EXPERIMENTAL ANALYSIS ON P.E.C. REACTOR CONTAINMENT
BY 1:10 MOCK-UPS WITH DIFFERENT CHEMICAL EXPLOSIVES

R. CENERINI, S. CURIONI, G. MILLIONI, G. VERZELLETTI

Istituto di Meccanica Applicata alle Macchine,
Facoltà di Ingegneria, Università di Bologna, Bologna, Italy

SUMMARY

In this work are reported the results of experiments on 1:10 mock-ups concerning the response of the P.E.C. reactor vessel and plug subject to a dynamic load due to an accidental power excursion.

In order to evaluate the influence on structures damage of detonation velocity and gas bubble volume, explosive tests have been carried out using different chemical explosives i.e.: a) plastit; b) semigel; c) mixture of semigel (1.8%) + KCLO₄ (44.5%) + Ba NO₃ (24.5%) + Magnesium (29.2%).

The originality of the present work is related to such a comparison that has been performed on particular geometries of the P.E.C. reactor system.

The measurements on mock-ups give the deformation energy absorbed by the reactor vessel and by plug bolts. Moreover, the pressure and impulse on the plug and on the vessel at different height have been measured by pressure transducers. The upper plug has been simulated through a stiff structure, constrained by bolts to the supporting structure. The impulse meeting on the plug has also been determined by using strain-gages located on tubes connecting the plug to the bolts. These tubes are compressed and are dimensioned to remain in elastic state during the plastic deformation of the bolts.

From first experiments it appeared that the energy equivalent to 50 gr of plastit can be contained in the reactor vessel without affecting the outer containment (concrete, graphite and outer steel shell), owing to the gap around the reactor vessel. Measurements have also been taken to determine the plug velocity by using pin contactors.

The experiments showed a strong influence of the explosive characteristics on vessel deformation and on the energy impacting the plug.

The vessel deformation along the axial direction is obtained with three kinds of explosive. A very slow explosive with large gas production (explosive c) causes a high energy impacting on the plug (7% of explosive energy) and large deformation in the upper part of the reactor vessel.

With plastit the energy impacting on the plug is about 1%, while with semigel (which has intermediate characteristics) the energy on the plug is 3%.

Plastit (high detonation velocity) causes a strong deformation of the reactor vessel in the surrounding of the charge, owing to the shock wave. From recent studies such an explosive does not seem to simulate conveniently the energy release modalities resulting from a reactor accident.

The results obtained with explosives b) and c) therefore seem to better represent the damaging of the structures of the prototype.
1 - Introduction

The primary containment of a liquid metal fast reactor to an accidental energy release may be investigated by proper explosives tests on reactor mock-up.

TNT has been used in the past to simulate nuclear excursions in fast reactors; the difficulty in comparing TNT tests to nuclear accidents is due to the different energy liberation rate. This work concerns a set of experiments on 1:10 PEC Reactor (+) mock-ups devoted to evaluate the response of the containment to a hypothetical core disruptive accident.

In order to evaluate the influence of energy rate release and gas bubble volume, different chemical explosives has been compared.

Main measurements performed on mock-ups concern the deformation energy absorbed by reactor vessel and plug bolts, pressure and impulse on the plug and on the vessel.

In this paper we will describe the results obtained by the tests. Radial deformations of the vessel have been compared with the Proctor's formula while energy absorbed by plug bolts has been evaluated by Aspirin code.

2 - Reactor mock-up

The mock-up (fig. 1 and 2) reproduces schematically (scale 1:10) the reactor vessel, the internals (thermal and neutronic shields, reflecting and shielding elements) and the external shielding structure.

Double containment vessel has been reproduced by a single tank; the shielding and reflecting elements reproduce only the equivalent mass of the prototype elements and are constructed by iron rods. The thermal have been reproduced by three shells and neutronic shields by four shells.

A concrete of 2,9 gr/cm³ density has been used (average density of the graphite and heavy concrete).

The plug has been constructed with the geometrical shape of the prototype and equivalent mass.

