SIMULATION OF THE DYNAMIC LOADS AND STRESSES DUE TO EXPLOSIVE RUPTURE OF A PRESSURE TUBE IN A SCALED DOWN MODEL OF THE CIRENE REACTOR STRUCTURE

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Summary

The paper presents the results of the tests performed on a 1:5 scaled-down model of the CIRENE reactor structure, called MARC, aimed at determining the dynamic loads and stresses in the main structural components surrounding the heavy water tank due to the explosive rupture of a pressure tube (a practically impossible event, nevertheless carefully examined in the frame of the safety studies).

The MARC structure is essentially composed of:

- the water tank, shaped as a vertical cylinder, limited above and below by two horizontal plates;
- 60 vertical tubes simulating the reactor power channels, supported by the two plates;
- the structures simulating the shields (neutron s. and biological s.), which in various ways may interfere on the water tank movements;
- the linkage elements between reactor assembly and reactor heavy structures.

The basic simulation criteria adopted in the model design were:

- reduction of the reactor structure dimensions by a factor 5;
- use in the model of the same materials as the reactor structure.

These criteria, which are standard for the mechanical modelling, were rigorously applied in all circumstances relevant to the main objectives of the model tests, which were (for explosion in central and peripheric positions):

- determination of strains and stresses in the linkage elements of the water tank;
- determination of the water tank motion.

The phenomenon here under study, i.e. the dynamics of an explosion in a confined volume, is essentially determined by pressure forces and inertial forces. Other types of forces, such as volume forces (e.g. due to gravity), are negligible. In this case the simulation is particularly simple. In order to obtain in the model the same strains and stresses as in the reactor structure, it is necessary to apply to the model components the same forces per unit area of the reactor but with the time scale compressed by the factor 5 of the geometrical dimension reduction.

Great care was given to the simulation of the explosive rupture. On the basis of the experimental results obtained in the Betulla facility, N_2 gas at room temperature and at a 3.0 MPa pressure has been adopted as the explosive fluid, instead of pressurized vaporizing hot water.

The main results of the first series of tests can be summarized as follows:

- strains and stresses in the linkage elements were found to be very small for both central and lateral ERPT;
- the water tank motion was cleary identified;
- interesting information was gathered on the significant damping role of the shield structures.

The pressure transients in the water tank were in satisfactory agreement with those measured in the full-scale tests in the Betulla facility. No damage to the model structures was observed, a further proof that all strains and stresses were well within the material elastic limits.

1. Introduction

The CIRENE reactor is a heavy water moderated prototype power reactor (40 MWe), cooled by vaporizing light water flowing in 60 vertical pressure tubes, which is now being built near Rome. In the frame of the safety studies for this reactor the Explosive Rupture of a Pressure Tube (the so-called ERPT accident), which has been demonstrated to be a practically impossible event, has been carefully examined. The detailed mechanism of this hypothetical accident and its effects such as the pressure peaks inside the heavy water tank and the possible damages on the power channels adjacent to the exploding-one, were extensively studied by nearly full-scale tests in a facility called Betulla at the Ispra Euratom Research Center. The main results of these investigations were presented at previous SMIRT conferences [1, 2].

Owing to the characteristics of the Betulla facility, those tests could not give information on the dynamic loads and stresses due to ERPT in the main components of the structure supporting the heavy water tank. Therefore it was decided to perform a special series of ERPT tests on a purposely built 1:5 scaled-down model of the reactor structure called MARC. This paper presents the main results of this measurement campaign.

2. Description of the MARC structure

2.1 Main components

The MARC structure is a scaled-down 1:5 model of the CIRENE reactor assembly. An overall view of this structure is given in the picture of Fig. 1. The vertical section and the plane view are presented in the schematic drawings of Figs. 2 and 3, respectively.

The main components of the MARC structure are the following:

- The water tank, mainly composed of two coaxial vertical steel cylinders closed at the bottom by an horizontal circular steel plate.
  The two volumes so formed, one central and the other annular, are in communication through an annular opening present at the lower end of the inner steel cylinder.
- Two horizontal circular structures, one above and the other below the water tank, each composed of several parallel steel plates.
- 60 vertical tubes, simulating the reactor power channels, arranged according to a square array with a lattice pitch $\frac{270}{5} = 54$ mm; 21 of these tubes are rigidly connected (by bolted joints) at both ends to the horizontal circular structures.
- The structure simulating the neutron and biological shields, surrounding the water tank.
  The vertical walls of this structure are shaped with the inner as a circular cylinder and the outer as a dodecagonal prism. This structure is entirely supported by the MARC heavy frame.
- The structural elements of linkage between each horizontal circular structure and the MARC heavy frame.
  The upper horizontal circular structure is suspended by 6 equal linkage elements consisting of I-beams, regularly placed along a circumference;

the lower horizontal circular section leans on the MARC heavy frame by means of 6 equal linkage elements similar to the previous ones, but not identical (Figs. 2 and 3).

