1. **INTRODUCTION**

During the past years, a large effort has been devoted to the study of the LMFBR containment response to a core energy release as well as from an experimental point of view as from a theoretical one. In this frame, the CEA-DRP Cadarache has realized the experimental MARA programme in order to develop and validate the containment code SIRIUS.

This programme, based on a scale model (1/30) of the SUPERPHENIX (SPX1) reactor, involves ten tests of gradual complexity due to the addition of internal deformable structures /1/, /2/, /3/, /4/. All tests have been interpreted with the SIRIUS code (2D axisymmetric Lagrangian, explicit, with finite element shells coupled to hydrodynamics) /5/.

In a first part, we attempt to clearly synthesize the most important results of this programme concerning the containment global response to an energy release and to analyze the reliability of the predicted SIRIUS calculations.

In a second part, we try to determine the weak points in the primary reactor containment in case of a core energy release; this part is based on sensitivity studies performed with the SIRIUS code.

2. **SYNTHESIS OF THE MARA RESULTS**

2.1 Experimental point of view

The same explosive charge (45 g of the L54/16 composition low density, low pressure) is used in all tests, leading, at least, to a ~ 1000 MJ full scale energy release.

The main important experimental results observed are :

- An high and rapid increase of the fluid pressure at the free surface when fluid roof impact occurs. The pressure peak reaches ~ 350 bar at the roof center, ~ 250 bar at mid radius and ~ 180 bar at the periphery near the vessel wall.

- The final impulse stays constant over the roof, except in the last MARA experiment (MARA 10 /4/), performed with a tight deformable above core structure (ACS) completely filled with water and consequently transmitting directly loading from the bubble to the roof.

- Due to the same slug momentum, the final roof impulse is not modified using a deformable roof but, it is time-delivered with several successive pressure peaks of decreasing amplitude.

- Due to the ACS, in the MARA 10 experiment, the final impulse is increased in the central roof region.

- Internal deformable structures as internal vessel, diagrid, diagrid support, peripheral components have a protecting effect on the main vessel by energy absorption but do not involve a change on the final roof impulse.
Peripheral components (pumps and heat exchangers) radially protect the main vessel and lightly increase the pressure peak at roof impact, just ahead and behind them, without changing the final impulse across the roof. The picture 1 shows the final roof impulse repartition measured in the MARA serie and leading to an average roof impulse of ~0.2 MPa.s full scale.

2.2 Theoretical point of view

The interpretations of these experiments, performed with the SIRIUS computer code (and also with other codes using different physical modelisations and numerical methods particularly as SEURBNK/EURDYN) have shown a general good agreement as well as on the global containment response as on the chronological event description. In particular, the different roof impulse time histories successively obtained in case of a rigid or of a flexible roof (and taking into account the ACS or not) are well predicted.

The most important difficulties encountered, have been related to the knowledge of reliable material properties and boundary conditions. In particular the very important coupling, due to the fluid roof impact, between the roof motion and the radial main vessel displacement at the upper part, requires to introduce in the code the realistic material strain-stress relationship; it needs also a firm experimental set-up for the realization of the roof-vessel connection (clamping, sliding, pinning).

The whole experimental-theoretical comparison (strains, displacements, roof impulses) through the entire MARA serie allows to estimate a ~25% accuracy of the predicted SIRIUS results, taking into account the material data uncertainties (which are important in case of the flexible roof).

It has to be noticed that the strain energy absorbed by the deformable structures represents the ~70% of the total bubble energy. The available part of energy absorbed in the containment upper part (roof and upper part of the main vessel) is shared out between the flexible roof and the upper vessel bulge or entirely absorbed in the upper bulge in case of a rigid roof.

3. Sensitivity studies and full scale transposition

A sensitivity study to basis parameters, performed using the SIRIUS code on a reduced scale (1/60 SPX1), simplified geometry (see Fig. 2), has shown that the global containment response (main vessel and roof) is greatly dependant not only on the total energy release but on the bubble p(v) relationship. In particular roof impulse and roof displacement are enhanced in case of a "slow" p(v) curve issued from a fuel-sodium interaction compared to results obtained in case of a "fast" energy release issued from an explosive charge (see table 1).

