaviour of the LMFBR reactor cores. This model is based on the results of previous researches on the dynamic behaviour of tube bundles in fluid.

7 FLUID STRUCTURE INTERACTION FOR TUBE BUNDLES, SOME ELEMENTS

Inertial effects: The common equation used, in seismic studies, to describe the inertial effects is the equation of a perfect, incompressible fluid (/13/). $\rho\frac{\partial V_F}{\partial t} = -\vec{\nabla}P$ and $divV_F = 0$ (Laplace equation), where V_F is the fluid velocity, t the time, ρ the mass density of the liquid, and P the pressure. The force, applied by the fluid on a structure immersed in a vessel, is: $F = M_w\ \ddot{x}_a - M_a(\ddot{x} - \ddot{x}_a)$ where F is the applied force, M_w the mass of water displaced by the solid, x the displacement of the solid, x_a the displacement of the vessel. M_a is the added mass. $-M_a\ddot{x}$ is the applied force for an acceleration of $\ddot{x}$ for the solid, and no movement for the vessel. Masses, forces, displacements and accelerations are scalar values for one degree of freedom systems, and matrix or vectors for multi degrees of freedom. Using the relative displacement of the assemblies $X = x - x_a$, the movement equation for the assemblies is: $(M_s + M_a)\ddot{X} + K\ X = -(M_s - M_w)\ddot{x}_a$ where K is the stiffness of the system, M_s the mass matrix of the solid, and M_w the mass of water displaced by the solid. The added mass matrix M_a contains non diagonal terms, that represent the coupling between the assemblies.

Damping effects: Water is commonly considered, in vibration problems, as a perfect fluid, as its viscosity is relatively low, corresponding to an high Reynolds number. For permanent flows, high Reynolds numbers lead to turbulence phenomena and dissipative effects. Those effect do not take place in fluid structure interaction problems, if the displacements of the structure are low. In our case, the hypothesis of the little displacements is no more valid. The space between two assembies (where is the water) is about 3 mm, about 40 times lower than the assembly diameter. In some configurations, to displacements of a few centimeters of the assembly will correspond a relative movement of the fluid of about one meter (40 times higher). In this condition, a quite permanent fluid flow will take place through the assembly, with dissipative effects (/7/).

8 MODEL

A simple qualitative physical model is built, in order to explain the results of the hexagonal tests in water. The bundle is represented by 7 x 7 = 49 elementary oscilators, in 2 dimensions, with 3 x 3 = 9 FA in the center and 40 NS. This model take into account the inertial effects of the fluid, with the coupling terms between the assemblies, and consequences on the relative displacements. It takes into account, too, the damping due to the fluid. This damping mainly limits, in our case, the relative displacements of the assemblies (/7/).

Calcuations are performed for different cases. The pulsation is of $\omega = 1$ for the FA, and $\omega = 1$ or $\sqrt{2}$ for the NS, The elementary reduced damping of the assembies take the values of $\beta = 0$, 0.1, or 0.3. Three Fluid Structure Interaction models are considered. For the W1 model, a global added mass is considered, without coupling terms. The coupling terms are taken into account for W2, with non diagonal terms in the FSI matrix. For W3, dissipative effects of the fluid are taken into account. A white noise excitation is used.

Figure 1 show the geometry of the model, and the characteristics of the modes, taking into account the fluid structure interaction ($\omega = 1$ and $\beta = 0$ for both FA and NS). Frequencies are from 0.06 Hz to 0.16 Hz (about the in air frequency) participation factors are high for frequencies about 0.13 Hz.

The most relevant results of the model are summarized in Table 2.

For identical characteristic of the assemblies ($\omega = 1$), the maximum displacements are, with the W1 model, identical for all the assemblies (0.06 for $\beta = 0.1$). With the W2 model, FSI effects lead to differential displacements of the assemblies, and the displacements may be higher for the NS. This result is mainly obtained for low values of the low elementary damping values (with $\beta = 0$, for W1, 0.24 for the FA and the NS, and, for W2, 0.24 for the FA and 0.30 for the NS). With the W3 model, the dissipative effects due to the fluid lead to a global damping of the bundle, and the displacemnts are lower (0.14 and 0.19, instead of 0.24 and 0.30).

