EXPERIMENTAL ANALYSIS OF A COMPOSED STRUCTURE SUBJECT TO A DYNAMIC LOAD

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Abstract

In this work are given the experimental result of a series of test on the dinamic response of a structure subject to an explosive loading. The structure simulates the assembly of vessel and external shields of the sodium-cooled fast reactor P.E.C. in case of an uncontrolled nuclear excursion.

A theoretical interpetration of the phenomenon has been provided .

1. INTRODUCTION

The containment definition of a composite structure, such as that of the radial shields of the P.E.C. (fuel element testing) "fast reactor", formed of several metallic sheets intercalated with fillers, necessarily requires an experimental support.

A series of experiments on models has been planned between the Fast Reactor Program of CNEN and the C.C.R. Euratom of Ispra, in order to specify the behaviour of this structure due to a dynamic loading.

In the first part of the experimental program, whose results are shown in this document, some charges of Plastit (Dinamit Nobel) have been ex ploded in simplified models on a 1/20 scale of the PEC vessel and of the sheets surrounding it, in order to obtain a containment law for the multilayers structures which would extend the aim of the law derived by Wise-Protor [1] for a single vessel.

The second step of the program foresees a series of explosive tests on models which will reproduce with a greater accuracy various details and the principal components capable of absorbing considerable quantities of deformation energy (fuel elements, pipings, etc. ....).

2. SCALE LAW

The chosen scale law, as it isually happens in the simulation of the explosive phenomena, is the Hopkinson's low. Such law retains, unmodified the number of Mach u/c (u = velocity of particles; c = rate of sound propagation in the material). Thus the dynamic similarity between the model and the prototype behaviours will be maintained if the linear dimensions of the explosive charge and mechanical sistem are multiplied by the scale factor λ and the materials remains the same.

In this series of test we have chosen as a scale of length reduction:

$$\lambda = \frac{1}{20}$$

In the table I are given the main scale ratios.

3. COOLANT SIMULATION

In the PEC, as it is usual in fast reactors, sodium is used as coolant. In the model sodium coolant has been substituted with water at ambient temperature; some difficulties would rise in the introduction of the charge which is sensitive to temperature and in addition some problems would always be present in handling sodium.

It seems, however, that is would be possible to utilize the results of explosive comparative experiments between sodium and water. These experiments show that - under the same conditions (charge, geometry, etc. ..) - the pressure peak in sodium is about 1.5 that present in water, while the impulse is about the same in both cases [2].

4. MATERIALS

In the explosive phenomenon the energy absorbed by the materials surrounding the reactor core, has a remarkable effect on the attenuation of the shock wave.

It is therefore of importance to reproduce in the model materials the some parameters $\sigma = \sigma$ (ε) being present in the prototype at operative temperature. In the first part of the experimental program we have deemed essentially necessary to comparatively investigate the containment capability of some structures by varying some parameters.

There has then been employed a kind of steel easily available on the market, while in the second part of the program (somely on the more accurate models of the reactor) there has been carried out a more precise reproduction of the characteristics of the metallic-sheet material at the operative temperatures.

5. MODELS

Figures 1 and 2 shows a 1/20 scale model utilized in the explosive testing.

In the prototype the reactor vessel consists of two contiguous cylindrical elements whose inside is 30 mm thick, and whose outside is 25 mm thick, ϕ_i = 3140 mm. Due to simplification both elements of the model have been coalesced in a single one 2.9 mm thick, and ϕ = 159 mm outside diameter.

Excepting for the first experiment in which three metallic sheets have been used, in the next tests only two ferrules have been usde (eliminating the intermediate one), the external being s_2 = 1.5 mm thick, and with ϕ_{21} = 300 while the internal being about 1 mm away from the vessel and 0.5 mm thick with ϕ_{2i} = 161 mm.

The filling materials employed so far are sand, concrete and water. The charge is inserted from the top into the vessel, filled with water, up to 20 mm from the upper end, through a hole, which is then plugged by a threaded cap passed axially through by the detonator wire. The upper and lower plates are spaced by means of 12 cylindrical sleeves passed through by steel tightening rods.

6. EXPLOSIVE CHARGE

Objective of the experiments is to define the containment limit of the outside sheet through a correlation between its deformation and the charge.

The Plastit (Dinamit Nobel) has been used as explosive. The charge has been exploded at 240 mm from the upper end of the vessel.

7. MEASUREMENT INSTRUMENTATION AND TECHNIQUES

In order to assess the containment capacity of the structure and to derive a law stating the weight of the maximum charge that can be contained according to the mechanical properties of the material used, the most important measurement in explosive testing is the deformation energy absorbed by the sheets. Such measurement has been carried out by plotting the sheets and evaluating the deformations after the explosion. Moreover also the measurement has been taken of the deformation velocities of the radial shields since the dynamic resistence of the materials may present sensitive variations as compared to the resistence under static conditions. This measurement has been effected by means of "pin contactors" connected to an oscilloscope (fig. 3).

8. MEASUREMENT RESULTS

Table III summarizes to tests performed with an indication of the charge, vessel material and fillers. The first two tests have been carried out with the aim to set up the instrumentation. In figures 4, 5, 6, 7, 8, 9 there is shown, for the vessel and outer shield, the average values of the percent deformation determined in relation to height.