Material properties have also a great influence, as it has been noticed in the previous paragraph, on containment displacements and on the energy distribution between vessel bottom, upper bulge and roof.

Fluid equation of state and fluid detachment from the roof after impact are weak parameters.

The direct transposition of the MARA results to reactor scale is not easy mainly due to, firstly, the explosive charge (not conservative effect) and secondly to dissipative effects (conservative effect) around the bubble (turbulent flow through porous structures) which are not simulated neither in MARA experiments nor in SIRIUS calculations such as:
- fluid radial turbulence through the 3D neutronic lateral shielding (replaced by a cylindrical internal vessel in MARA 10)
- fluid which can axially flow through the bottom perforated plate of the ACS and radially splash out of the ACS at the free surface level (the ACS is completely tight in the MARA 10 experiment)

These dissipative effects seem to be important as it has been observed in the MARS experiment /6/ (complete simulation 1/20 scale of the SUPERPHENIX containment response to a 800 MJ HCDA) where vessel and roof displacements are respectively reduced by 25% and 70% with respect to equivalent results issued
from the SIRIUS calculation of the SUPERPHENIX containment response to a 800 MJ energy release.

4. REACTOR ESTIMATIONS

Recent improvements in the study of the basis hypothetical accident (loss of flow without scram) lead to consider a lower core energy release (~ 200 MJ). So the containment response to different bubble energy levels is studied using the SIRIUS code on a simplified SUPERPHENIX geometry type (bare vessel, fixed roof).

The bubble laws are shown in picture 3.

Roof impact always occurs except in the case of a 50 MJ energy release.

If the total sodium kinetic energy is linearly dependent on the total bubble energy, it is not the same for strain energy (absorbed by the main vessel) and final roof impulse (see fig. 4). In case of a 80% energy decreasing (800 → 150), the roof impulse and the vessel strain energy are successively reduced by 40% and 85%.

For economic reasons the future European LMFBR projects (French SPX2 /7/ 1500 MW, European EFR 1500 MW) consider in the global design a reduced main vessel diameter compared to the SXPL one. For a same total available bubble energy (150 MJ for a bubble expansion up to 400 m²), the diameter reduction involves a vessel displacement decrease and a final roof impulse increase. The table 2 summarizes the calculated results.

So, the roof slab represents the weakest point of the containment response as soon as roof impact occurs even if a low energy release is considered.

In addition, when roof impact occurs, the behaviour of the roof lower plate (this thin flexible plate, spaced from the massive roof structure, allows the roof gas cooling in new projects) has to be considered; due to its high own frequency, the bottom thin plate is greatly depending on the pressure peaks resulting of fluid roof impact /7/.

The realistic modelisation of the global roof and its support - material properties and boundary conditions, as we have seen in paragraph 2 - is required to estimate the global roof slab deflection and the supporting collar behaviour with sufficient accuracy.

In the case of a 150 MJ energy release, SIRIUS calculations have been performed in a SPX2 geometry without internal structures; these calculations take into account the gravity loading and the modelisation of the whole primary containment support : supporting collar, secondary containment with an antiseismic device at its base (Fig. 5).

Changing the roof modelisation - rotating plugs, roof slab, joining collars, added masses (ACS, components) or equivalent homogeneous plate with added masses - or changing the boundary conditions at plugs and slab joining (clamping or pinning), there is at least a factor of 2 on the roof slab deflection as it is reported in table 3.

Due to the antiseismic device (modelised in the code by an elastic shell with viscous damping), these calculations show an important axial movement of the whole containment.

5. CONCLUSIONS

The weakest part of the containment is the roof slab. This is enhanced by the fact that fluid roof impact takes place as soon as a 100 MJ core energy is released. It is necessary to modelise with realistic conditions the whole roof and its global support in order to correctly estimate the roof slab deflection and its consequences, such as the sodium leakage through the roof penetrations and the buckling risk of the supporting collar.