$\omega^2 = 1$ Hz FA + NS			$\omega^2 = 1$ FA only	$\omega^2 = 1$ et 2	$\omega^2 = 1$ $\beta = 0.1$ et 0.3
	$\beta = 0.0$	$\beta = 0.1$	FA $\beta = 0$	$\beta = 0.1$	
Air	0.19	0.057	0.19		
W1 FA	0.24	0.060	0.24	0.060	0.060
W1 NS	0.24	0.060		0.038	0.032
W2 FA	0.23	0.060	0.24	0.049	0.047
W2 NS	0.30	0.066		0.050	0.041
W3 FA	0.14	0.058	0.22		0.046
W3 NS	0.19	0.066			0.040

Table 2: Results of the Model: The FA pulsation is 1. The NS puslsation is 1 or $\sqrt{2}$.

For different characteristics of the FA and the NS. leading to lower displacments for the NS, Fluid Structure Interaction lead to an average phenomena, and low displacements for both FA and NS. If the NS are stiffer ($\omega^2 = 2$), displacement are, without coupling (W1 model), higher for FA (0.060) than for NS (0.038). The displacements are much closer, with the W2 model, that take into account the coupling: 0.049 for the FA and 0.050 for the NS. If the elementary damping is higher for the NS ($\beta = 0.3$) the displacements are, with the W1 model (without coupling) 0.032 for the NS, lower than 0.060 for the FA. In this case also, the displacements are much closer, with the W2 model (with coupling): 0.047 for the FA and 0.041 for the NS.

This model give a qualitative explaination to the hexagonal tests in water. The low displacements of the NS are due to their high elementary damping. Fluid Structure Interaction phenomena lead to a limitation, by the NS, of the displacements of the FA. PREUMONT (/9/) obtained similar theoretical results, with FA displacements limited by high frequency NS.

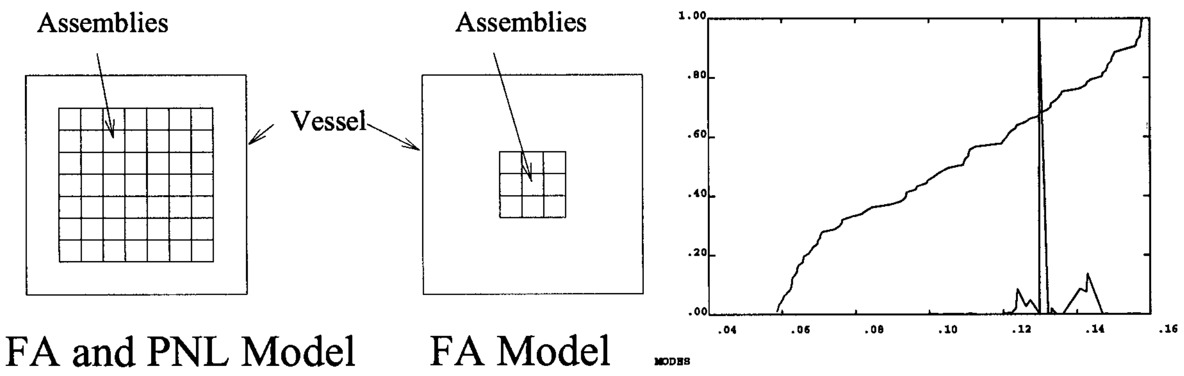

Figure 1: Model and characteristics of the modes: Frequencies are from 0.06 Hz to 0.16 Hz (about the in air frequency) participation factors are high for frequencies about 0.13 Hz

9 CONCLUSION

The results of the SYMPHONY experiment constitute a comprehensive base of valuable and reliable data, that permit to understand the seismic behaviour of the LMFBR reactor cores. The most significative tests were those in the hexagonal configuration, in water, as they correspond to the real configuration of a reactor core. The objective of the other tests, in air, with one or three rows, or with only one assembly, was to prepare the last tests, and to validate elementary models for the vibration of the assemblies and for their interactions (shocks or Fluid Structure Interaction). The row model is the design model for the LMFBR reactor cores.

