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VALIDATION OF THE CONTAINMENT CODE SIRIUS : INTERPRETATION OF AN EXPLOSION EXPERIMENT ON A SCALE MODEL

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RESUME :

The explicit 2-D axisymmetric Langrangian code SIRIUS, developed at the CEA/DRNR, Cadarache, deals with transient compressive flows in deformable primary tanks with more or less complex internal component geometries. This code has been subjected to a two-year intensive validation program on scale model experiments and a number of improvements have been incorporated. This paper presents a recent calculation of one of these experiments using the SIRIUS code, and the comparison with experimental results shows the encouraging possibilities of this Lagrangian code.

INTRODUCTION

Reactor safety studies consider the propagation and the mechanical effects of a sudden release of energy from the core area, which is distributed in the reactor vessel internal structures and in the upper cover.

The structural integrity of a reactor in this type of accident is demonstrated using mechanics codes which numerically determine the loadings and stresses which occur during this dynamic excursion.

The CEA/DRNR, Cadarache, currently uses the explicit Lagrangian code SIRIUS and the coupled explicit Euler-Lagrange code CASSIOPEE [1]. The possibilities of the SIRIUS code are described in this paper together with the major principles of the experimental program set up at Cadarache (Zesfir area) to validate these codes. This program, which began two years ago, is carried out on Super-Phenix vessel mock-ups according to a step-by-step procedure by which one parameter is modified or added each time. The explosive used is the low-density explosive L 54/16. One of these experiments, MARA 04, is described and the results are compared with those obtained from the calculation using the code SIRIUS : the good estimation of the deformations of the main vessel and its internal structures indicates encouraging possibilities for future calculations.

PRESENTATION OF THE CODE SIRIUS

SIRIUS is a 2-D axisymmetric, Lagrangian hydrodynamic elastoplastic code developed at the CEA Cadarache, France, for fast reactor containment analysis. It was developed from the code HEMP-ESI which has already been described in [2].

The hydrodynamic domain is simulated explicitly according to M.L. WILKINS' finite differences formulation.

The branched shell structures are treated by a finite element technique which is based on the "convected coordinates" concept elaborated by T. BELYTSCHKO and which uses a Lagrangian explicit scheme of resolution. The shells can behave elastoplastically with small strains, large displacements and large rotations. A slide line technique is used for coupling fluid or solid zones which may lie along the shell structures.

A specific overlay has been introduced to provide the program with automatic rezoning capabilities :

- several lines can be deleted in one block at regular time intervals during the problem
- a smooth mesh can be generated within a section of the grid at regular intervals
- special capabilities enable mesh redefinition during the simulation of an HCDA in the Super-Phenix reactor ; the mesh can be redefined adequately around the bubble explosion zone.

Major improvements were made to the SIRIUS code so that thick shells could be dealt with more effectively (e.g. the deformable cover and the diagrid), and to cover the coupling of shells with thick elastoplastic media.

Two different models were developed for the latter point :

- New algorithms were introduced into the first one to calculate internal and external forces on the shells and to take into account the action of forces of rotational or anti-hourglass viscosity of the elasto-plastic or hydrodynamic meshes.
- In the second model, the fluid meshes in contact with the shells were considered to be finite elements in which the shape functions were linear.

INTERPRETATION OF THE MARA 04 TEST WITH SIRIUS

Description of the experimental program

The MARA experimental program, designed to validate the containment code SIRIUS in a Super-Phenix configuration is conducted at the Zesfir zone of the CEA/DRNR, Cadarache. The tests consit of well instrumented firings (at present, 37 measurements per test) designed to supply reliable data on the stresses, deformations and pressures obtained when a known energy source explodes in a scale model vessel partially filled with water.

The tests are conducted in Super-Phenix 1/30 scale models which best reproduce the main features of the full-scale pool-type reactor. However, the geometry had to be simplified to make calculations possible, in particular axisymmetry is imposed. The accident is simulated using a 45 g spherical charge of solid low pressure, low density L 54/16 explosive developed by the CEA-DAM [3]. This explosive was obtained by mixing and heating polystyrene, PETN and powder graphite microballoons is the following proportions by weight : 50.5 % polystyrene ; 49 % PETN ; 0.5 % graphite. After cooling, a solid, porous product with a vacuum factor of 68 % and a density of 0.4 g/cm^3 was obtained.

