Summary:

In support of the safety analysis related to the reference Hypothetical Core Disruptive Accident (HCDA) of the CREYS-MALVILLE reactor, we have performed a scale model experiment to test the integrity of the containment (main vessel and reactor cover) and to provide information on the behaviour of major components and internal structures during the accident. The effects of the energy release on the containment and the emergency decay heat removal exchangers are of particular interest.

This method, which is complementary to the code development and validation approach, allows to check the modelling techniques used in the two-dimensional axisymmetric codes. Furthermore, the behaviour of the complex internal structures and their overall effect on the reactor response can thus be estimated.

The choice of the materials and the determination of the various thicknesses of the mock-up components have been performed so as to obtain the same deformations as those of the reactor (after scale factor correction). The differences in temperature and strain rate between the reactor and the mock-up have been taken into account and the gravity contribution was not scaled.

This leads to a 1/20 scale mock-up of the main vessel (~ 1 m diameter) including all the significant internal components of the reactor. The main and inner vessels, baffles, lateral neutron shielding, main components, emergency heat exchangers, core cover plug, core catcher, core and the different joining and supporting rings are mainly made of steel while the roof slab, rotating plugs, core support structure and diagrid support are made of aluminium.

The sodium coolant is simulated by water at 20°C and the HCDA load is generated by the expansion of the detonation products of a low density explosive placed in the core; this explosive produces an energy release equivalent to 800 MJ at the reactor scale.

The mock-up is equipped with instrumentation allowing the following measurements: displacements and strains of the main vessel, displacements of the reactor cover (the roof slab and the 3 plugs), accelerations and pressures under this structure and strains of the different joining and supporting rings of the reactor cover. These data were recorded by strain gages, accelerometers, piezoelectric transducers and 3 high speed cameras.

Observations made after the test indicate no water leak of the mock-up cover, a maximum roof slab displacement of the order of 1 cm and low permanent plastic strains of the main vessel (1 and 2 % for the bottom and upper bulge regions, respectively).

The maximum deformations concern, as expected, the structures located in the vicinity of the explosive: core cover plug, core, lateral neutron shielding and diagrid support. For the remaining components, one can note a limited buckling of the inner vessels and of the peripheral part of the core catcher support structure. Nevertheless, the core catcher plate remains practically undeformed and its horizontality has been preserved. No plastic deformations occurred on primary pumps, nor on intermediate heat exchangers nor on emergency decay heat removal systems.
1 - Introduction

The mechanical consequences of the refence HCDA of the CREYS-MALVILLE plant are essentially investigated on one hand with global calculations, using 2D hydrodynamic codes and with specific calculations and on the other hand with a purely experimental method; these two approaches are complementary.

The construction of a scaled model, loaded with a suitable explosive charge, was decided to provide general information on the behaviour of the main reactor structures during the accident (MARS experiment). Three special objectives conditioning the radioactivity released at short-time (containment integrity) and at medium-time (emergency heat exchangers and core catcher integrities) are obviously of prime interest. This paper summarizes the approach used in the MARS programme and the main features of the results obtained.

2 - Generalities on the simulation

The well-known principles of dimensional analysis have been frequently applied to the definition of scaled models /1/ more or less sophisticated to demonstrate that reactors can withstand HCDA loads, for example for licencing the Clinch River Breeder Reactor /2-3/.

2.1 - Scaling laws

Considering mass, length and time as the three basic quantities and according to scaling laws, the usual variables involved in the similitude are modified as indicated in the following table.

<table>
<thead>
<tr>
<th>PHYSICAL QUANTITY</th>
<th>MOCK-UP TO REACTOR RATIO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strain, stress, pressure, velocity, density</td>
<td>1</td>
</tr>
<tr>
<td>Acceleration, strain-rate</td>
<td>1/a</td>
</tr>
<tr>
<td>Length, time, impulse</td>
<td>a</td>
</tr>
<tr>
<td>Surface, force</td>
<td>a^2</td>
</tr>
<tr>
<td>Volume, energy, momentum</td>
<td>a^3</td>
</tr>
</tbody>
</table>

2.2 - Scale of the model

The scale factor must be a compromise between the requirements of cost, components handling, experimental area facilities (which tend to reduce the scale factor) and structural detail modelling and instrumentation (which limit the minimum size of the mock-up). The 1/20 scale factor adopted corresponds to a one meter diameter main vessel.

2.3 - Main keys of the mock-up definition

The type of simulation adopted for each component depends essentially on the relative importance of the component in the reactor and on its foreseeable behaviour during the test. The simulation was so designed as to reproduce the deformations and displacements (containment structures, safety-involved components, supporting struc-
tures), deformation energies (mainly thin structures) and critical buckling forces (core support structure, core catcher flanges, joining and supporting rings).