The plug bolts (AISI 304) have a diameter Ø = 7,8 mm and deformation length l = 105 mm.

The vessel has been constructed by Fe 00 (chemical composition and mechanical characteristics see table 1); the mechanical properties are rather similar to AISI 304 at reactor operating temperature.

All the welds have been controlled by X-ray.

(+) PEC fast reactor is a test fuel facility under construction by Italian CNEN
3 - Chemical explosives

The hypothetical core disruptive accident has been evaluated for PEC reactor in 200 MJ.

It is difficult to simulate properly this accident by a chemical explosives; the major difficulty is due to the difference in the energy release rate between usual chemical explosives and accidental reactor excursion. In order to compare the hydrodynamic and structural effects as a function of energy rate, different chemical explosives have been utilized:

1) **Plastit**
   - **composition:** $C_5H_8O_{12}N_4 + 12\%$ grease
   - **energy released:** 1200 Cal/gr
   - **detonation rate:** 7000 m/sec

2) **Semigel**
   - **composition:** $C_3H_5(NO_3)_3 + C_2H_5NO_3$ 17%, TNT 6%, NH$_4$NO$_3$ 71,7%
   - **energy released:** 1000 Cal/gr
   - **detonation rate:** 3500 m/sec

3) **Low-burning explosive**
   - **composition:** Semigel (1,8%), KClO$_4$ (44,5%), Ba(NO$_3$)$_2$ (24,5%), Mg (29,2%)
   - **energy released by 1600 gr:** 100 Kcal
   - **detonation rate measured by detector inserted in the charge:**
     - from center to $r = 22,6$ mm 3700 m/sec
     - from $r = 22,6$ mm to $r = 37$ mm 600 m/sec
     - from $r = 37$ mm to $r = 52,6$ mm 460 m/sec

4 - Experimental techniques

Main measurements performed in reactor mock-ups are the vessel and metallic shielding sheets deformations at different axial heights, the elongation of plug bolts, pressure peaks in some mock-up position (fig. 1), the initial plug velocity and the dynamic load on the bolts.

The deformations have been measured by tracing previously the vessel and in some cases by strain-gauges inserted on external shielding.

The pressure pulses have been measured by Kistler and rod pressure transducers.

The maximum plug velocity has been measured by pin contactors, giving the plug displacement as a function of time.

A special apparatus allows the measurement of dynamic load on the plug bolts; it consists of a thick tube, coaxial to the bolt and instrumen-
ted with strain gauges, that is compressed during the bolt elongation; the material and compressed surface of the tubes are chosen in order to remain in elastic field.

Bolt area and ultimate stress are

\[ A_b = 48 \text{ mm}^2 \]
\[ \sigma_{ub} = 60 \text{ Kg/mm}^2 \]

while tube area and yield stress area:

\[ A_t = 124 \text{ mm}^2 \]
\[ \sigma_{yt} = 120 \text{ Kg/mm}^2 \]

Usually strain gauges on different tubes are connected in series in order to reduce noise influence. The transducers are connected to an oscilloscope where the signal is recorded by a Polaroid camera.

From oscilloscope signal \( \Delta V \), the bolt dinamic stress \( \sigma_b \) and the impulse \( I \) are evaluated:

\[ \sigma_b = K \frac{A_t}{A_b} \Delta V \]
\[ I = K N_b A_t \int_0^\infty \Delta V(t) dt \]

where:

\[ K \] = constant depending on bulk modulus and strain gauges loop characteristics

\[ N_b \] = number of bolts

5 - Experimental results

Table 2 gives for different experimental conditions the deformation energy adsorbed by plug bolts and by reactor vessel, neutronic and thermal shielding in core \( h = 28 \text{ cm} \) and upper region \( h = 45 \text{ cm} \).

The deformation energy is expressed in KCal and as a percentage of the explosive energy liberated by the charge.

In test N. 1 the charge consists of 50 gr. Plastit. The mock-up has a concrete shield constructed in a single block with a metallic sheet in between.

This sheet did not seem to contribute to the containment and has been suppressed in other tests.