The energy developed by the explosive charge in the MARA tests is about 40 KJ or at the reactor full-scale a level of 1100 MJ. Approximately 15 firings will be carried out during this validation program with a deformable main vessel and a rigid or deformable roof (fig. 1) : the first test (MARA 01) was conducted using a bare vessel, then the internal structures are introduced one after the other (deformable inner vessel with a conical extension, diagrid, matting, matting support collar), followed by the peripheral components (12 deformable cylinders located on the same circumference), the core cover plug and lateral neutron shieldings. Whenever possible firings are repeated in order to check the validity of the results and correct operation of the charge. Each experiment is interpreted using at least one of the two codes SIRIUS or CASSIOPEE.

Description of the MARA 04 test

The main vessel (figure 2) is a deformable 1.28 mm thick steel cylinder, closed at the top by a rigid flat roof and a curved deformable bottom the thickness of which varies from 1.04 mm near to the cylinder weld to 1.28 mm on the vertical centerline. The total height of the vessel is 551 mm and its inside diameter 703 mm ; the vessel is filled with water, the free surface of which is separated from the roof by a 43 mm air space.

The main vessel contains :

- an inner flanged vessel which is extended at the top by a 0.5 mm thick cylindrical collar flat against the main vessel and just touching the bottom of the roof.
- a matting with its support and a diagrid.

An annular cavity machined under the roof simulates the gaps existing in the cover for a volume of 5000 cm^3 of air contained in these gaps.

Before the firing several meshes were drawn on the deformable structures (main and inner vessels, core diagrid) so that their final mean deformation could be measured and their respective deformation energies inferred. Chronological records of axial and circumferential strains of these structures are given by 11 strain gauges and two ultra-rapid movie cameras which enable the main vessel to be visualized. The pressure values in water are measured by 14 transducers, the wave arrival times by 6 rods and the main vessel load on the cover by 3 deformation rings and 3 strain gauges.

Calculation models

The vessel cover is simulated by a rigid wall. The inner and main vessels and the core diagrid are modelled as shells while the matting is treated as a thick elastoplastic material. The inner vessel vertical extension is simulated by increasing the main vessel thickness by 0.5 mm. The conical portion of the inner vessel is joined to the main vessel by a false shell element which has no strength.

The different material equations of state used in the calculation are :

- for the explosive gases : $P = P_0 \left(\frac{v_0 - \beta}{v - \beta} \right)^{\gamma}$

where : $P_0 = 2.88\ 10^{-3}$ Mbar initial pressure of the explosive

v_o = 112.5 cm^3 initial volume of the charge

γ = 1.535

β = 19.0665 cm^3

- for the water : $P = C_1 \mu$

where : C_1 = 0.0225 Mbar

$$\mu = \frac{\rho}{\rho_o} - 1, \ \rho \text{ density}$$

The tension model for water is a "Pmin - model" in which the water sustains a negative pressure (i.e. the water can support tension). In this calculation the Pmin value was taken to be zero.

- the air space is described by an ideal gas law in the form :

$$P = P_o \left(\frac{v_o + 5000}{v + 5000}\right)^{\gamma} - P_o$$

where : $P_o = 10^{-6}$ Mbar initial pressure

v_o = 16550 cm^3 initial volume

γ = 1.4

5000 cm^3 being the volume of the annular cavity in the cover.

Different static stress-strain relations were introduced to simulate the elastoplastic behaviour of the vessel and internal structures materials. The variation in the thickness of the main vessel bottom and its initial strain-hardening (supposed isotropic) were taken into account.

Comparison between Experiment and Calculation

The calculation was made up to the time t = 5.2 msec. At this moment the solid structures stopped or oscillated around a balancing position.

The automatic mesh rezoning was used six times. Figures 3a and 3b show the aspect of the mesh at the initial and final times of the calculation. Figures 3c and 3d show the effects of the automatic mesh rezoning on the redistribution of the meshes situated above the inner vessel tapered flange.

A chronological list of the major events during calculation is given below :

t = 0	Beginning of calculation ; pressure in the bubble zone is 2.8[illegible] kbars.
t = 1.6 ms	Maximum displacement of the main vessel lower bulge, slightly above the centre of the bubble zone : 0.8 cm.
t = 1.8 ms	Water starts to hit the center of the roof.
t = 2.8 ms	Maximum axial displacement of the bottom of the main vessel : 2.5 cm.
t = 3.6 ms	Maximum air compression : pressure is equal to an absolute value of 7.7 bars and the energy 3.6 KJ. The impact of the water on the roof stops with the closure of the vacuum on the edge of the cover.
t = 4.65 ms	Maximum displacement of the main vessel upper bulge : 1.1 cm.
t = 5.2 ms	End of calculation ; final deformations obtained.