The sheet adyacent to the vessel has quite always been destroyed; in the calculation the deformation course for this sheet has assumed as equal to that of the vessel.

From the graphs there clearly results an outline of the vertical deformation of the wavy type with swellings in proximity to the edges; this is probably ascribable to the reflection of the shock wave on both ends. The results of the measurements of the deformation velocities have not given very high maximum values (150÷140 sec^{-1}) for the external vessel, while in the only measurement where we were able to observe the deformation velocity of the internal vessel, it has resulted as considerably high (1800 sec^{-1}). It should be noted that the deformation velocities in the prototype are 20 times as small as the model.

According to what stated by Wise-Proctor [1] and on the basis of the results of Manjoine [3], for these values of deformation velocity the dynamyc yield stress may be subject to a remarkable elevation as to the static values. Very little is known about the material behaviour in the plastic domain at these high deformation velocities.

The results of the tensile tests under dynamic conditions are not available for the materials used in metallic shields. Such tests are at present under preparation at the C.C.R. Euratom Ispra.

Though the deformation velocity has a considerable influence on the yield stress, from the experiments of Wise-Proctor it is clear that it has a modest influence on the deformation energy: in fact the variation from 200 sec^{-1} to 3000 sec^{-1} involves a variation in the deformation energy of 20÷25% as compared to the static case. In the next assessments the influence of $\dot{\varepsilon}$ on the deformation energy of the sheets has therefore been neglected. According to the three main directions for a material assumed as incompressible the deformations are linked in the plastic field by the relation

$$\varepsilon_1 + \varepsilon_2 + \varepsilon_3 = 0$$

In our case there are cylindrical structures with a radius/thickness ratio higher than 20 and which are free to suffer transverse contractions. It has therefore been admitted that the deformation work was practically to be connected to the circumferential elongations. In addition also the Ludwik's law has been assumed as valid in the dynamic field:

$$\sigma = k\, \varepsilon^n$$

where k and n are experimental values.
The deformation work is thus given by:

$$L_d = \frac{2\pi R\ k\ s}{n + 1} \int_h \varepsilon_h^{n+1} \cdot dh$$

In table IV is shown the energy absorbed for deformation by the metallic structural elements. From the study of such results the following considerations can be drawn:

1) the overall absorbed energy in the deformation of the sheets and vessel reaches values fluctuating from 9% (concrete filling), to 11% (sand filling) and 16% (water filling) of the total energy released by the charge explosion. Thus only a part of the explosion energy is equivalent to the deformation energy of the metallic structures. This seems to find a confirmation by using the Cole's equations [4] according to which the energy combined with the shock wave at the time of the impact against the vessel wall is of the order of 25%-30%. A part of this energy is reflected towards the inside.

2) There are no direct methods to calculate the energy which can remain in the sand or in the concrete after the explosion.
In the discussion which will be presented afterwards, a criterion is illustrated to derive such energy indirectly.

3) The comparison between the tests with sand filling and concrete filling shows that owing to its highest compactedness the latter trans-

mits better than the sand the shock wave to the external sheet which therefore absorbs a much higher deformation energy as compared to the sheet with sand filling

9. CORRELATION WEIGHT OF CHARGE-ENERGY OF DEFORMATION

In the present paragraph the correlation "charge-energy" of deformation presented by Wise-Proctor [1] for the single sheets is extended to the shield with two metallic sheets and interposed filling.

Consider the shield represented in fig. 10.

The law of momentum for a unit heght of the shield astride the charge plane (namely the plane where the greatest deformations take place) may be written:

$$2\pi R_{i1} I_{T_r} = \frac{w_1 \pi}{g} (R_{e1}^2 - R_{i1}^2)\, V_{o1} + \frac{w_2 \pi}{g} (R_{e2}^2 - R_{i2}^2) V_{o2} + \frac{w_F \pi}{g} (R_{i2}^2 - R_{e1}^2) V_{oR} \quad (1)$$

The specific impulse absorbed by the vessel wall is related to the free water impulse I by and "efficiency factor" function $\xi = \xi\ (R_i/h_o)$ taking account of the wall reflection such that lbsec/ft^2

$$I_{TR} = 144\ \frac{I_f}{\xi}$$

The power law relating charge weight W and charge distance Ri to specific impulse is given by Cole [1] as

$$I_f = K\ W^{1/3}\ (W^{1/3}/R_i)^{\beta}$$

It can be assumed for plastit K = 2,18; $\beta \simeq 1$

In the case of shield formed by a single metallic wall, the § coefficient has been experimentally derived.

$$\xi = 1.47 + 0.0373(Ri/ho)$$

In the model of the PEC reactor a gap of about 1 mm exists between vessel and filling. The velocity measurement taken shows that the internal vessel reaches the maximum velocity before the displacemente exceeds 1 mm. It may thus be admitted that the vessel acquires all the energy that the explosion may provide to the structures by behaving as if it was a single ferrule. In such hypothesis, in our case we have $\xi \simeq 2.3$. The law of conservation of energy for the ring of unit height is written:

$$\frac{w_1 \pi}{2g} (R_{e1}^2 - R_{i1}^2) V_{o1}^2 + \frac{w_2 \pi}{2g} (R_{e2}^2 - R_{i2}^2) V_{o2}^2 + \frac{w_F \pi}{2g} (R_{i2}^2 - R_{e1}^2) V_{o2}^2$$

$$= \pi (R_{e1}^2 - R_{i1}^2) D_1 + \pi (R_{e2}^2 - R_{i2}^2) D_2 + \pi (R_{i2}^2 - R_{e1}^2) D_F \qquad (4)$$

The densities of energy D_1 and D_2 are experimentally determined. From eq. (1) and eq. (4) the velocity V_{o1} can be eliminated, thus the following quantities remain unknown:

$$\beta = \frac{V_{o2}}{V_{o1}} \ ; \quad \delta = \frac{V_{oF}}{V_{o1}} \ ; \quad D_F$$

In the hypothesis that the impact if perfectly plastic there would exist $\beta = \delta = 1$ (see calculation of the shield of the Seafor reactor [5]).