In test N. 2 (50 gr. Plastit) the concrete shield consists of briks in order to avoid any tangential resistence. A gap of 1 cm is left between vessel and concrete.

A charge of 1,6 Kg of low-burning explosive has been used in test N. 3.

In test N. 4 a charge of 100 gr Plastit has been used while in test N. 5 100 gr. semigel have been exploded.
The mock-ups used in test N. 3, 4, 5 are similar to test N. 2.

Fig. N. 3 shows the vessel deformation along the axis for each test. Tab. 3 gives, for different experimental conditions, the pressure peaks at different positions (Fig. 1), the pressure impulse on the plug (measured by pressure transducers and strain gauges on the bolts), the dynamic loads on the bolts and the maximum plug velocity.

Fig. 4 gives the diagrams of the plug displacements as a function of time, measured by pir-contactors.

From experimental results it is possible to infer that:

- the radial deformation energy absorbed by vessel and metallic shields varies between 12% - 19% of the explosive energy, depending on the charge weight and properties

- the deformation energy absorbed by plug bolts varies between 1% - 7% of the explosive energy; higher values are connected with low detonation velocity explosives

- a strong influence of the charge characteristics is found on the vessel deformation along the axial direction: semigel and low-burning explosives produce a stronger deformation in the upper region of the vessel, compared with plastix effects that prevail in proximity of the charge

- the pressure peaks on the plug ranging from 700-1500 Kg/cm², are higher with low burning explosive

- the maximum velocity (ranging from 7 : 15 m/sec) is higher with low burning explosive. The low value obtained in exp. N. 4 is due to the rupture of the vessel.

6 - Analysis of experimental results

A semiempirical formula has been proposed by Wise-Proctor correlating the TNT charge with radial deformation of a cylindrical vessel [1].

Fig. 5 gives the charge weight W as a function of vessel radius for some wall thickness (s) and vessel maximum deformation (ε).

For mock-up radius (R₁ = 15 cm), vessel thickness (s = 5 mm) and deformation ε = 3,5% a charge of W = 16 gr of TNT has been obtained; the same deformation is obtained with wall thickness s = 18 mm (corresponding to vessel + thermal and neutronic shields) when the charge is W = 100 gr. of TNT.

Last result is in agreement with experiment N. 4 giving ε = 3,5% in core region with W = 100 gr. of Plastix and total radial sheets thickness s = 18 mm.

A good agreement is also obtained between calculations and experiments with 50 gr. plastix.

Some calculations have been performed with Asprin code [2]. It has been assumed that 50% of explosive energy is converted in shock energy,
50% give rise to blast pressure (whose effects are evaluated by the code).

Assuming for 50 gr. Plastit an initial pressure of the gas bubble \( p = 2000 \text{ Kg/cm}^2 \)\(^{(1)}\) and inserting the proper dimensions and materials of the mock-up, an energy absorbed by the plug \( E_p \approx 2.5\% \) of total explosive energy has been obtained.

References


\(^{(1)}\) This value seems reasonable supposing that 50% shock energy is generated by initial adiabatic expansion of explosive gas products.

<table>
<thead>
<tr>
<th>Material</th>
<th>Fe 00</th>
</tr>
</thead>
<tbody>
<tr>
<td>thickness</td>
<td>mm</td>
</tr>
<tr>
<td>yield stress</td>
<td>Kg/mm(^2)</td>
</tr>
<tr>
<td>ultimate stress</td>
<td>Kg/mm(^2)</td>
</tr>
<tr>
<td>ultimate elongation</td>
<td>45%</td>
</tr>
<tr>
<td>Cr%</td>
<td>≤ 0.01%</td>
</tr>
<tr>
<td>Ni%</td>
<td>0.47</td>
</tr>
<tr>
<td>Mo%</td>
<td>≤ 0.005</td>
</tr>
<tr>
<td>Ti%</td>
<td>≤ 0.005</td>
</tr>
<tr>
<td>Mn%</td>
<td>0.55</td>
</tr>
<tr>
<td>C%</td>
<td>0.042</td>
</tr>
<tr>
<td>S%</td>
<td>0.021</td>
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### Tab. 2