The two horizontal circular structures are strongly linked together by means of the 60 vertical tubes. The whole weight of the water tank is directly transmitted to the lower horizontal circular structure, to which the water tank circular plate is linked by the 60 penetration joints. With the only exception of the MARC heavy frame, all the above mentioned structures are in 1:5 scale with respect to the CIRENE reactor. In normal operating conditions, the central volume of the water tank is almost entirely filled with water, whereas the surrounding annular volume is filled with gas; the gas pressure is set at a value which maintains the presence of a water level in the annular opening between central and annular volumes.

The MARC structure components have been purposely built for the tests here presented, except for the water tank, previously built by ISMES for other tests on the CIRENE reactor. A summary of the main component data is given in Table 1.

2.2 General simulation criteria

The basic simulation criteria adopted in the model design were:

- reduction of the reactor assembly dimensions by a factor 5;
- use in the model of the same materials as in the reactor structure.

These criteria, which are standard for the mechanical modelling, were rigorously applied in all circumstances relevant to the main objectives of the model tests. As already said, the tests were generally aimed at determining the structural effects of an ERPT accident occurring in central or peripheric position. More precisely, the main interest regarded the linkage elements between the two horizontal circular structures and the heavy frame. In fact, these elements are by far the most loaded structures in an ERPT accident (outside the water tank), as shown even by a rapid analysis.

The phenomenon here considered, i.e. the dynamics of an explosion in a confined volume, is essentially determined by pressure forces and inertial forces. Other types of forces (due to gravity, viscous friction, etc.) are negligible. In this case the simulation is particularly simple. In order to obtain in the model the same strains and stresses as in the reactor structure, it is necessary to apply to the model components the same forces per unit area (pressures) as in the reactor, but with the time scale compressed by the factor 5 of the geometrical dimension reduction.

On the basis of these considerations, assuming an elastic behaviour of the materials, the following ratios are obtained between the quantities in the reality and in the model (R/M): 5 for the lengths, 25 for the surfaces, 125 for the volumes, 125 for the masses, 5 for the times, 25 for the forces, 1 for the pressures, 1 for the mechanical strains and stresses, 0.2 for the frequencies, 125 for the energies.

2.3 Instrumentation

The following primary sensors were used in the MARC structure:

- No. 10 piezoelectric pressure transducers and No. 2 piezoresistive pressure transducers for pressure measurements in the water tank;
- No. 5 LVDT, radially or axially directed at different heights and angles, in contact with the wall outside the water tank for its motion measurement;
- No. 2 piezoresistive transducers for pressure measurements in the water gap between shield and water tank;
- No. 4 strain gages on each of the 6 + 6 linkage elements, attached on the vertical section of the I-beam, 2 in each side, measuring the vertical strains, along the vertical symmetry axis at two different height;
- No. 12 strain gages (of the rosette type), arranged in various positions on the water tank walls (8 on the upper circular plate, 1 on the lower circular plate, 4 on the inner cylinder).

The signals of these primary sensors were amplified and conditioned as usual, and were recorded on a 32-trace FM magnetic tape recorder (tape speed: 30 ips; max frequency 20 kHz; signal-to-noise ratio 45 dB).

2.4 Burst element

A key component of the MARC structure was obviously the burst element, one of the 60 tubes simulating the CIRENE power channels, positioned either in central or in peripheric positions, as shown in fig. 3. The design of this element was based on the following considerations.