The results of final experiment measurements are compared with the calculation in tables I and II. The main vessel geometrical deformations at the upper and lower bulges are estimated with high precision. However the vertical displacements of the bottom of the main vessel and the structures directly connected to the bottom (diagrid, matting) are underestimated by the code SIRIUS ; but the final diagrid deflection is correctly assessed. The buckling of the sphero-toric section of the bottom of the main vessel and the inner vessel cylindrical shell ring is not allowed for by the code SIRIUS. The other comparisons between predicted and experimental values cover primarily the wave arrival times under the roof and velocities of the "water hammer", the velocity of the initial shock wave in the water, the strain rate of the main vessel bottom, the chronological record of the impact of water on the roof, the deformation time histories of the different structures and the pressure and impulse time histories on the roof. Grid plots are given at regular intervals and the system total energy versus time graph can be used to check the accuracy of the calculation.

CONCLUSION

The CEA/DRNR, Cadarache now has the results of several clean experiments which were purposely designed to validate its containment codes. Among these codes the 2-D Lagrangian code SIRIUS has already given encouraging results and has shown that it can reproduce the main hydrodynamic features, even after the impact of the water on the roof, in case of an HCDA in a Super-Phenix configuration.

The MARA 04 experiment calculation described in this paper predicts quite accurately the final deformations of a vessel with simple inner structures. Some difficulties appeared because of sharp corners in the inner structures but the automatic mesh rezoning was very efficient in this case. There is still room for improvement in the prediction of impulses and strain profiles but considerable progress has been made in calculating the main vessel deformation by taking into account the different thicknesses and the strain hardening of the curved bottom.

The coupled Euler-Lagrange code CASSIOPEE will soon be used to interpret MARA 04 before being used for more complex calculations which are outside the scope of the code SIRIUS.

REFERENCES

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TABLE I
MARA 04 : EXPERIMENT - CALCULATION COMPARISON. DISPLACEMENTS

	SIRIUS CALCULATION	EXPERIMENT
Final displacement of the center of the diagrid (cm)	2.68	3.2
Final diagrid deflection (cm)	1.6	1.6
Final matting displacement (cm)	1.08	1.6
Final axial displacement of the main vessel bottom	$\Delta Z = 1.95$ cm ; $\frac{\Delta Z}{Zo} = 3.5\%$	$\Delta Z = 2.89$ cm ; $\frac{\Delta Z}{Zo} = 5.3\%$
Maximum radial displacements: inner vessel main vessel (at upper bulge)	 $\frac{\Delta\phi}{\phi_o} = 8.3\ \%$ * $\frac{\Delta\phi}{\phi_o} = 3.1\ \%$ ($Z = 6.4$ cm)	 $\frac{\Delta\phi}{\phi_o} = 12.1\ \%$ $\frac{\Delta\phi}{\phi_o} = 3.4\ \%$ ($Z = 5.8$ cm)
Maximum main vessel radial displacement at lower bulge	$\frac{\Delta\phi}{\phi_o} = 1.7\ \%$ ($Z = 20$ cm) $\frac{\Delta\phi}{\phi_o} = 2.3\ \%$ ($Z = 28$ cm)	$\frac{\Delta\phi}{\phi_c} = 1.9\ \%$ ($Z = 20$ cm) $\frac{\Delta\phi}{\phi_o} = 2.7\ \%$ ($Z = 30$ cm)

* This displacement was underestimated by the calculation, the water touching the inner vessel being poorly discerned from 2 ms onwards.