From eq. (1) and eq. (2) we derive:

$$W = \left(\frac{\xi}{144\ K}\right)^{3/2} \frac{1}{2g} \left\{ \left[w_1 (R_{e1}^2 - R_{i1}^2) + \beta w_2 (R_{e2}^2 - R_{i2}^2) + \delta w_F (R_{i2}^2 - R_{e1}^2) \right] \right.$$

$$\left. \times \left[D_1 (R_{e1}^2 - R_{i1}^2) + D_2 (R_{e2}^2 - R_{i2}^2) + D_F (R_{i2}^2 - R_{e1}^2) \right] \right\}^{3/4} \qquad (5)$$

In the test (8) and (9) (see table III) in which the filler is formed of water, there will surely have $D_R = 0$.

Eq. (5) allows therefore to obtain(known W, D_1, D_2) the values of β and δ assumed as equal. The values of β and δ result remarkably equal to zero.

This means that there is no sensible contribution of the filler and external sheet in the interval of time from the instant of the impact of the shock wave with the vessel wall to the instant when such shock wave ends to act on the vessel wall.

Since it is considered that such phenomenon does not depend upon the type of filling, $\beta = \delta = 0$ is assumed for all tests.

Eq. (5) allows thus to derive the value of D_R from the explosive tests carried out.

In table V we give the values of D_1, D_2, D_1/D_2 experimentally obtained and the calculated values of D_F and D_F/D_2:

From the above table it is clear that the D_1/D_2 and D_F/D_2 ratios for a given filling material and geometry can be considered as considerably constant. If this will be confirmed by other explosive tests at present under way, eq. (5) will permit to derive the radial deformation of the external sheet in relation to the explosed charge.

Nomenclature

D_1 = vessel deformation-energy density of unit ring - ft $lb/_{ft}^3$

D_2 = external shut " " " " " " "

D_F = energy density of unit ring that the filler has medially absorbed ft $lb/_{ft}^3$

h_o = vessel wall thickness, ft

I_{tr} = specific impulse absorbed by unit ring, lb $sec/_{ft}^2$

I_f = " " of explosion in free water

k = material constant

K = explosive constant

n = material constant

R_{i1} = internal radius of vessel, ft

R_{e1} = external " " " , ft

R_{i2} = internal radius of external sheet, ft

R_{e2} = external radius of " " , ft

References

|1| Wise,W.R., Proctor,J.F.: "Explosion Containment Laws for nuclear Reactor vessels" NOLTR 63-140

|2| Drevon,G., Falgayrettes,M., Walford,F.,: "Comparison of Pressure Loading Produced by Contained Explosions in Water and Sodium", Proc. of the Conference on Safety, ANL7120, Oct. 1965

|3| Manjoine,M.: "Influence of Rate Strain and temperature on yield stresses of Mild Steel", Journal of Applied Mech., Dec. 1944

|4| Cole,R.H.: "Underwater Explosions", Princeton Univ. Press.

|5| Southwest Experimental Fast Oxide Reactor 1969, Comunicazione privata.

TABLE I

Physical quantity	Dimensions	Full scale value	Model scale value
Explosive charge mass and other masses	M	Z	$Z\ \lambda^3$
Pressure	$ML^{-1}\ T^{-2}$	P	P
Length	L	R	$R\ \lambda$
Time	T	t	$t\ \lambda$
Area	L^2	A	$A\ \lambda^2$
Specific impulse	$ML^{-1}\ T^{-1}$	I	$I\ \lambda$
Force	$ML\ \ T^{-2}$	F	$F\ \lambda^2$
Velocity	LT^{-1}	V	V
Acceleration (eccept that due to gravity	LT^{-2}	2	a/λ
Stress	$ML^{-1}\ T^{-2}$	σ	σ
Strain		ϵ	ϵ
Strain rate	T^{-1}	ϵ	ϵ/λ
Energy	$ML^2\ \ T^{-1}$	E	$E\ \lambda^2$

TABLE II

COMPARISON OF WATER AND HOT SODIUM COOLANT

	Water at 20°C	Sodium at 400°	Sodium at 600°
Sound velocity C $m\ sec^{-1}$	1484	2420	2310
Density ρ, gr/cm^3	0.998	0.856	0.808
Acoustic impedence ρC $gr\ cm^{-2}\ sec^{-1}$	148×10^3	206×10^3	186×10^3

