PLASTIC DYNAMIC ANALYSIS OF LIQUID METAL COOLED REACTOR COMPONENTS. USE OF CEA-SEMT SYSTEM

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SUMMARY

The development of a Liquid Metal Fast Reactor implies the ability of designed structures to stand up successfully to highly improbable accidental circumstances. Moreover, it is useful to know the ultimate loading that the various components can stand. Behaviour of the mechanical structures in the event of sudden accidents such as very strong and rapid pressure evolutions must be know. Given such high loads and considering the material characteristics (low yield stress, high elongation capacity, high strain hardening) the analysis must account chiefly for no linear dynamic phenomena involving plasticity and high distorsions.

The CEA-SEMT system of structures calculation by finite elements method has been used extensively for these analysis. It allows static and dynamic calculations in the plastic (and of course elastic) range with large deformations. It includes isotropic and kinematic hardening models. Structures suitable for analysis include:

- bidimensional, plane or axisymmetric (by PASTEL);
- three-dimensional shells of any shape (TRICO);
- piping system (TEDEL);
- three-dimensional solid structures.

Indications are given on real plastic and dynamic analysis performed by that system for various components of the French LMFR project:

- top cover;
- rotating plug;
- core support system;
- main reactor vessel;
- upper internal containment.

1. Introduction

The development in France of sodium-cooled fast reactors implies the need to take account of highly improbable accidental circumstances in structural design work. Moreover, it is of great interest to know the ultimate loads that the various components can withstand.

A detailed analysis of such situations requires consideration of the phenomenon of inertia (dynamic calculations) and of the real constitutive laws of the materials employed (plasticity, cyclings, etc.). The vessel-roof slab-plug assembly, for instance, can be subjected to rapid and intense variations in internal pressure (explosion). This extremely severe type of loading leads to stress values which make no sense (500 to 1,000 kg/mm^2) if calculated on the assumption of elastic behavior, and to widely underestimated values of strains and displacements. This point is of special importance in this type of reactor, particularly since the materials employed have a relatively low yield strength, but high hardening capacity.

In order to resolve these delicate matters, the CEA developed a group of programs using the finite element method (CEA-SEMT System).

This system is briefly described in the following pages, and information is provided on actual cases, in order to provide a picture of the overall structural calculations carried out in fast reactor design.

2. Some theoretical considerations

This paper is not intended to summarize the finite element method, equilibrium equations, or numerical techniques, which are nevertheless of primary significance. We shall restrict ourselves to a rapid examination of two special points :

- plasticity in thin shells,
- buckling of thin shells.

2.1 Plasticity in thin shells

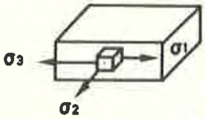
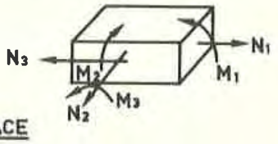
This point has already been discussed [1]. However, after two years of intensive use of the proposed model (See [4]), we feel that a brief summary of the principle [6] is in order.

One method consists of considering the stress-strain relationships at each point of thickness. This leads to the development of a practically three-dimensional formalism, which is likely to prove very costly in view of the extensive computations to be carried out and the memory storage problems involved.

For these reasons and for other, more physical reasons -in a shell the materials is not isotropic- we preferred a global plasticity model which takes account of generalized forces, such as moments and tensile forces. The "stress" and "strain" vectors are generalized by the introduction of moments and curvatures, and Hill's principle is applied to the plasticity potential :

$$\phi \text{ (tensile forces, moments)} = 0$$

PLASTICITY IN SHELLS TWO WAYS FOR ANALYSIS

	USUAL	GLOBAL
STRESS VECTOR	σ_1 σ_2 σ_3 (In each point on the normal)	N_1 N_2 N_3 M_1 M_2 M_3
STRAIN VECTOR	ε_1 ε_2 ε_3	θ_1 θ_2 θ_3 χ_1 χ_2 χ_3
		