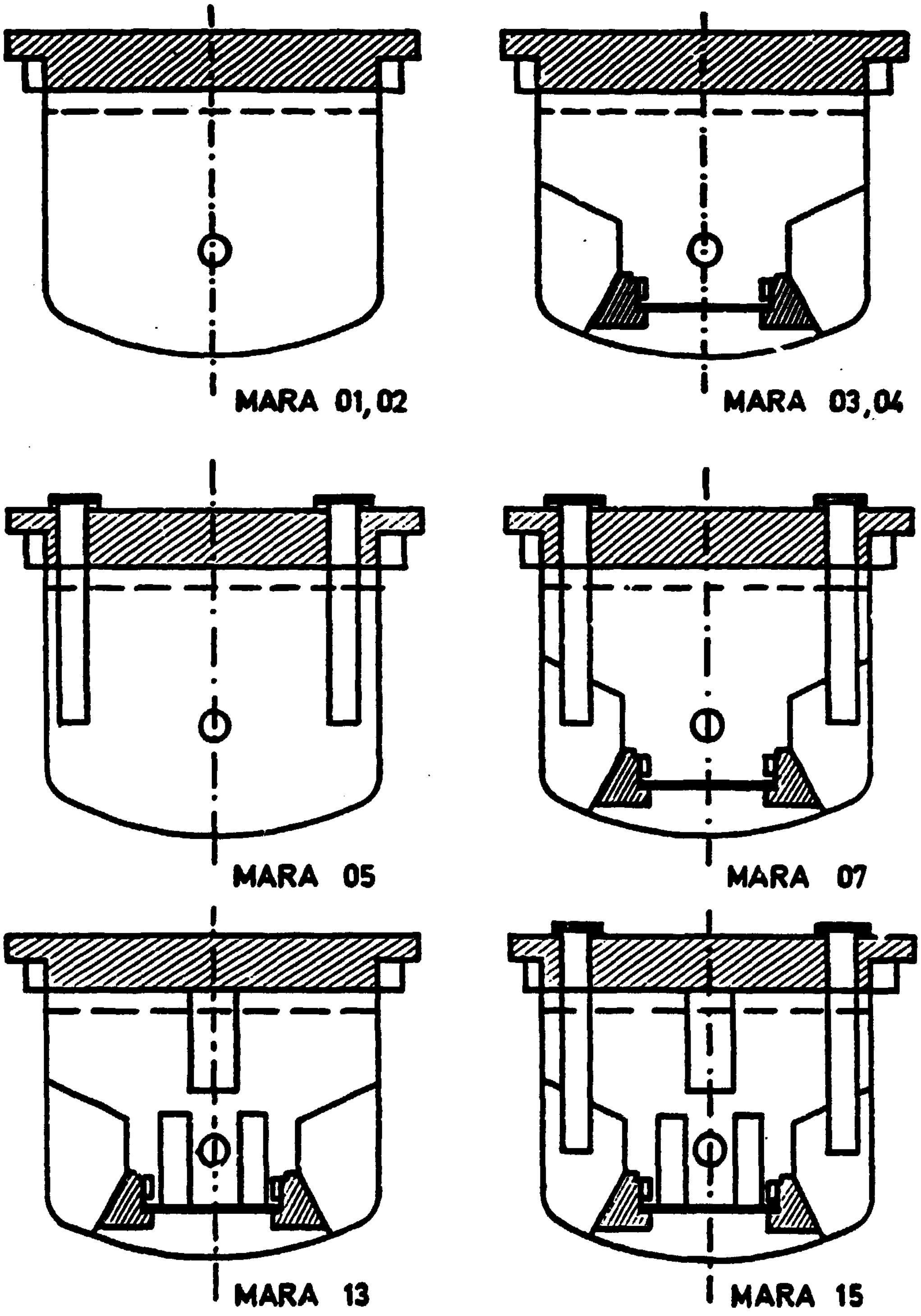
Z : vertical dimension from the point considered (origin is at bottom of the roof)

ϕ : vessel diameter.

TABLE II
MARA 04 : EXPERIMENT - CALCULATION COMPARISON, PRESSURE VALUES AND TIME

	SIRIUS CALCULATION	EXPERIMENT
Combustion gas residual pressure (bars)	1.45 (at 5.2 msec)	1.4 (1 min after test)
Maximum pressure (bars) under the roof on radii 3 cm 14 cm 21 cm 32.5 cm	 330 280 340 400	 417 - 252 * 353 - 243 * 131 - 228 * 177
Displacement stopping time (cm)	5.2	5.4

* The experimental pressure values were given by 2 transducers located on the same radius (the dispersion of these values should be noted).