The main simulated quantities are as follows:

i) overall dimensions, masses and inertia
ii) structure stiffnesses, depending on their expected deformation types
iii) cross-sectional area of fluid flow for internal structures located in the vicinity of the core (lateral neutron shielding and core cover plug).

The temperature effects on the reactor material properties and the strain-rate induced hardening on the steel of the different vessels of the mock-up have been taken into account.

The parameters which can be varied to ensure simulation are the material selection, structure thicknesses and additional masses.

3 - Approach adopted

3.1 - Thin structures (shells)

Type 304 L stainless steel is generally chosen for its interesting mechanical and welding properties to simulate the austenitic steel reactor structures.

The principle of the method consists in conserving between the reactor and the mock-up for each structure region the same strain and strain energy. The shell thicknesses $e_M$ of the model are thus obtained according to the following formula:

$$e_M = e_R \cdot SF \cdot C$$

(1)

where $e_R$ are the corresponding reactor thicknesses, SF the scale factor and C a correcting factor taking into account the differences between the mechanical properties of the steels of the reactor under the accidental conditions and of the model in the test. This coefficient, equal to:

$$C = \frac{\sigma_R(\theta, \varepsilon)}{\sigma (\theta = 20^\circ, \varepsilon)} \cdot SRF (\varepsilon, \ddot{\varepsilon})$$

(2)

is the ratio of the stresses, for the same strain $\varepsilon$, given by the two stress-strain curves of the steels. SRF is the strain-rate hardening factor of the mock-up steel depending on the strain $\varepsilon$ and on the strain-rate $\ddot{\varepsilon}$ by the formula:

$$SRF = 1 + \left[ \frac{\varepsilon}{k(\varepsilon)} \right]$$

(3)

$k(\varepsilon)$ and $n(\varepsilon)$ are two adjustable coefficients obtained by fitting the above formula to dynamic tensile test data derived from tests performed on 304 L stainless steel specimens in the range $\varepsilon = 10^{-4}$ to $300 \text{ s}^{-1}$.

For the main vessel, calculated maximum strains of the cylindrical and bottom parts are respectively 5 and 3 % and the strain-rate is of the order of $15 \text{ s}^{-1}$; this leads to two C coefficients equal to 0.7 and 0.6. For the internal structures, a conservative C factor of 0.5 is used.

3.2 - Thick structures

Massive structures of complex geometries and those made of heterogeneous materials are simulated by equivalent models using a suitable material. This approach has been retained for the following components: roof slab, rotating plugs, core support structure and diagrid support.
The static rigidity of the roof slab was determined using a 3-dimensional code, integrating the influences of the component penetrations and of the concrete. The mock-up roof slab was then defined on the basis of parametric studies, providing data which could be used to reproduce these properties by determining a suitable couple geometry (mainly thickness, as the other dimensions are fixed) -material stress-strain curve. The couple thus defined corresponds to a virtual geometrical similitude between mock-up and reactor covers. The properties of the corresponding material, which are characterized by low young's modulus and yield strength, led us to select A5 aluminium.

A similar approach was used for the core support structure and the diagrid support. In this case, the use of A5 aluminium was imposed, so that the only parameters which had to be determined were the geometrical characteristics. For these two components, similitude in thickness between the reactor and mock-up versions is not perfect.

3.3 - Fluids

Sodium coolant at operating temperature is simulated by water at 20°C. Despite the fact that densities and sound velocities are somewhat different, indicating that pressures and impulses cannot both be exactly simulated, calculations using the two fluids indicate that the corresponding structure responses are very close.

Cover gas of the mock-up is the same as in the reactor (argon).

3.4 - Loading

The applied loads consist in simulating the total mechanical energy release of the reference SUPER-PHENIX HCCA equal to 800 MJ. This is done by using a low density explosive /4/, known to limit the detonation pressures, introduced in the core region.

The pressure-volume change relationship is described by the following law:

\[ p(V-B) = \text{constant} \]

de pending on the two adjustable \( B \) and \( \gamma \) parameters. The total mechanical energy transmitted by the charge to the structures is thus determined in simple and easily calculable calibration tests. Using the hydrodynamic code CASSIOPPE and dynamic steel material properties, it is possible to fit the calculated strains to experimental ones so as to obtain the two parameters defined above. This permits to obtain a potential mechanical energy equal to 1.3 KJ/g of explosive; consequently, a charge mass of about 80 g was chosen to simulate the 800 MJ mechanical energy release during the accident.