YIELD SURFACE	$\Phi(\sigma_1 \sigma_2 \sigma_3) = 0$	$\Phi(N_1 N_2 N_3 M_1 M_2 M_3) = 0$
COMPARAISON	Large computation time and memory storage Seems to be exact	Lower computation time and memory storage Only an approximation
DISCUSSION	Material is assumed isotropic and homogeneous	Direct utilisation of shell sample test results

2.2 Buckling of thin shells

A special effort was devoted to this area, particularly with respect to thin circular shells which are encountered in fast reactors (e.g. main reactor vessel).

The analytical expression of first and second order membrane deformations was calculated with respect to axisymmetric geometry and non-axisymmetric deformation, together with the second order terms relative to the work of pressure forces. These different terms were established in the usual matricial form of finite elements and incorporated in the Aquamode program [3]. The use of this program provided all the known analytical results, particularly with respect to ellipsoidal vessels, as well as certain amusing problems such as buckling of a pipe subjected to internal pressure.

3. General description of programs

The different programs briefly discussed below are part of a complete system ranging from automatic meshing to automatic analysis. These two stages can be carried out with cathode ray screen display.

3.1 Pastel program [2]

This program permits the analysis of plane or axisymmetric two-dimensional structures consisting of massive sections or shells. It has proved to be an extremely valuable, widely employed tool, owing to its various possibilities with respect to structure complexity, its ability to solve problems involving high plastic deformation (cyclic static or dynamic, isotropic or kinematic hardening, creep, etc.), and its low running cost. Most of the reactor structures were calculated by means of Pastel, wherever the geometry and loads are plane or axisymmetric.

3.2 Aquamode program [3]

The analysis of thin circular shells in the presence of liquid required the writing of a specific program in statics and, above all, in dynamics. The classic breakdown of the Fourier series displacement field, with the introduction of the tangential coordinate, enables calculation of this type of structure under non-axisymmetric loads, and determination of the corresponding deformations.

A special routine calculates the critical buckling loads. A considerable effort was exerted in this area in order to clarify the different terms and effects influencing instability problems. The program was also coupled with the Pastel program to analyze elastoplastic buckling.

3.3 Trico program [1]

This program was developed for the elastoplastic analysis of thin three-dimensional shells of any shape, both in statics and dynamics (modal analysis or direct integration). By accounting for geometric non-linearities, it became possible to determine the non-symmetrical behavior of thin elbows -when they where mechanically shut and opened- employed in the cooling circuits of fast reactors of the Phenix and Super-Phénix type [4].

Critical buckling loads can also be computed.

The large components of the reactor, roof slab, rotating core support system, plug, beam and upper internal containement, were calculated in plastic dynamics by means of the Trico program.

3.4 Tedel program [5]

This program is designed for determination of three-dimensional piping and structural frameworks in statics or dynamics, elastic or plastic. With respect to plasticity, a global plasticity model taking account of generalized forces-moments, tensile forces - was introduced to facilitate elastoplastic studies in three-dimensional situations at relatively low cost. The effects of accidents occurring to Super-Phenix piping systems were thus studied in plastic dynamics.

3.5 Bilbo program

This program is concerned essentially with massive three-dimensional structures (cubic or prismatic elements), possibly coupled to thin shell parts. Here also plasticity and inertia effects are accounted for. Massive three-dimensional plastic dynamics computations were carried out on the rotating plug structures.

4. Some applications

Some applications of the CEA-SEMT system are described here, essentially involving the vessel, roof slab, core support, system assembly (figure 1).

4.1 Analysis of roof slab (figures 2 and 3)

A considerable number of calculations were carried out on this type of structure. Certain results have been presented in [1]. The slab is initially dressed and is then subjected to rapid, intense variations in pressure at its lower side. The weights of components and filler concrete were taken into account. This structure was represented by about 600 points and 2 000 elements.