MARA 01,02 MARA 03,04

MARA 05 MARA 07

MARA 13 MARA 15

FIGURE 1 - MARA MODEL TEST PROGRAMME

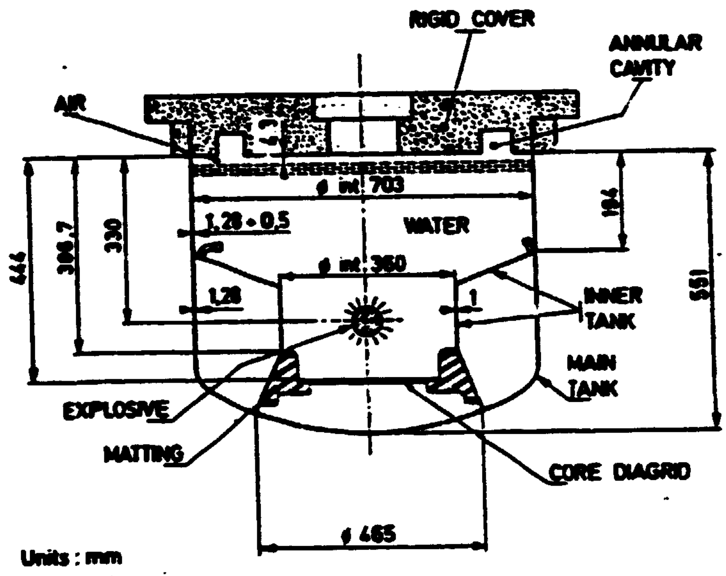
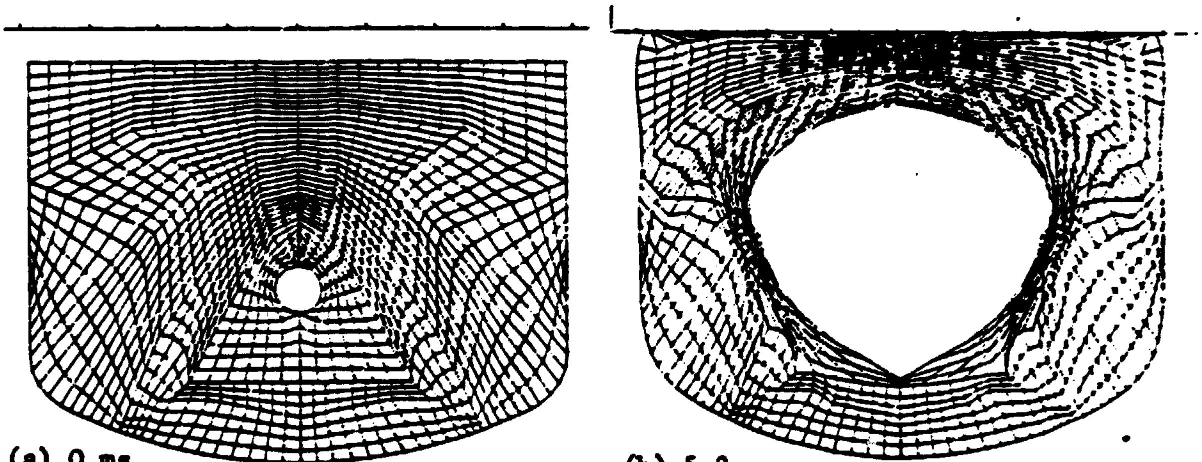
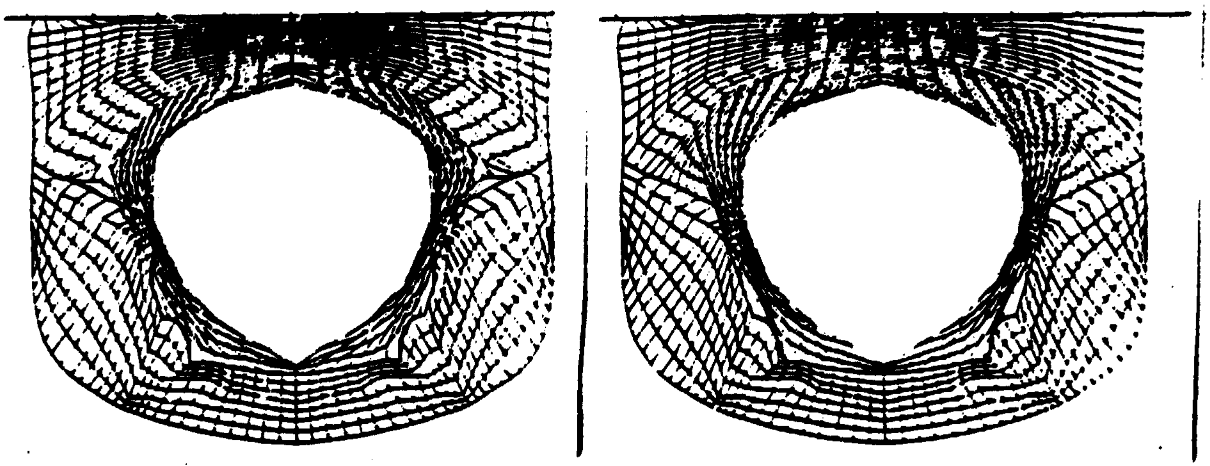


FIGURE 2 - MARA 04 EXPERIMENTAL SET-UP



(a) 0 ms

(b) 5.2 ms



(c) 4 ms : before rezoning

(d) 4 ms : after rezoning

FIGURE 3 - CONFIGURATIONS OF DEFORMED MESHES