- In order to maximize the explosion effects, no insulation tube surrounded the pressure tube. It is worth recalling that this was also the case of the great majority of the Betulla tests [1, 2].
- The fluid volume in the burst element acting as the explosive fluid, i.e. being in direct contact with the surrounding water immediately after the rupture of the pressure tube, was equal to 100 cm^3, i.e. to about 1/125 of the whole coolant volume in the active length of a CIRENE power channel. This condition is again a very conservative one.
- Gas N_2 at room temperature and at a 3.0 MPa pressure was used as the explosive fluid instead of pressurized vaporizing hot water. This choice, suggested by the remarkable simplification of the experimental apparatus, was justified by some experimental results obtained in the Betulla facility, where similar pressure peaks in the water tank were observed having, in the burst element, gas N_2 or pressurized hot liquid water or pressurized hot steam-water mixtures [1].
- Owing to the impossibility of finding on the market a Zircaloy-2 tube of dimensions reduced by the factor 5 with respect to those of the CIRENE pressure tube and owing also to the necessity of having a very rapid pressure tube rupture exactly at the desired pressure, a burst element of special design was adopted for the MARC tests.

As shown in Fig. 4, the burst section of this element, only 445 mm long on a total free length of 930 mm, was placed at the tank mid-height, with gas access from above (through a de-coupling orifice) and pressure measurement from below. This burst section was essentially composed of a cylindrical bar (Ø 30 mm) with a longitudinal slot (6 mm wide, 17 mm deep) obtained by milling machine) and of a thin AISI 304 sheet (0.05 mm thick) covering the entire slot opening, welded to the cylindrical bar and tightly sealing its volume. The explosion direction, determined by the slot orientation, was always radial towards the outside (see the arrows in Fig. 3). The burst condition was reached by progressively increasing the gas pressure up to the point where abruptly the AISI 304 sheet ruptured. In all the tests the rupture opening length was about 1/4 of slot length. The burst pressure ranged between 2.8 and 3.2 MPa, with an average of about 3.0 MPa, which is a remarkably uniform result.

3. Results

3.1 Generals

The measurement campaign on the MARC structure consisted of 8 burst tests, performed in 1978. A summary of the main test conditions is given in Table 3.

The tests performed in fully representative conditions were only the last two (Nos. 7 and 8). Very similar results were obtained in tests Nos. 5 and 6, where out of the 60 tubes only the burst element and the two instrumented tubes were present. In tests Nos. 3 and 4 the massive shield structure surrounding the water tank could not affect its movements, owing to the absence of water in the gap. The two first tests were performed with only half of the linkage elements mounted, to enhance their strain. In each different MARC condition, two tests were carried out, with the burst element in central position in one case,and in peripheric position in the other case.

It is a very hard task to adequately summarize in this few pages the large amount of data and information gathered in the 8 tests, (in each test more than 30 different transient signals were recorded). The results are essentially presented as examples, in Figs. 5 to 9 and in Tables 4 to 6.

3.2 Pressure peaks in the water tank

The full time evolution of the pressure transient in the water tank is well represented in Fig. 5. The upper curve (label KCL 2), which refers to the pressure in the central gas volume, clearly shows some compression cycles, strongly damping-out (only the two first cycles are shown), corresponding to expansions and contractions of the gas "bubble" generated by the explosion. The two other curves present typical pressure transients in the water volume, on the instrumented tube placed in front of the explosion (DV2) and on the water tank bottom (KFS11). These transients are similar in shape and amplitude to those observed in the Betulla tests and can be considered as consisting of a first pressure "peak", due to the exploding phase, actually articulated in 3 or 4 pressure pulses of rapidly decreasing amplitude, and of a second pressure peak, due to the first gas bubble implosion. The subsequent pressure peaks are negligible from the engineering point of view.

As to the first pressure peak, the oscillating shape with several pressure pulses can be interpreted as the result of the transient excitation of a resonance phenomenon of the mass-spring type. The term "spring" refers to all the important elastic forces, in particular to the gas bubble compression forces and to the elastic forces exerted on the water by the vessel wall contractions and expansions. This resonance phenomenon was much less evident in the Betulla tests, where the first pressure peak in the water had essentially an almost triangular shape without oscillations, probably because of the much lower importance of the above mentioned "spring" actions.

The detailed shape of the pressure transient in the water volume during the explosion phase (the first 10 ms) is shown in Fig. 6. The upper curve (KS1) refers to the pressure inside the burst element: notice the very rapid depressurization. The two subsequent curves present typical pressure transients within the water tank on the peripheric instrumented tube (DV1, Fig.3) and on the inner steel cylinder (KDC1). The lower curve refers to the strain transient in the tangential direction near the position of the pressure transducer KDC1. Notice the correspondence between pressure pulses and strain pulses, which tends to confirm the contribution of the vessel wall elasticity to the pressure pulse formation. On the whole, in this explosion phase the first pressure pulse is by far the most prevailing and is the one to be considered in the comparison with the so-called "first pressure peak" of the Betulla tests [1, 2].