3.5 - Limitations of model tests

An exact simulation of all the phenomena involved in the accident is obviously not possible. For example, the gravity forces are 20 times smaller in the model that in the reactor; this means that some vertical movements could be notably altered. Uncertainties in material properties, due to temperature and strain-rate hardening effects and cold-working due to manufacture of thin structures have to be considered. Thickness reduction of structures to below \( \sim 1 \) mm could induce also weld embrittlement which must be carefully analyzed.

In addition, one must mention, as pointed out in /5/, the limitations introduced by cavitation of cooling fluid, transient pressure drops of fluid flow through complicated geometries and the use of an explosive source. All these phenomena complicate the test result interpretation.
4 - Description of the mock-up

The mock-up includes all the significant structures and components of the reactor (Fig. 1) which are briefly described hereafter.

4.1 Thin structures

The main vessel, of variable thickness (0.8 to 1.6 mm), is an assembly of a cylindrical part and of a two part torospherical bottom. The two inner vessels are modelled, together with the anti-convecting device and the main vessel cooling system.

The core cover plug is a rather complicated structure; despite the necessary oversimplifications, the model includes the top plate, the in-pile shell with its pipes, the spacer plates and the heat-insulation. For the core catcher, we have modelled the catcher plate, support structure, vertical flanges, chimney and spacing feet.

The lateral neutron shielding is represented by four radially split shells and their supporting structures. The mass of the unmelted part of the core is simulated by a mixing of aluminium cylinders and steel hexagons fixed into two AG3 aluminium plates.

The main components inserted through the roof slab are modelled: 4 primary pumps, 8 intermediate heat exchangers, 4 emergency cooling exchangers and 2 integrated purification devices (aligned on the same radius). The various supporting rings (roof slab, core support structure, large components) and joining rings (between the roof slab and the rotating plugs) were properly scaled using the same steel as in the reactor (black or stainless steel types).

4.2 Thick structures

They are represented on Fig. 1 by shaded areas and are simulated by aluminium equivalent massive models. One can distinguish the roof slab, constituted by two circular plates of different thicknesses to simulate the roof stiffness. Openings are drilled to permit the passage of the large components and the two rotating plugs are concentrically off centre as in the reactor.

The core support structure and the diagrid support are represented by a non-axisymmetric ring and a cylinder, respectively. The diagrid, the stiffness of which is negligible with respect to that of the diagrid support, is not represented.

The mass deficit of the mock-up cover simulation is compensated by lead plates providing additional weights on the cover.

4.3 Other simulations

The safety vessel, which would mask the primary vessel movements, is represented only by its inertia using lead plates, likewise the dome, the biological shield plates and the handling machine (see Fig. 1). Rubber-ring bands simulate the heat-insulating material between the roof and the main vessel and permit representation of the gas intervals of the roof slab.

Fig. 2 and 3 present selected views corresponding to two steps of the mounting phase of the mock-up.

5 - Instrumentation

Extensive instrumentation is placed on the mock-up. Details on the dynamic data acquisition concerning pressures, accelerations, strains and displacements are summarized in table 2.
### Table 2
Summary of the mock-up instrumentation

<table>
<thead>
<tr>
<th>INSTRUMENTATION DEVICE</th>
<th>NUMBER</th>
<th>CONCERNED COMPONENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure transducers</td>
<td>19</td>
<td>Roof slab and rotating plugs</td>
</tr>
<tr>
<td>Accelerometers</td>
<td>5</td>
<td>Reactor cover</td>
</tr>
<tr>
<td>Strain gages</td>
<td>24</td>
<td>Main vessel, roof slab support ring, cover joining rings</td>
</tr>
<tr>
<td>High speed cameras (6000 to 8000 pictures/s)</td>
<td>3</td>
<td>• Main vessel</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Roof slab and large plug</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Small plug and core cover plug</td>
</tr>
</tbody>
</table>

Precise locations of strain gages are depicted Fig. 4.

Internal structures are not instrumented but the initial positioning of some structures is carefully noted in view to compare with the final configuration. In addition, it is planned to measure permanent strains using grids drawn on these structures.

6 - Results

6.1 - Dismantling of the mock-up and general observations

Overviews of the main vessel and mock-up cover after firing are presented in Fig. 5 and 6, respectively. The disassembly of the model was done without any great difficulties; this is due to the fact the deformations of most of the components are relatively small. No leak is observed neither on the reactor cover nor on the main vessel which has the characteristic after firing shape. First data examination indicates that the maximum deformations of the reactor cover and of the main vessel were reached at a time less or equal to 15 ms but oscillations occurred for at least 50 ms.

6.2 - Containment response

6.2.1 - Main vessel

The maximum displacement of the pole of the bottom part is equal to 14 mm as given by the camera measurements (Fig. 7); the corresponding strain is of the order of 1%. The upper bulge has a relatively large spread but a small amplitude as indicated by the maximum and residual diameter increases equal to 2.4 and 1.8 %, respectively (Fig. 8).