TABLE III

Exp	CHARGE gr	FILLER	VESSEL MATERIAL	MEASUREMENTS			
				DEFORMATION		DEFORMATION RATE	
				VESSEL	EXT. SHIELD	VESSEL	EXT. SHIELD
1	43	S	A_q 52	yes	yes	no	no
2	30	S	C 35	yes	no	no	yes
3	30	C	A_q 45	yes	yes	yes	yes
4	30	S	A_q 45	yes	yes	no	yes
5	43	C	A_q 45	yes	yes	no	yes
6	60	C	A_q 45	yes	yes	yes	yes
7	43	S	A_q 45	yes	yes	yes	yes
8	25	W	A_q 45	yes	yes	no	yes
9	15	W	A_q 45	yes	yes	no	yes

S = Sand
C = Concrete
W = Water

TABLE IV

ENERGY-RELEASED DISTRIBUTION BY THE EXPLOSIONS

Exp	CHARGE gr	ENERGY /Kcal/	FILLER	$E_{def}^{(1)}$ /Kcal/	$E(1)_{TOT} / E_{def}$	$E_{def}^{(2)}$ /Kcal/	$E(2)_{TOT} / E_{def}$	$E_{def}^{(3)}$ /Kcal/	$E(3)_{TOT} / E_{def}$	E_{TOT} /Kcal/	E_{TOT} / E_{Exp}
1	43	52	S	-	-	-	-	-	-	-	-
2	30	36	S	-	-	-	-	-	-	-	-
3	30	36	C	1,7	0,55	0,36	0,12	1	0,33	~ 3,1	0,086
4	30	36	S	2,9	0,725	0,6	0,15	0,47	0,125	~ 4	0,112
5	43	52	C	2,75	0,56	0,57	0,116	1,58	0,324	~ 4,9	0,098
6	60	72	C	-	-	-	-	-	-	-	-
7	43	52	S	4,2	0,716	0,8	0,138	0,86	0,146	~ 5,86	0,112
8	25	30	A	2,4	0,54	0,28	0,11	1,78	0,39	4,46	0,15
9	15	18	A	1,35	0,47	0,272	0,09	1,26	0,44	2,88	0,16

S = Sand
C = Concrete
W = Water

(1) Vessel
(2) Sheet adjacent to the vessel
(3) External sheet

TABLE V

W /gr/	FILLER	D_I lb/sqft	D_2 lb/sqft	D_F lb/sqft	D_I/D_2	D_F/D_2
30	CONCRETE	$4,8.10^5$	$3,1.10^5$	$3,8.10^4$	1,55	0,12
43	"	$8,1.10^5$	$5,1.10^5$	$7,1.10^4$	1,58	0,14
30	SAND	$8,4.10^5$	2.10^5	$3,6.10^4$	4	0,18
43	"	11.10^5	$3,1.10^5$	$6,5.10^4$	3,6	0,21
25	WATER*	$8,6.10^5$	$4,4.10^5$	8.10^3	0,95	0,018
15	"	$4,5.10^5$	$4,9.10^5$	$- 4,8.10^3$	0,9	0,01