4.2 Rotating plugs

The assemby of three rotating plugs was also computed in plastic dynamics under loading condition of the same type as that applied to the roof slab. Some indications of the results obtained are given in figure 4.

4.3 Vessel, core support system, slab assembly (figure 1)

A first stage series of three-dimensional plastic dynamics computations (figure 5) was carried out over the main vessel-plating assembly. One of the conclusions was to show the superiority of annular core support system over continuous core support system. Annular plating and the rate of deformation on continuous plating are shown in figures 5 and 6 respectively.

The calculation also led to the definition of equivalent plates with respect to the slab and core support system. The slab-vessel-plug-core support system assembly was analyzed by the Pastel program in axisymmetric and plastic-dynamics modes (figure 7).

4.4 Analysis of upper internal containement (figure 9)

The most important study was the plastic dynamics computation of the dome under the impact of the revolving lock chamber during an hypothetical accident. The calculation was performed with 1 000 points i.e 6 000 degrees of freedom. It was carried out up to 80 ms, with various recomputations of the different matrices.

4.5 Earthquake behavior of Super-Phénix buildings (figures 10 and 11)

The overall buildings were schematically treated and computed by means of the Aquamode program. This dynamic analysis was carried out in the elastic region. A comparison was made between various methods, including the following :

- modal analysis for response with respect to time and determination of maximum stresses,
- modal analysis with the use of oscillator spectra and quadratic combination of different modes,
- direct integration. The accelerograms of several earthquakes were introduced into Aquamode and the results averaged out over the range of earthquakes considered.

4.6 Behavior of containments with respect to aircraft and missiles crashes

Some of the foregoing programs were used to calculate the behavior of containments with respect to falling aircraft and missiles. This matter raised relatively few problems. However, local problems involving perforation by hard missiles require greater consideration. Consequently an extensive perforation test program was undertaken in combination with dynamic calculations, by means of the Pastel program, by using special concrete behavior models [7].

5. Summary and conclusions

As a frist step, the dimensional design of the various components was carried out by taking account of static loads. Following this the dynamic effects of the highly improbable accident were taken into consideration. The results of these computations carried out in plastic dynamics, some examples of which have been given above, had a certain number of consequences on dimensional design. The thickness of slabs and plugs were increased, and annular plating was substituted for continuous plating. Mainly, however, all the clamping systems of the various components were reviewed and strenghened in order to ensure complete leaktightness of the system in case of large displacements.

All these studies showed that the system of programs employed and described previously is well adapted to the specific problems posed by fast reactors. This is due to certain computational characteristics, as well as the ability to account for non-linear behavior such as the following :

- plasticity,
- creep,
- large displacements,
- elastic and elastoplastic buckling,
- dynamic effects.