The main data regarding the pressure peaks measured in the water tank are summarized in Table 4.

One of the most important objectives of the MARC tests was to evidence the differences between ERPT in central and in peripheric position, which could not be measured in the Betulla campaign, where the burst element was always in central position. In particular, it was feared that for a peripheric pressure tube explosion towards the inner steel cylinder, strong net lateral forces could be acting temporarily on this vessel, thus exciting the lateral vibration modes of the whole reactor assembly and possibly excessively stressing its supports. Indications on these net forces can be drawn from the diagrams of the circumferential distribution of the maximum pressures at the vessel wall in the first pressure pulse (e.g. Fig. 7). In the cases of central explosion (continuous lines in Fig. 7), uniform pressure distributions were observed, whereas for peripheric explosions (dotted lines) the wall pressures in the positions directly invested by the explosion were found to be up to 2-3 times higher than the average values. The resulting net forces acting on vessel lasted however no more than few ms.

As well-known [3] , the time distance ΔT_{I-II} between the first and the second pressure peak is a meaningful index of the mechanical energy delivered by the explosion. In order to estimate this mechanical energy it is very useful to consider the compression energy delivered to the gas volumes (central and annular) during the first gas bubble expansion, i.e. during the first half of the time interval between the first and the second pressure peak. In the MARC tests the compression energy of the gas volumes was determined to be about 1 Kj. It is worth recalling that in the Betulla full-scale tests characterized by a burst element rupture 1 m long only, the gas volume compression energy was about 125 Kj, i.e. 1 Kj multiplied by the energy scale factor of the model (125) and the corresponding ΔT_{I-II} about 150 ms, i.e. 30 ms multiplied by the time scale factor of the model (5).

In the MARC tests, approximately 1/3 of the total mechanical energy (1 Kj) was delivered in the first instants (1 ms) of the explosion, during the very rapid depressurization (necessarily adiabatic) of the burst element gas.

3.3 Transient motion of the water tank

The pressure tube explosion originated a complex water tank transient motion, essentially occurring in the radial plane of the burst direction (see typical LVDT signal transients in Fig. 8). This motion, of basic oscillatory nature, with the prevailing frequencies concentrated around 30 Hz (6 Hz for the CIRENE reactor), appears to be composed of radial translation and rotation and of axial translation.

The maximum measured displacement values are summarized in Table 5.

As expected, in the case of peripheric explosion the radial displacement in the explosion direction was larger than in the case of central explosion (see also Fig. 8). The displacements in the axial direction were in general much lower than those in the radial direction. The radial motion substantially reduced passing from 3+3 to 6+6 linkage elements and further reduced when the gap between shield structure and water tank was filled with water. The containment action of the shield structures is also evidenced by the pressure transient in the water filling the gap, which reached peak values up to 0.05 MPa. It may be useful to recall that the static radial elasticity of the water tank was found to be equal to 195 x 10^6 N/m (88 x 10^6N/m for 3+3 linkage elements only). These data and the rather low displacement values found in the case of peripheric explosion, allow to conclude that the net forces acting on the water tank walls were always rather small and lasted only very short times.

3.4 Linkage element strains

Strains and stresses in the linkage elements (material Fe42) essentially arose because of and in correspondence with the radial water tank displacements. Typical strain transients are shown in Fig. 9. The maximum measured strains are summarized in Table 6. For simplicity's sake, the results reported in Table 6 refer to 4 linkage elements only, 2 upper and 2 lower, in the positions A and B (Fig. 3). The data refer to the strain gage signal (out of 4) which measured (on the average) the highest strain values. On the whole, the strains measured were fully within the elastic limits of the materials and were indeed very low. The lower linkage elements appeared to be slightly less strained than the upper ones.

4. Conclusions

On the basis of the experimental results obtained in a series of tests performed in a 1:5 scaled-down model of the CIRENE reactor assembly called MARC, it can be concluded that the hypothetical explosion of a pressure tube in the water tank, no matter of its position, does not cause any permanent damage to the structures outside the water tank, the stress transient due to the explosion being well within the material elastic limits.

References

[1] Famiglietti M., Galbiati L., Parmeggiani A., Possa G.: "Pressure bursts due to power channel explosion in a pressure tube reactor," Proc. Third Intl. Conf. on Structural Mechanics in Reactor Technology, London, Great Britain (1975).