The main contribution of the SYMPHONY program is to point out the strong FSI coupling between the assemblies in the hexagonal configuration in water. The presence of the fluid do not lead only to inertial effects, but to dissipative effects also. The tube bundle is no more considered as a single degree of freedom system. Simpler models, that neglect the coupling between the assemblies, and only take into account, for the water tests, a change in the frequencies, due to a global uniform movement of the bundle, are not able to explain those phenomena. The dissipative effects due to the fluid may lead to a global equivalent damping of the bundle, and much lower displacements.

The FSI model presented here need to be fully validated, mainly the possible influence of the dissipative effects dues to the fluid. Other physical phenomena are not taken into account in this model, as the impacts between the assemblies. But this model gives a realistic qualitative explaination of the SYMPHONY experiment, applicable to the seismic behaviour of the LMFBR reactor cores.

One of the conclusions in that the one row models, used to describe the seismic behaviour of the reactor cores, overestimate, in most of the cases, the displacements of the assemblies.

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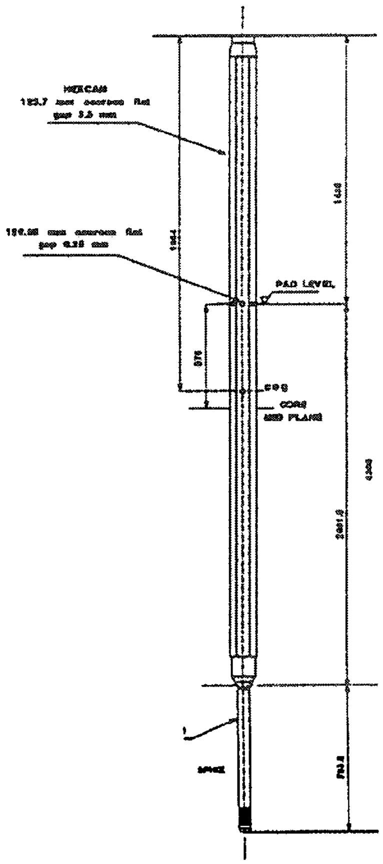


Figure A-1: SYMPHONY Fuel Assembly

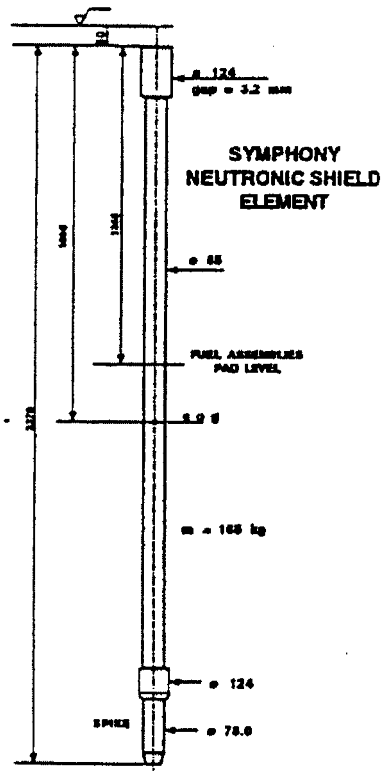
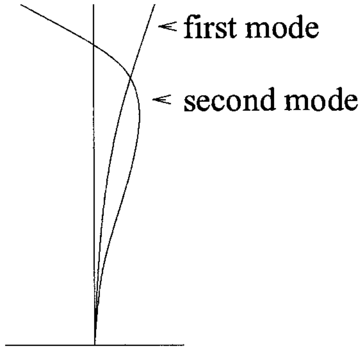