It has to be noticed that the roof behaviour calculated by a code such as SIRIUS (no viscous fluid, no treatment of a turbulent flow through porous structures, no shell buckling model) is pessimistic. The future trends will be mainly related on the study of dissipative effects around the bubble in order to reduce the roof impact loading.
REFERENCES

1. D. ACKER, A. BENUZZI, A. YERKESS, J. LOUVET
"MARA 01-02 : Experimental validation of the SEURBNUK and SIRIUS containment codes" - SMIRT 6th - E 3/6 - Paris 1981
2. B.L. SMITH, C. FICHE, J. LOUVET, A. ZUCCHINI
"A code comparison exercise based on the LMFBR containment experiment MARA 04" - SMIRT 8th - E 4/7 - Bruxelles 1984
3. C. FICHE, J. LOUVET, B.L. SMITH, A. ZUCCHINI
"Theoretical experimental study of flexible roof effects in an HCDA's simulation" - SMIRT 8th - E 4/5 - Bruxelles 1985
4. J. LOUVET, P. HAMON, B.L. SMITH, A. ZUCCHINI
"MARA 10 : An integral model experiment in support of LMFBR containment analysis" - SMIRT 9th - E 6/9 - Lausanne 1987
5. Y. BLANCHET, P. OBRY, J. LOUVET
"Treatment of fluid structure interaction with the SIRIUS computer code" SMIRT 6th - B 8/8 - Paris 1981
6. M. FALGAYRETTES et al.
"Response of a 1/20 scale mock-up of the SUPERPHENIX breeder reactor to an HCDA loading simulation" - SMIRT 7th E 4/1 - Chicago 1983
7. C. BOUR, M. SPERANDIO, J. LOUVET, C. RIEG
"LMFBR's core disruptive accident. Mechanical study of the reactor block" SMIRT 10th Division E - Anaheim 1999

MARA PROGRAMME

FINAL ROOF IMPULSES VERSUS THE DISTANCE FROM AXIS

![Diagram showing final roof impulses versus distance from axis with axis labels and numerical values.]
INITIAL SIRIUS MESH WITH THE WHOLE ROOF MODELISATION AND REACTOR SUPPORT

VESSEL DIAMETER EFFECT IN CASE OF A 150 MJ (to 400m³ expansion) CORE ENERGY RELEASE IN A SIMPLIFIED REACTOR GEOMETRY

<table>
<thead>
<tr>
<th>Parameter</th>
<th>SPx1</th>
<th>SPx2 &quot;reference&quot;</th>
<th>EFR</th>
</tr>
</thead>
<tbody>
<tr>
<td>main vessel diameter</td>
<td>+5%</td>
<td>20m</td>
<td>-15%</td>
</tr>
<tr>
<td>bubble energy</td>
<td>+0.7%</td>
<td>144MJ</td>
<td>-14%</td>
</tr>
<tr>
<td>final roof impulse</td>
<td>-6.6%</td>
<td>0.9bar.s</td>
<td>+21%</td>
</tr>
<tr>
<td>vessel strain energy</td>
<td>-13%</td>
<td>68MJ</td>
<td>-13.7%</td>
</tr>
<tr>
<td>axial maximum vessel</td>
<td>-12%</td>
<td>0.25m</td>
<td>-78%</td>
</tr>
<tr>
<td>displacement</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>radial maximum vessel</td>
<td>+15.5%</td>
<td>0.45m</td>
<td>-20%</td>
</tr>
<tr>
<td>displacement</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

FIGURE 5

TABLE 2

ROOF SLAB BEHAVIOUR IN CASE OF A 150MJ (to a 400m³ bubble expansion) RELEASE SIRIUS CALCULATIONS IN A SIMPLIFIED SPx2 GEOMETRY (without internals)

<table>
<thead>
<tr>
<th>Roof modelisation</th>
<th>Roof slab deflection (maximum) cm</th>
<th>Roof strain energy MJ</th>
<th>Roof impulse bar.s</th>
</tr>
</thead>
<tbody>
<tr>
<td>rotating plugs, collars and roof slab</td>
<td>3.6</td>
<td>5.0</td>
<td>0.89</td>
</tr>
<tr>
<td>clamping at plug-slab joining &quot;reference&quot;</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>rotating plugs, collars and roof slab</td>
<td>8.6</td>
<td>8.5</td>
<td>0.9</td>
</tr>
<tr>
<td>pinning at plug-slab joining</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>equivalent roof plate</td>
<td>7.3</td>
<td>4.9</td>
<td>0.88</td>
</tr>
</tbody>
</table>

TABLE 3

310