[2] Dallavalle F., Hotz A., Possa G.: "Explosive rupture of a power channel pressure tube in a D_2O reactor," Proc. Fourth Intl. Conf. on Structural Mechanics in Reactor Technology, San Francisco, USA (1977).

[3] Cole R.H.: "Underwater explosions," Dover Publ. Inc., New York (1965).

Table I - Summary of the dimensional data of the MARC main components.

	Unit	CIRENE reactor	MARC structure
Water tank			
- ID of the central volume (cylinder)	cm	369	73.8
- ID of the annular volume (outer wall)	cm	520	104.0
- inner cylinder thickness (AISI 304)	mm	20	4
- outer cylinder thickness (AISI 304)	mm	20	4
- water level in the central volume	cm	450	89
- water level in the annular opening	cm	75	15
- gas volume in the central volume	dm^3	$2.14x10^3$	17
- gas volume in the annular volume	dm^3	$33.5x10^3$	265
- distance between the two horizontal circular structures	cm	465	93
- minimum net radial distance between annular volume and shield	cm	5	1
Power channel			
- main components: pressure tube (TP), insulation tube (TI), 18 UO_2 rod bundle	-	TP + TI+ UO2	one tube only
- OD of the outer tube	mm	126	25
- weight per unit length	g/cm	664	23
Weights			
- water tank (only structures)	Kg	$37.2x10^3$	298
- upper horizontal circular structure	Kg	$70.4x10^3$	563
- lower horizontal circular structure	Kg	$43.9x10^3$	351
- moderator	Kg	$52.9x10^3$ (D_2O)	385 (H_2O)

Table II - Summary of the dimensional data of the MARC linkage elements.

	Unit	Lower	Upper
Linkage elements (I-beams); the vertical part consists of two equal parallel steel plates			
- Length	mm	120	100
- Total height	mm	117	98
- Plate height	mm	95	78
- Plate thickness	mm	4	2
- Plate gap	mm	0.6	0.6
- Mounting circle radius	mm	355	480

Table III - Summary of MARC tests

	Test No.							
	1	2	3	4	5	6	7	8
- burst element position (C Central, P peripheric)	P	C	C	P	P	C	C	P
- array of the 60 tubes (P present; NP not present)	NP	NP	NP	NP	NP	NP	P	P
- water in the gap between water tank and shield (P present, NP not present)	NP	NP	NP	NP	P	P	P	P
- mounted linkage elements (3+3 or 6+6)	6	6	12	12	12	12	12	12

Table V - Summary of MARC test results: maximum values of the vater tank displacements (μm).

	Test No.							
	1	2	3	4	5	6	7	8
maximum radial displacement at a 90 cm height								
- in the explosion direction	182	180	16	174	39	22	17	68
- opposite the explosion direction	112	121	23	75	24	16	30	29
maximum axial (vertical) displacement								
- upwards	31	31	19	34	9	15	18	12
- downwards	26	27	18	22	11	11	9	8

Table IV - Summary of MARC test results: pressure peaks in the water tank.

	Test No.							
	1	2	3	4	5	6	7	8
first pressure pulse								
- P_{max} (MPa)								
. DV1	0.31	0.29	0.30	0.52	0.39	0.31	0.26	0.29
. KDC1	0.57	0.34	0.36	0.74	0.53	0.32	0.26	0.53
. KFS11	0.17	0.15	0.20	0.19	0.13	0.20	0.22	0.20
- $\int pdt$ (MPa·ms)								
. DV1	0.33	0.33	0.30	0.66	0.48	0.34	0.31	0.34
. KDC1	0.52	0.31	0.29	0.87	0.55	0.28	0.26	0.49
. KFS11	0.15	0.12	0.13	0.14	0.10	0.19	0.26	0.17
- duration (ms)								
. DV1	1.8	1.9	1.8	1.8	2.2	1.9	2.4	1.9
- pressure rise velocity (MPa/ms)								
. DV1	0.47	0.33	0.43	1.22	0.66	0.46	0.31	0.39
second pressure peak								
- $\int pdt$ (MPa·ms)								
. DV1	-	0.72	0.49	1.01	0.63	0.58	0.43	0.48
. KDC1	0.88	0.90	0.55	2.30	0.93	0.40	0.33	0.58
. KFS11	0.25	0.28	0.22	0.18	0.13	0.31	0.39	0.20
- ΔT_{I-II} (ms)								
. DV1	30.8	24.8	23.6	30.0	26.0	27.0	30.8	35.2

pressure transducer positions:

. DV1 : on the instrumented tube placed in peripheric position (marked in black and white in Fig. 3);
. KCD1 : on the inner vessel wall in front of the explosion;
. KFS11 : on the water tank bottom, near the center.