Figure A-2: SYMPHONY Neutronic Shield



Modes for the FA and the NS

Figure A-3: FA et NS modes

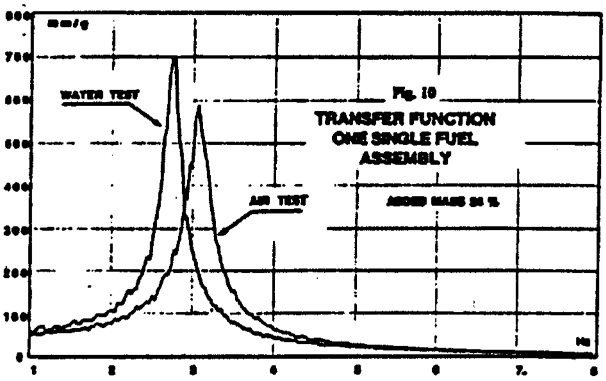


Figure A-4: One FA Test, Transfert Function

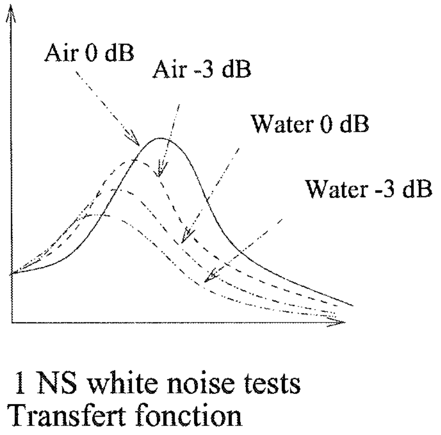


Figure A-5: NS, Transfert Functions

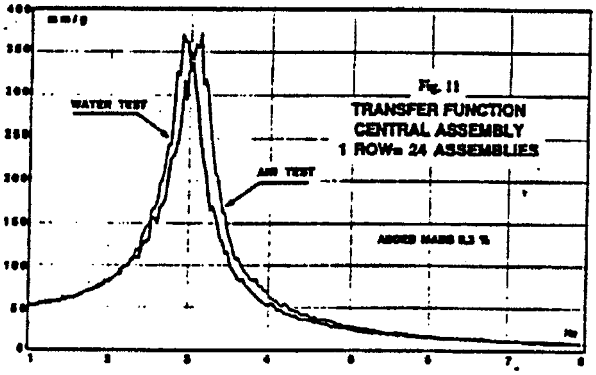


Figure A-7: Row Test, Transfert Function

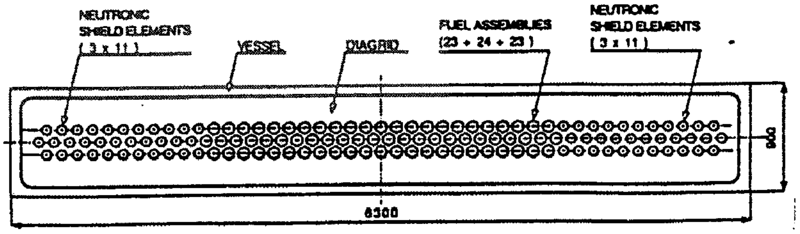


Figure A-6: Row Test Mock-up

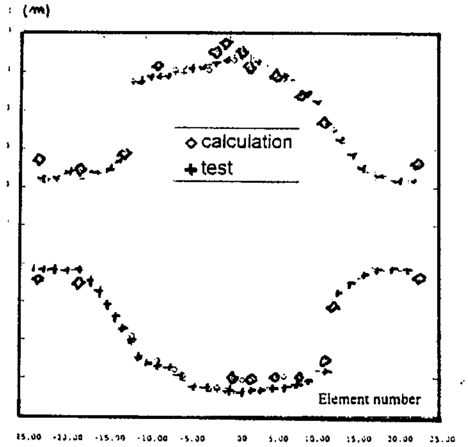