(*) During this test the external shield has broken down during the deformation

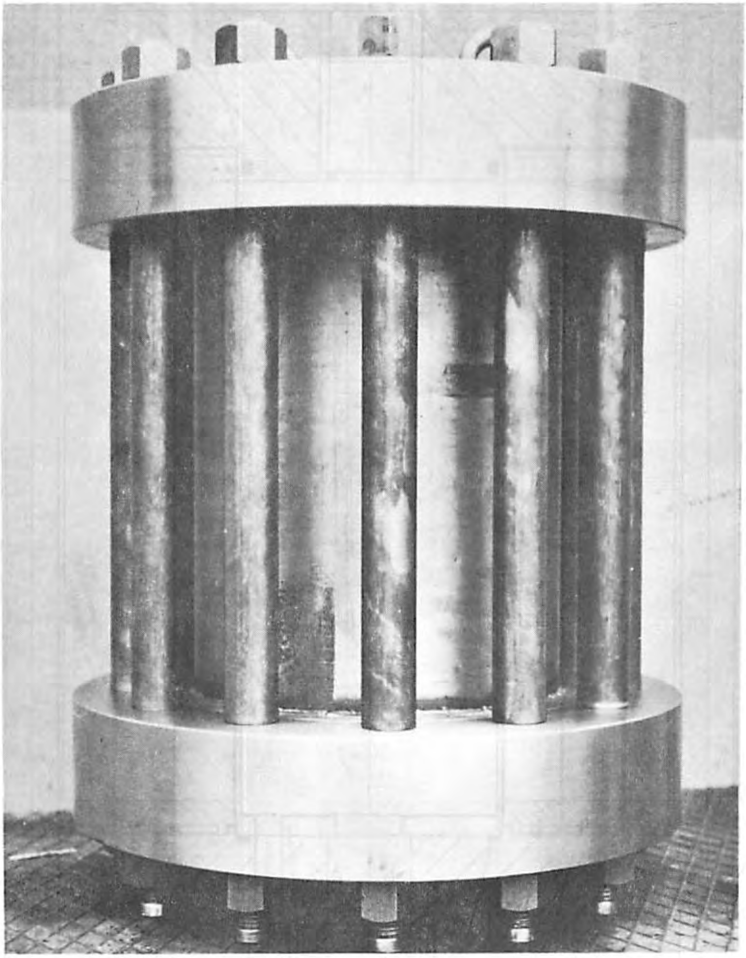


Fig. 1 - Photo of the Model