Table VI - Summary of MARC test results: maximum strains in the linkage elements ($\mu\varepsilon$).

	Test No.							
	1	2	3	4	5	6	7	8
upper linkage elements								
- A, outer side								
. compression	267	230	38	163	61	41	54	60
. tension	249	252	39	190	57	29	36	54
- B, outer side								
. compression	196	302	82	215	57	47	55	56
. tension	285	456	43	199	72	62	55	64
lower linkage elements								
- A, outer side								
. compression	134	64	31	103	11	14	23	14
. tension	155	83	32	81	31	25	23	42
- B, outer side								
. compression	138	65	11	63	16	9	12	22
. tension	148	72	18	98	17	12	10	17

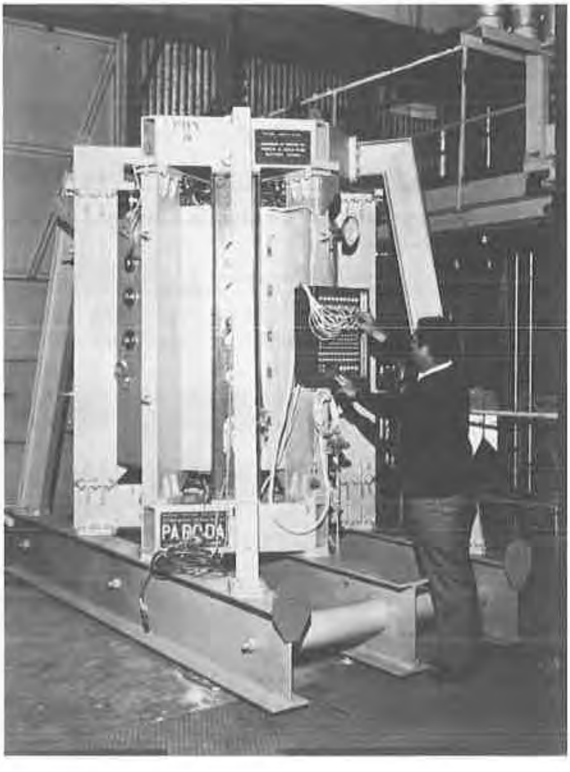


Fig. 1 - Overall view of the MARC structure.

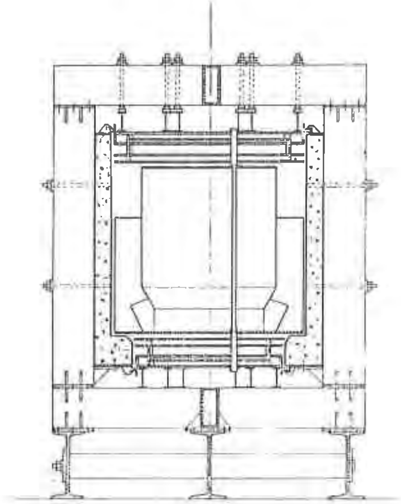


Fig. 2 - Vertical section of the MARC structure (schematic drawing).

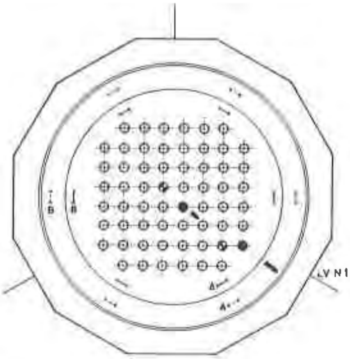


Fig. 3 - Horizontal section of the MARC structure (schematic drawing).

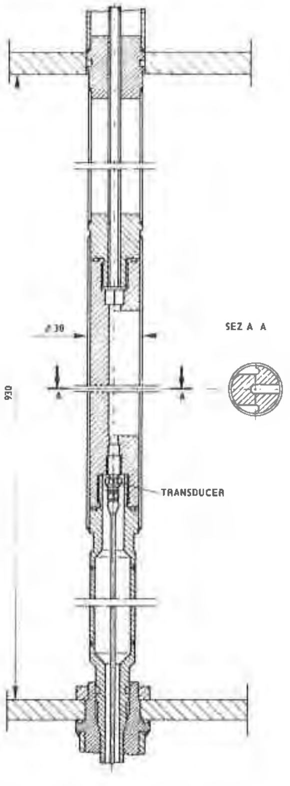


Fig. 4 - Burst element sections.