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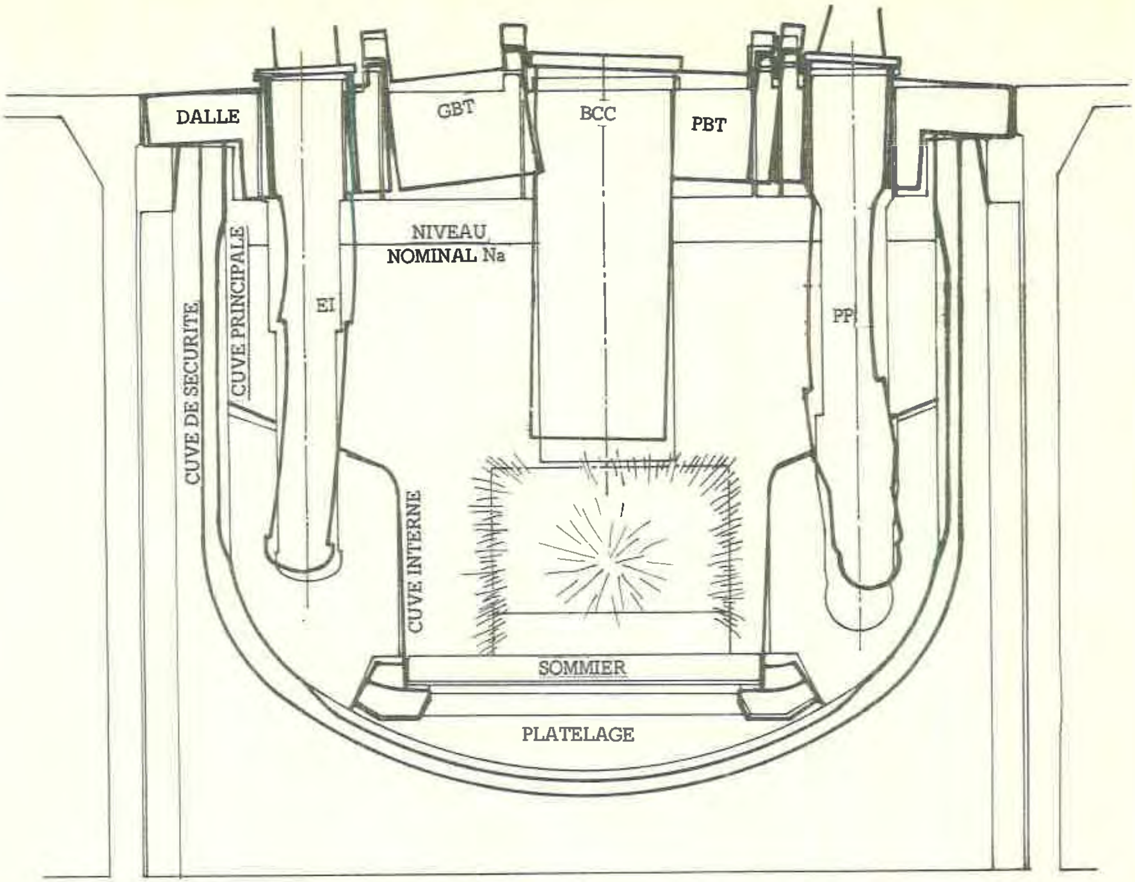
Figure 1 DEFORMATION D'UN BLOC REACTEUR EN CAS D'EXPLOSION : SYSTEME A CUVE SUSPENDUE ET COMPOSANTS INTEGRES



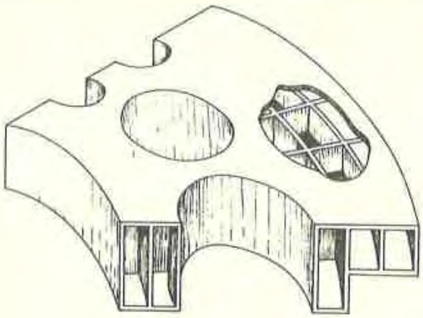


Figure 2

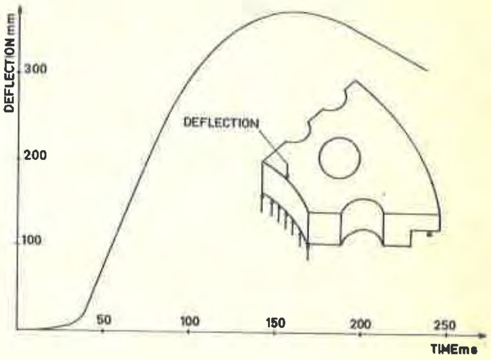
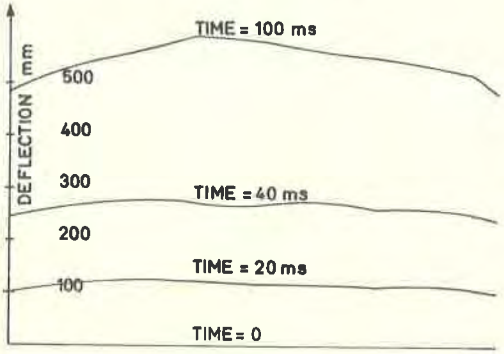