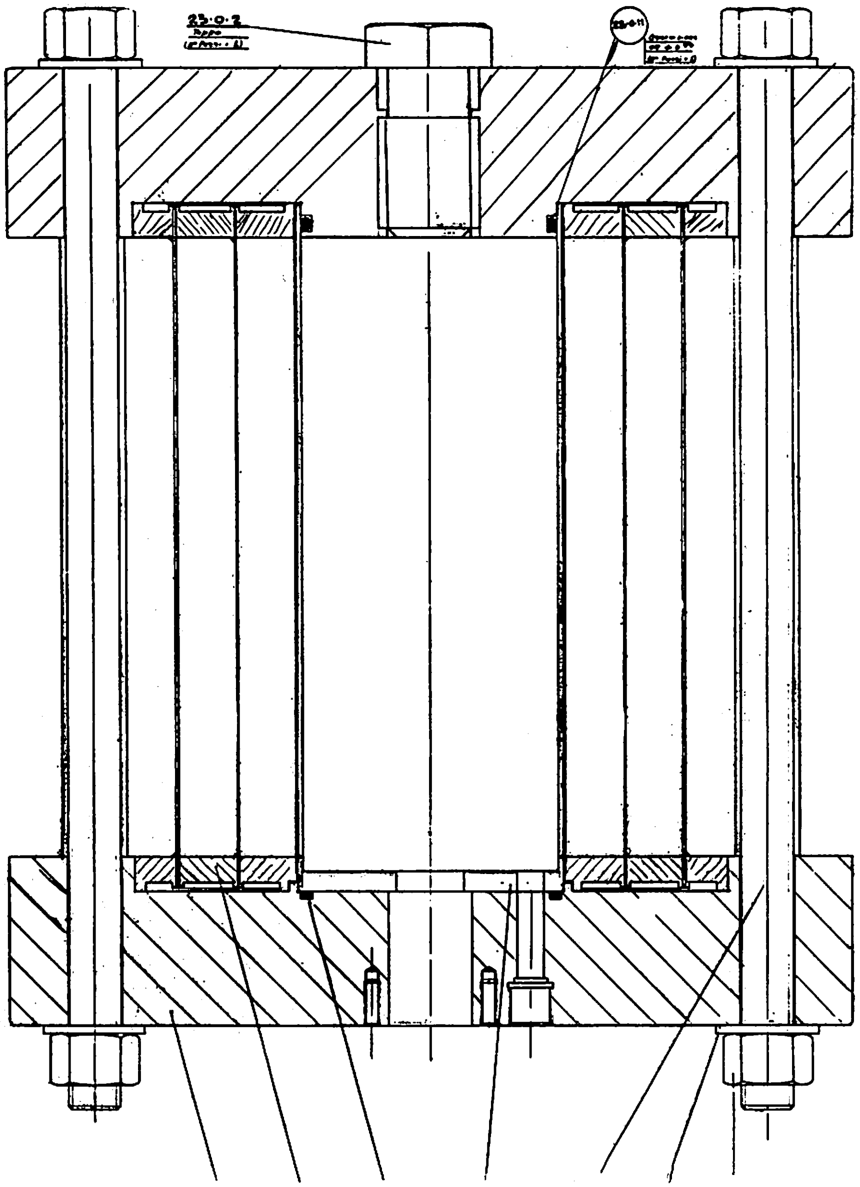


Fig. 2 - Cross Section of the Model

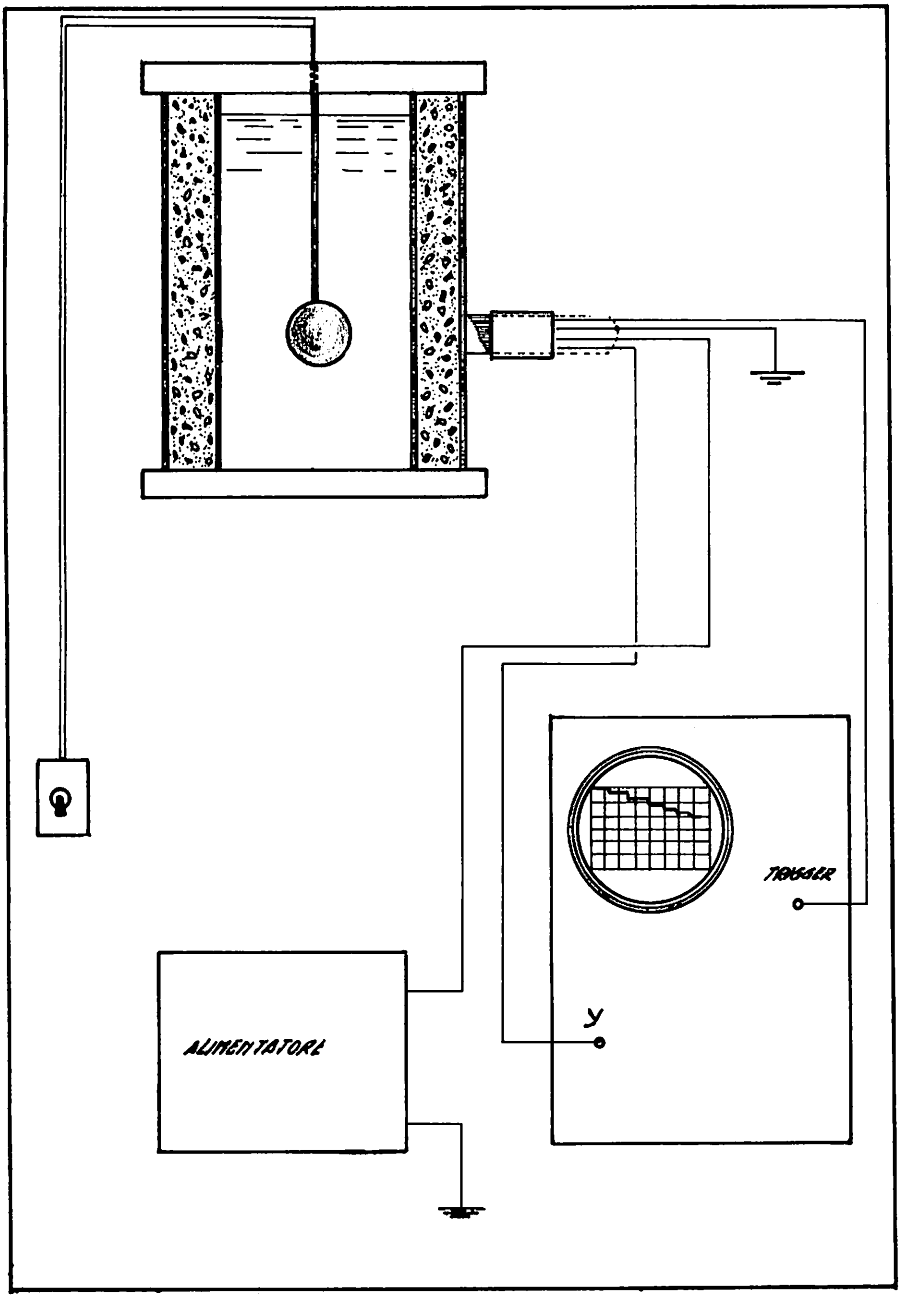
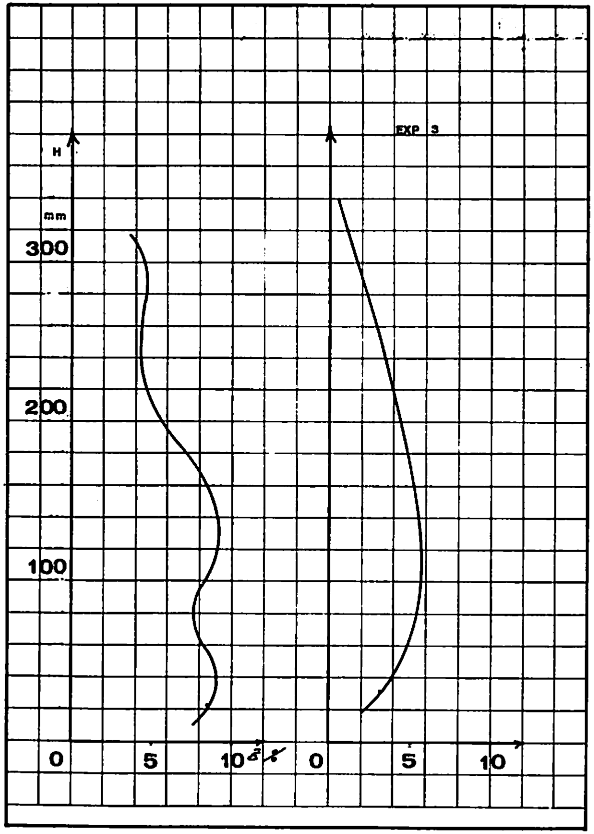