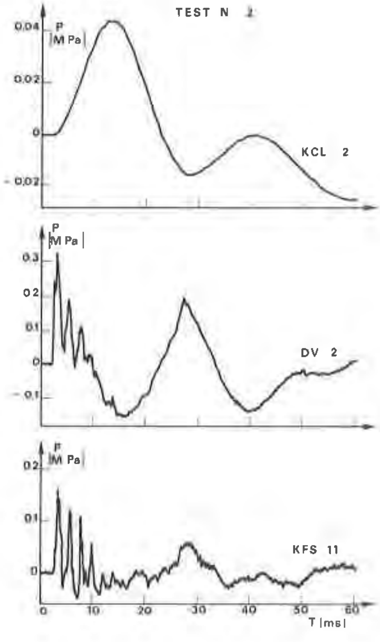


Fig. 5 - Pressure transients in the water tank.

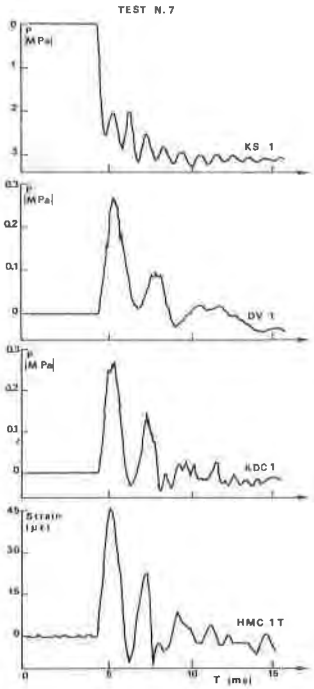


Fig. 6 - First pressure peak in the water tank.

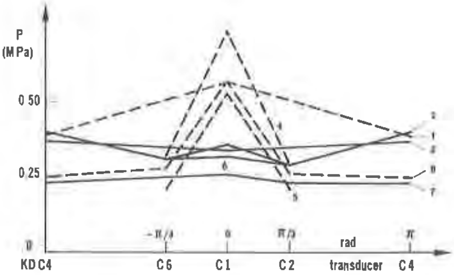
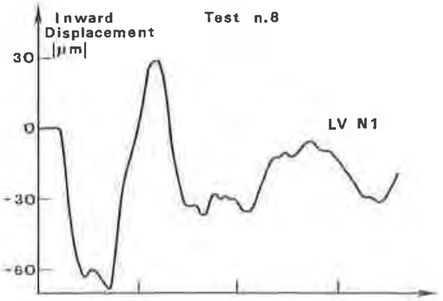


Fig. 7 - Peak pressures on the inner vessel wall (first pressure pulse).



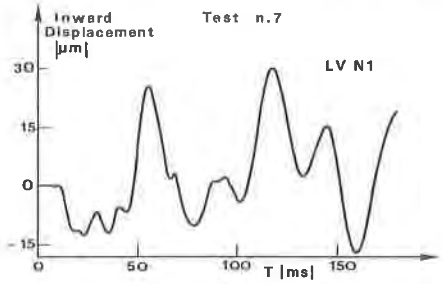
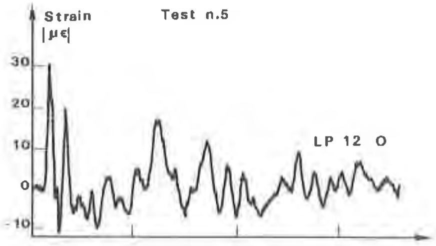


Fig. 8 - Typical water tank displacements in radial direction.



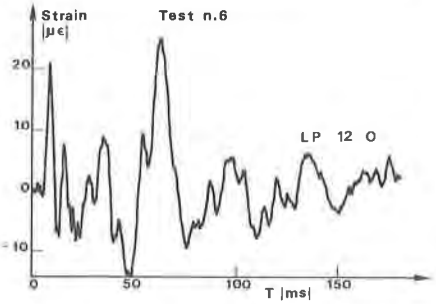


Fig. 9 - Typical strain transients in the linkage element A.