Figure 3



ROTATING-PLUGS

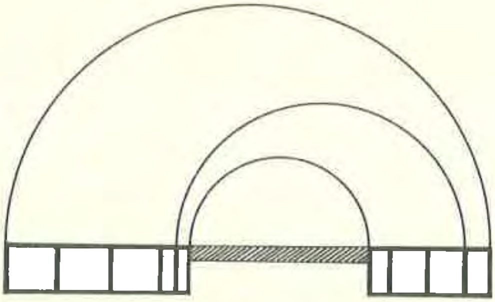


Figure 4

ANNULAR PLATING SUPPORT

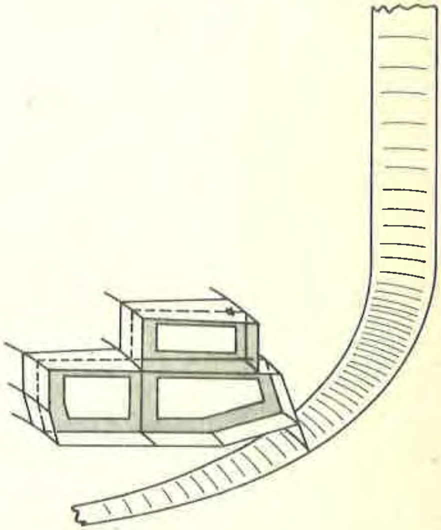


Figure 5

CONTINUOUS PLATING SUPPORT