Fig. 3 - Apparatus to measure deformations



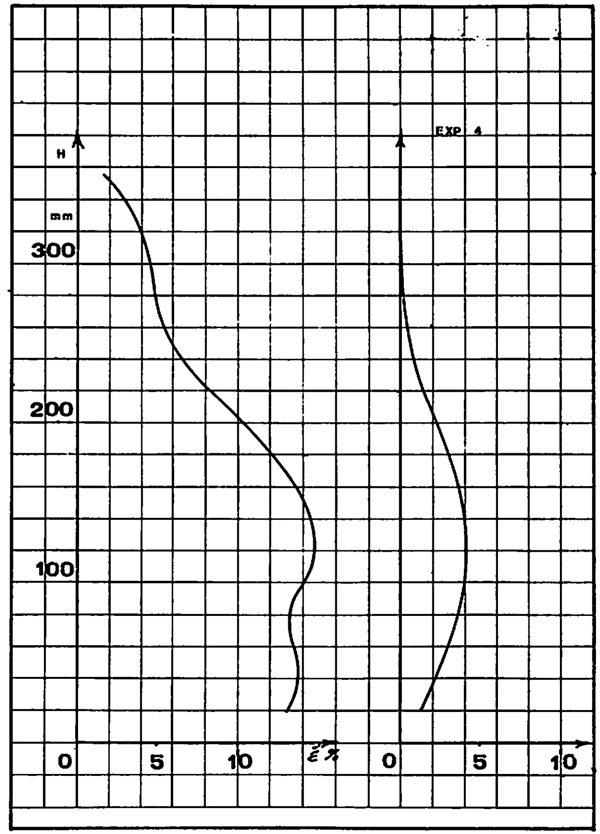
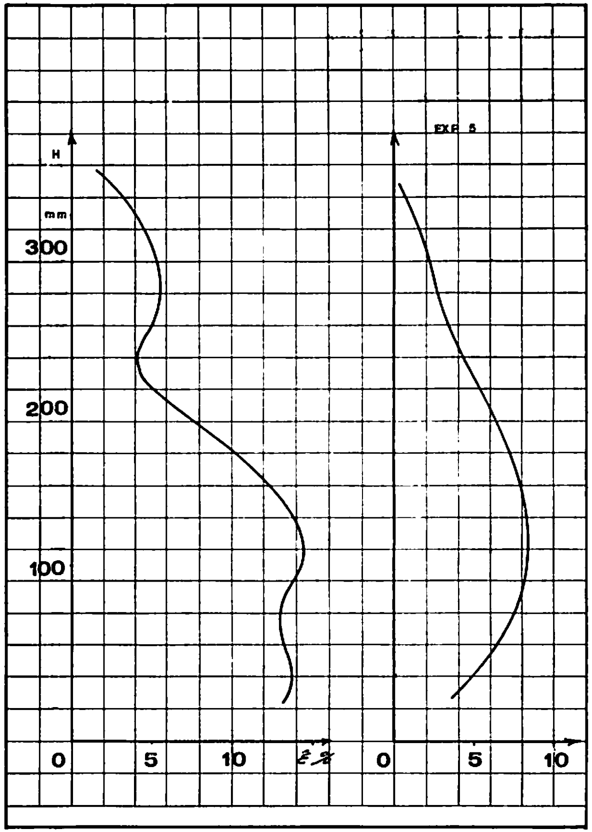


Fig. 4 - Vessel and external sheet deformation (Exp. 3)

Fig. 5 - Vessel and external sheet deformation (Exp. 4)



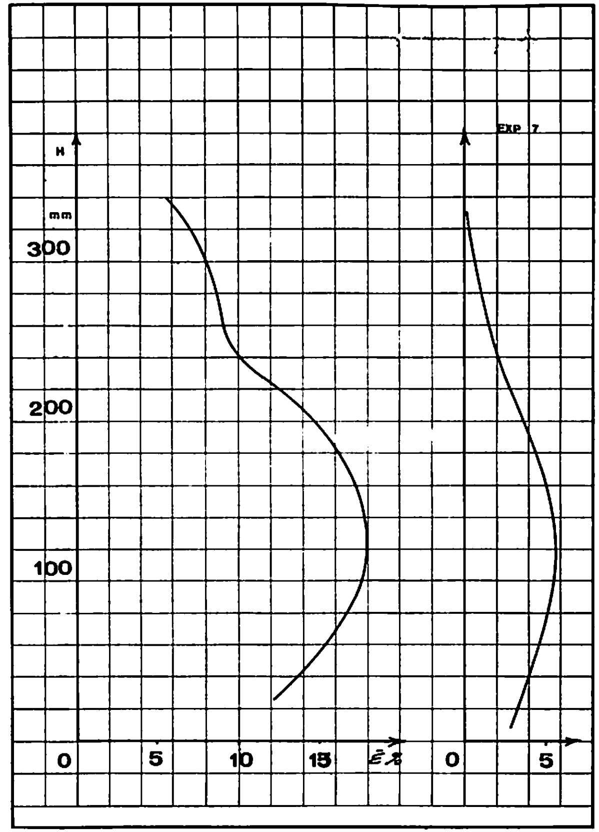
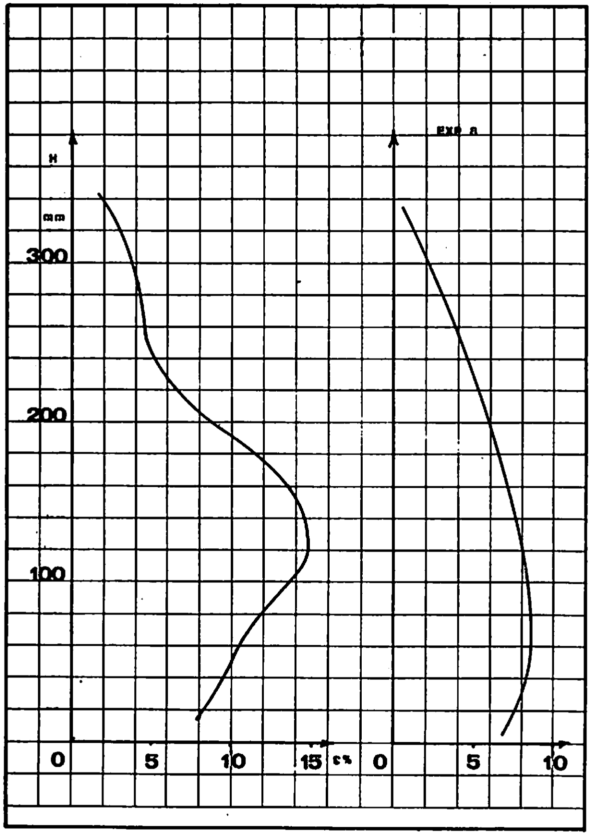


Fig. 6 - Vessel and external sheet deformation (Exp. 5)