These data are 4 to 5 times smaller than the corresponding results obtained in a preliminary experiment performed in the same -but bare- vessel, underlying the major role played by internal structures in the energy partitioning and absorption.

6.2.2 - Cover

The displacements as a function of time of the head of the roof slab and of the core cover plug are shown on Fig. 9. The corresponding displacements of the large and small rotating plugs (not shown) are intermediate between these two curves. Mean maximum and residual values are respectively of the order of 6 and 3 mm and differential movements between different components are of small amplitude. No plastic deformations occurred on the different joining rings; typical strains histories are displayed on Fig. 10. The roof slab support ring also remains in the elastic region, the maximum
strain being equal to 0.04 %. No deformations are observed on components bolted on the cover head.

The mean spike pressure values as a function of the cover radius range from 250 bars (small plug) to 100 bars (roof slab). Two typical recorded pressure curves are shown in Fig. 11. Impulses communicated to the cover by the fluids at ~ 15 ms are found to be nearly independent of the radius and equal to 0.05 bars on an average; the corresponding value measured in the preliminary experiment mentioned above was two times higher.

6.3 - Safety components

An important result of this experiment concerns the behavior of the core catcher during the accident simulation. The core catcher support structure presents locally a buckling due to the eccentric position of the loading with respect to the structure. The two concentric cylinders constituting the chimney have been deformed in their upper regions by the fluid pressure transmitted by the diagrid support. Nevertheless, the catcher plate remains practically undeformed and its horizontality has been preserved.

The four emergency decay heat removal systems do not present any visible deformation.

6.4 - Other internal structures

The in-pile section of the core cover plug has undergone very extensive deformation (Fig. 12). The lower grid has moved ~ 10 cm upwards under the loading which compresses the columns and causes a pronounced buckling of the structure which cannot be separated from the small rotating plug. One should emphasize that this component plays a major role in the limitation of HCDA mechanical consequence propagation; in particular, it protects the reactor cover by elastoplastic energy absorption and turbulent fluid flow generation.

The core is open to become conical in shape but all the subassemblies remained in place and kept their straight form (Fig. 13). The different rows of the lateral shielding structures lean on each other and some failures are observed in the vicinity of welding areas.

The two inner vessel post-test shape profiles show significant vertical and radial buckling but without any failure (Fig. 13); for the upper one, the 13 buckling mode is directly related to the number of large components passing through the roof (excepted for the emergency decay heat removal systems which are masked by the intermediate heat exchangers).

The core diagrid support has a regular deformed shape and a relatively large deflection. We observed that the core support structure has rotated non-uniformly towards the bottom of the main vessel by 1 to 1.5 degree.

The large components, pumps and intermediate heat exchangers, present no appearance deformations.

7 - Conclusions

Bearing in mind the limitations involved in the simulation, interesting conclusions can be drawn from the MARS experiment on the general behavior of the reactor structures consecutively to the reference CREYS-MALVILLE HCDA.
The deformation level of the containment structures — main vessel and upper closing structures — is relatively low due to the presence of internal structures which play the role of dash-pots because of the creation of three phenomena: elastoplastic energy absorption, turbulent fluid flow generation, degrading the energy and shadow effects protecting efficiently some structures.

The safety components, emergency heat exchangers and core catcher are demonstrated to be almost intact after the accident and so able to remove the decay heat and to catch the core debris.

References


Fig. 1: Schematic view of the mock-up installed on the experimental rig.
Fig. 2: Overview of the mock-up during the mounting phase. One distinguishes more particularly the core catcher, core support structure, anti-convecting device and the upper inner vessel. The roof slab and some supporting and joining rings are also visible.

Fig. 3: Next step of the mounting phase. The diagrid support, core, lateral neutron shielding and roof slab hanging components have been introduced.

Fig. 4: Strain gage locations on the main vessel and cover rings.

Fig. 5: Main vessel general view after test.

Fig. 6: Overview of the mock-up cover after firing; an intermediate heat exchanger have been removed.

Fig. 7: Displacement histories of two points of the main vessel spherical bottom.
Fig. 8: Radial displacement of the main vessel upper bulge.

Fig. 9: Example of measured displacement of the mock-up cover.

Fig. 10: Typical cover joining ring strain histories recorded during the test; C and D refer to strain gage locations indicated in Fig. 4.

Fig. 11: Selected pressure histories recorded on the mock-up cover.

Fig. 12: General view of the small rotating plug and of the core cover plug (unseparated) after test.

Fig. 13: Post-test view of the mock-up internal structures after cover removal.