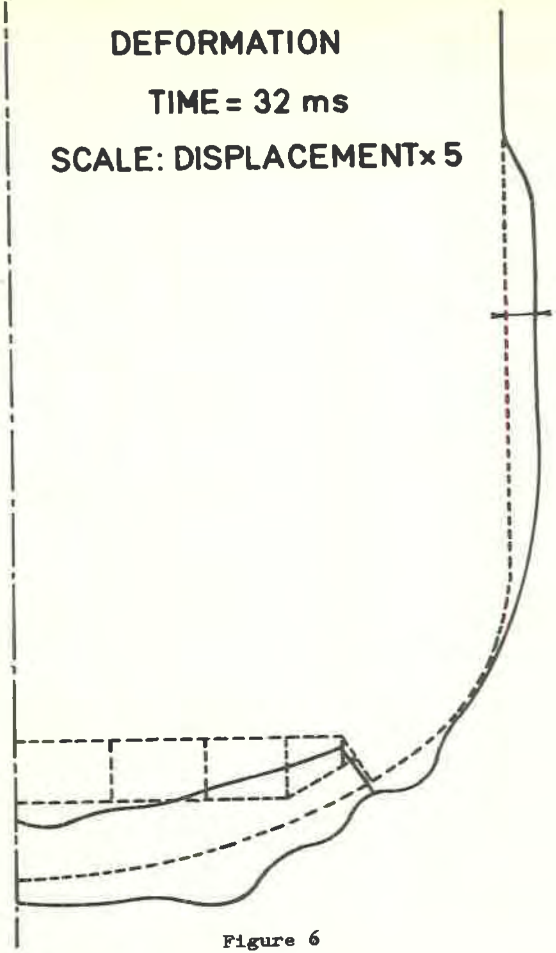


Figure 6

OUTSTANDING COMPONENTS

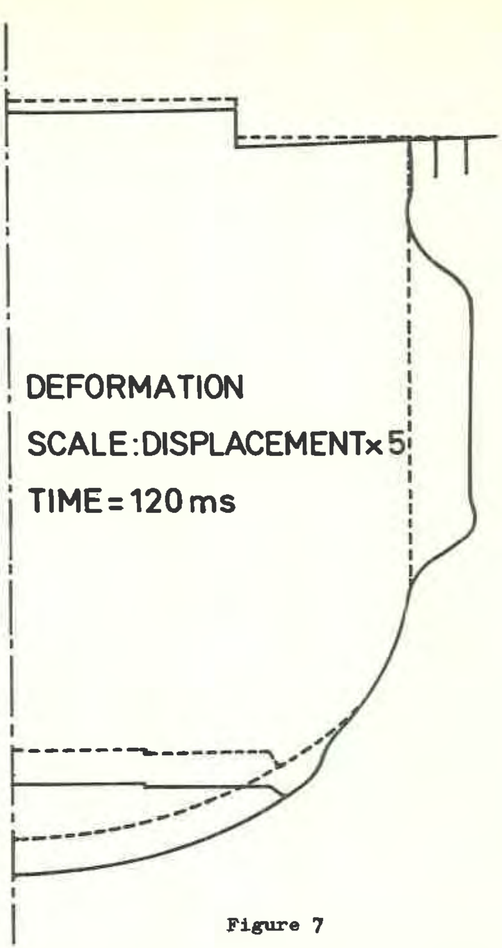


Figure 7

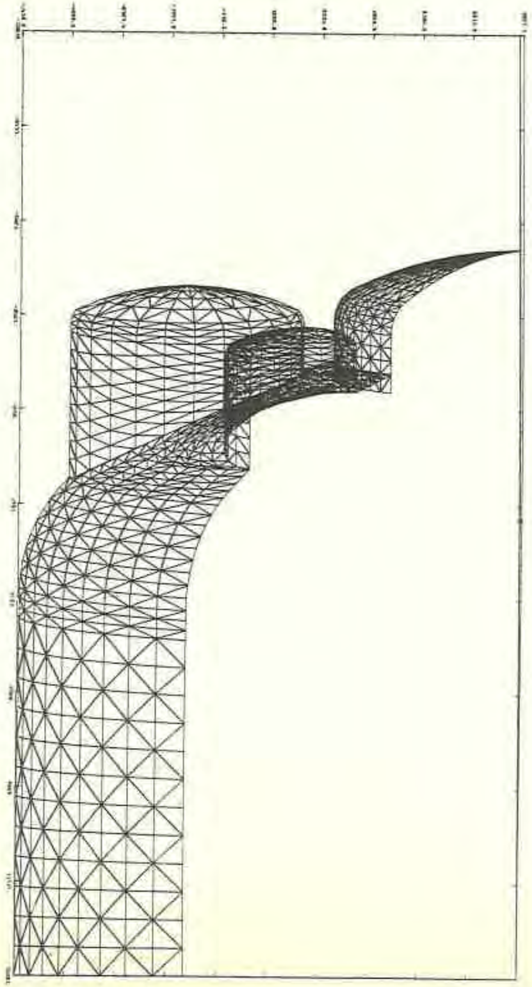


Figure 8

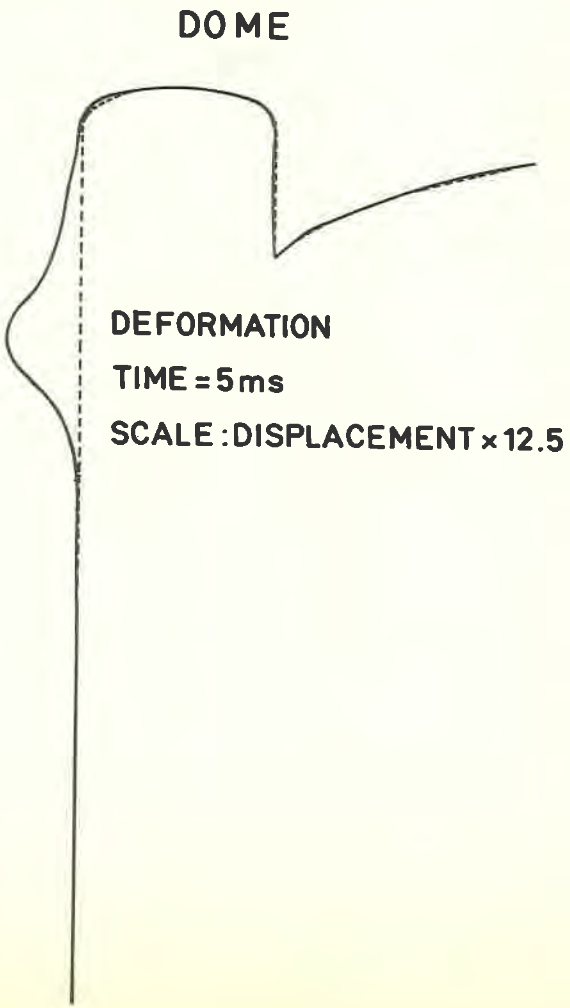