Fig. 7 - Vessel and external sheet deformation (Exp. 7)



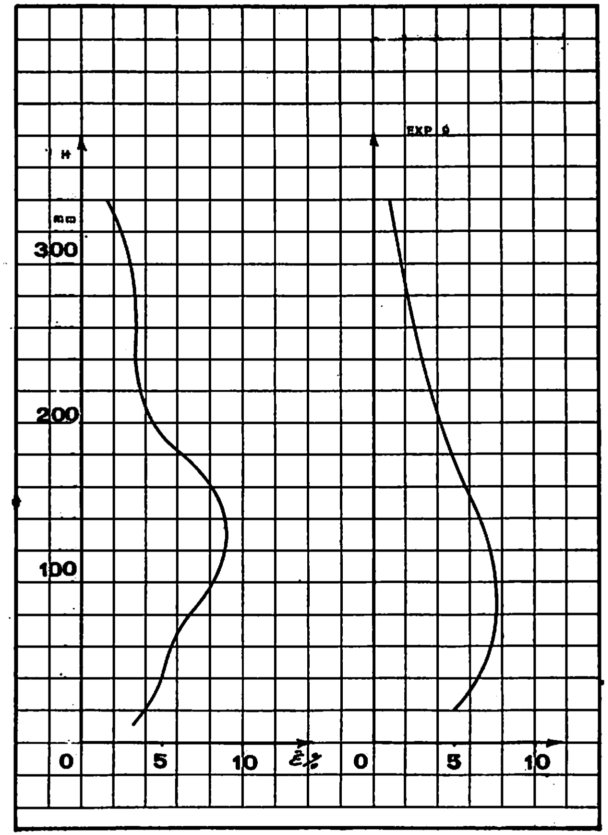


Fig. 8 - Vessel and external sheet deformation (Exp. 8)

Fig. 9 - Vessel and external sheet deformation (Exp. 9)

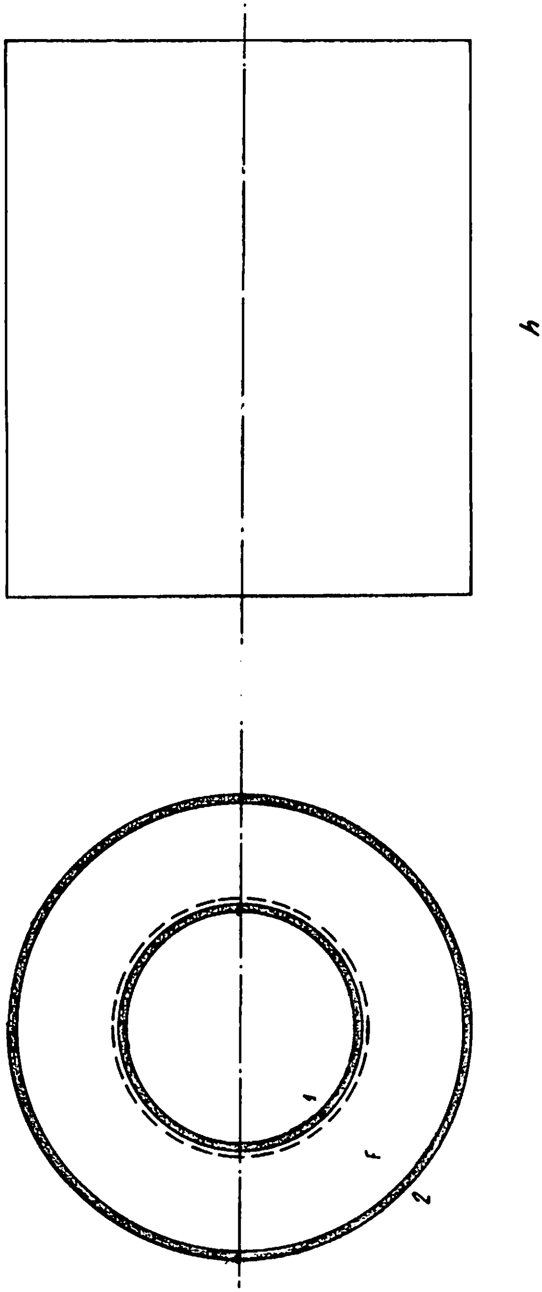


Fig. 10 - Schematic model

DISCUSSION

Q

T. A. DUFFEY, U. S. A.

I recall that Wise and Proctor observed that roughly 50% of the high explosive energy was eventually imparted to the outer shell. Is there a reason for the difference between that result and your results of approximately 12% of initial explosive energy finally imparted to the structure ?

A

R. CENERINI, Italy

I think one must take care of how the explosion energy is calculated. Our results seemed anyhow to be in agreement with the Cole's equation giving the energy impacting on the reactor vessel as a function of the explosive charge and of the distance : in our case this calculation gives 20-25% of the total explosion energy. A part of this energy is reflected.

Q

G. R. ABRAHAMSON, U. S. A.

Are not the high pressures produced by TNT like explosives unrealistic ? Such explosives probably enhance close-in damage at the expense of overall damage.

A

R. CENERINI, Italy

In order to compare the damage that results with different explosion velocity, we will perform a set of measurements with a low detonation velocity explosive. We agree that TNT could not reproduce correctly a possible nuclear excursion.