<table>
<thead>
<tr>
<th>Test Nr.</th>
<th>Charge</th>
<th>Expl. energy Kcal</th>
<th>Total def. energy Kcal</th>
<th>Thermal shield def. energy Kcal</th>
<th>Electronic shield def. energy Kcal</th>
<th>Radial def. energy Kcal</th>
<th>Belts</th>
<th>Elongation length (mm)</th>
<th>Plug bolts along 45°</th>
<th>Plug bolts Kcal</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>50 gr plast. 60</td>
<td>1.1</td>
<td>1.8</td>
<td>4.3</td>
<td>1.5</td>
<td>2.1</td>
<td>0.94</td>
<td>2.97</td>
<td>4.60</td>
<td>7.57</td>
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<tr>
<td>2</td>
<td>50 gr plast. 60</td>
<td>1.94</td>
<td>3.24</td>
<td>3.42</td>
<td>1.6</td>
<td>2.05</td>
<td>1.75</td>
<td>5.29</td>
<td>4.46</td>
<td>9.75</td>
</tr>
<tr>
<td>3</td>
<td>1600 gr low-burning 100</td>
<td>0.67</td>
<td>0.67</td>
<td>5.22</td>
<td>0.52</td>
<td>4.42</td>
<td>4.62</td>
<td>2.26</td>
<td>8.64</td>
<td>11.8</td>
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<tr>
<td>4</td>
<td>100 gr plast. 120</td>
<td>5.32</td>
<td>2.93</td>
<td>4.52</td>
<td>2.5</td>
<td>7.2</td>
<td>17.06</td>
<td>5.43</td>
<td>22.47</td>
<td>26</td>
</tr>
<tr>
<td>5</td>
<td>100 gr semi-plast 100</td>
<td>2.12</td>
<td>3.32</td>
<td>1.82</td>
<td>2.05</td>
<td>0.97</td>
<td>4.3</td>
<td>18.22</td>
<td>6.19</td>
<td>14.4</td>
</tr>
</tbody>
</table>

(1) only 26 bolts have been mounted with coaxial tubes

### Tab. 3

<table>
<thead>
<tr>
<th>Test Nr.</th>
<th>Charge</th>
<th>pressure peak (Kg/cm²)</th>
<th>Pressure transducer (Pos.1)</th>
<th>Pressure transducer (Pos.2)</th>
<th>Pressure transducer (Pos.3)</th>
<th>Plug impulse (Kg/sec)</th>
<th>max. bolt stress (Kg/ft²)</th>
<th>plug velocity (m/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>50 gr plast.</td>
<td>1000</td>
<td>850</td>
<td>900</td>
<td>55 (2)</td>
<td>110</td>
<td>6400</td>
<td>8</td>
</tr>
<tr>
<td>2</td>
<td>50 gr plast.</td>
<td>1100</td>
<td>1000</td>
<td>1000</td>
<td>95</td>
<td>120</td>
<td>6400</td>
<td>9.5</td>
</tr>
<tr>
<td>3</td>
<td>1600 gr low-burning</td>
<td>1400</td>
<td>1300</td>
<td>1000</td>
<td>200</td>
<td>120</td>
<td>6400</td>
<td>15</td>
</tr>
<tr>
<td>4</td>
<td>100 gr plast.</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
<td>170</td>
<td>-</td>
<td>-</td>
<td>6.7</td>
</tr>
<tr>
<td>5</td>
<td>100 gr plast.</td>
<td>700</td>
<td>1000</td>
<td>1000</td>
<td>220</td>
<td>-</td>
<td>-</td>
<td>8</td>
</tr>
</tbody>
</table>

(1) two peaks are present with time interval 400 usec
(2) pressure has been measured only for 400 usec
Fig. 1 - Mock-up vertical section
Fig. 2 - Mock-up photo

Fig. 3 - Axial deformation of the vessel for different tests
**Fig. 4** - Plug displacement for different tests

**Fig. 5** - TNT charge as a function of vessel radius for different deformations (Proctor's formula)