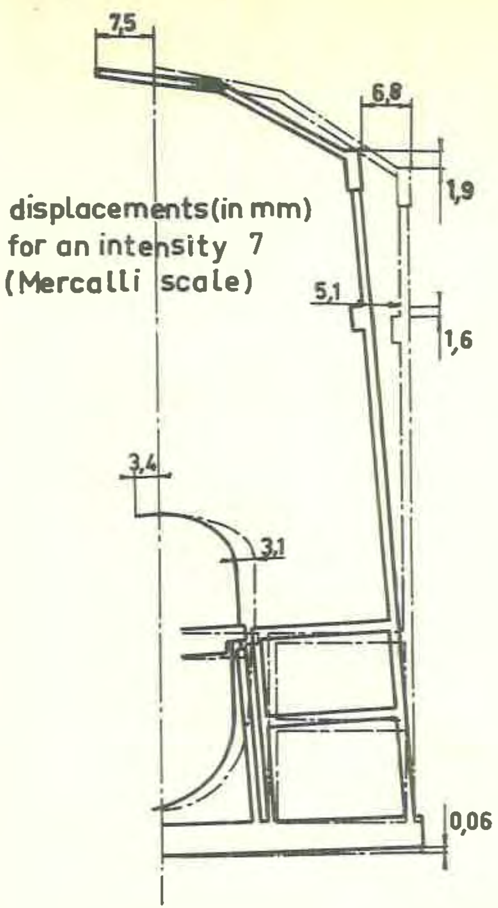
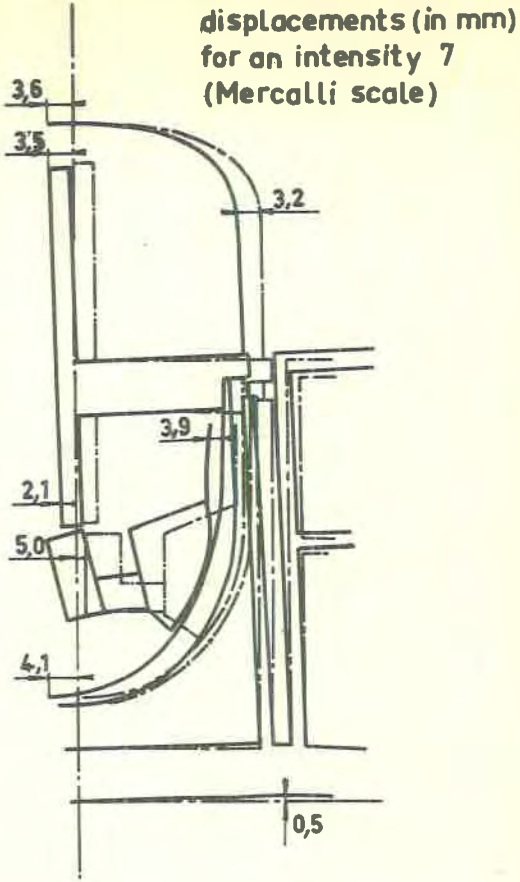


Figure 9



Deformation of the containment

Figure 10



Deformation of the vessel structures

Figure 11