Figure A-8: Row test, Displacements

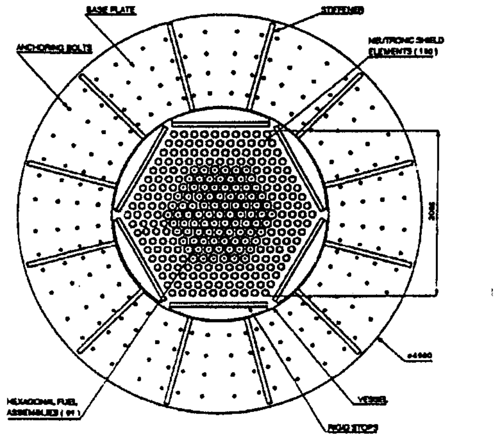


Figure A-9: SYMPHONY hexagonal bundle, top view

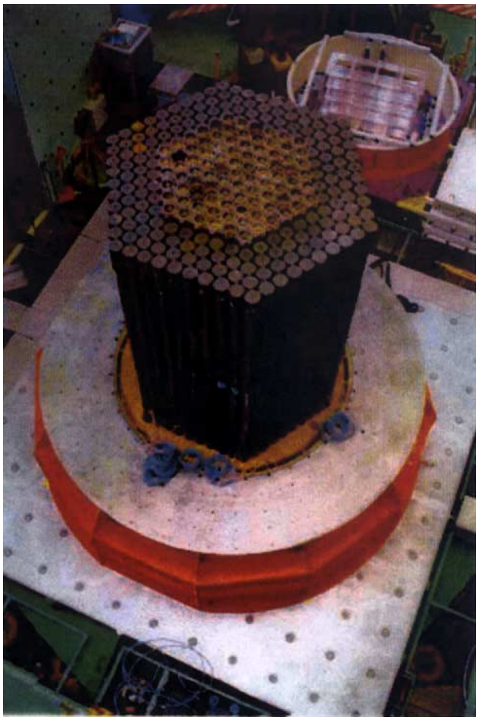


Figure A-10: SYMPHONY hexagonal configuration (without the vessel)

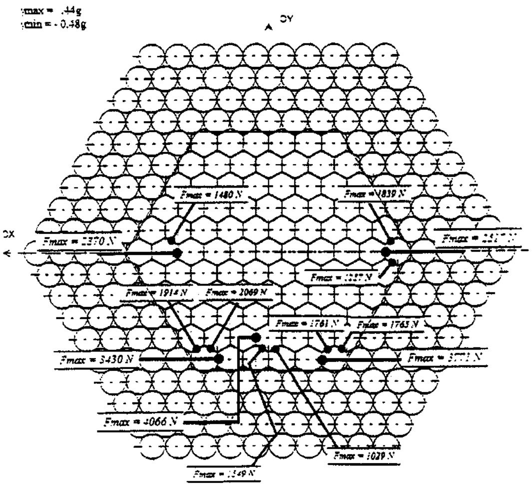


Figure A-11: SYMPHONY hexagonal configuration, shock forces

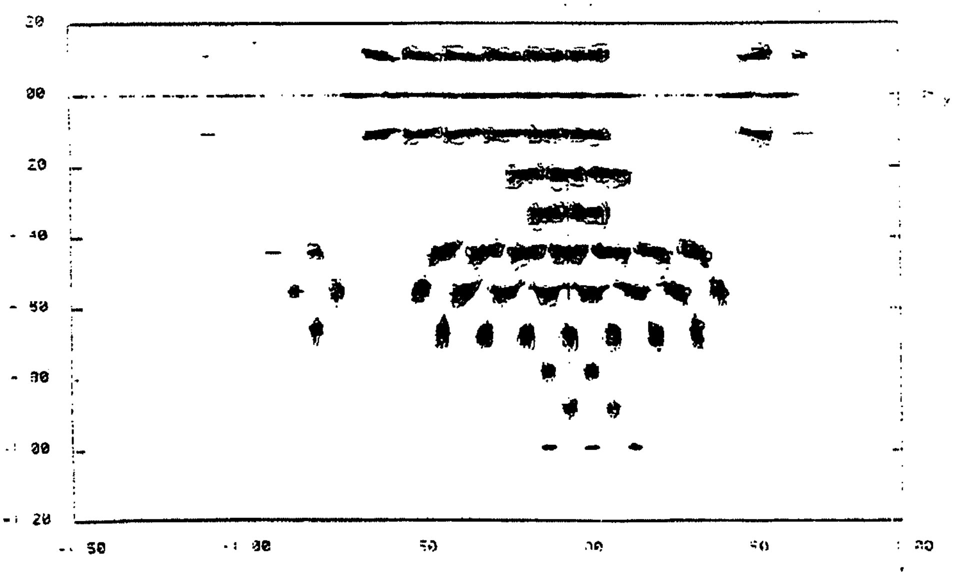


Figure A-12: SYMPHONY hexagonal configuration, displacements