PRESSURE VESSEL LOADING DUE TO A CHANNEL RUPTURE IN A PRESSURE TUBE REACTOR

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ABSTRACT

The present state of knowledge concerning the loading of a vessel of a pressure tube reactor during a channel rupture accident is dicussed in this paper. Tests were performed in which water cooled channels were exploded at 264°C and 50 atm. The results show that the pressure peaks generated in the water are due to the fast expansion and recondensation of a big vapour bubble in the first 0,1 second after the explosion. The condensation velocity of this bubble and the collapse pressure are calculated and the results are compared with experimental data.

1. INTRODUCTION

The rupture of a whole channel in the vessel of a pressure tube type reactor is one of the severe accidents which has to be considered in the hazards analysis. A knowledge of related problems is essential in defining the criteria for the design of the reactor vessel.

An experimental and theoretical programme was undertaken to study the rupture of a channel filled with saturated water at 50 atm and 264°C. The experiments carried out simulated the essential parts of the actual geometry of a pressure tube reactor but light instead of heavy water was used.

2. EXPERIMENTAL RIG - CHARACTERISTICS

A detailed description of the plant is given in ref. [1]. The main characteristics of this plant are :

- a high temperature and high pressure circuit (450°C, 50 atm; capacity 5 m^3)
- a vessel and related water circuit constructed for 185°C and 12 atm (capacity 12 m^3)
- a building structure and control bunker.

The high temperature and pressure circuit (see flowsheet in fig. 1) comprises two tanks S_2 and S_3, a pump and the test section. The liquid leaving the pump enters the bottom of tank S_2. The S_2 tank outlet is connected to the test section from which the liquid goes to tank S_3 and from there returns to the pump. The pump, tanks and test section have each a bypass.

The vessel simulates the reactor vessel and has dimensions as given in fig. 2. It is of extra-rugged construction and supported by four strong brackets, which transfer all loads to the prestressed concrete base.

The vessel has dished heads. A false bottom is fitted to guide the elements to the same flat level as that in an actual vessel. The top cover of the vessel, which is used to house a gas blanket, is connected via a 300 mm diameter pipe to the safety disc.

3. THE RUPTURE OF A CHANNEL BENEATH THE LEVEL OF THE MODERATOR

3.1. Description of experiments

Three experiments have been performed.
The exploding channel (see fig. 3) consisted of a SAP (10% Al_2O_3) pressure tube rolled onto two stainless steel ends which are connected to the high temperature circuit. A calandria tube, which was of Aluminium, separated the pressure tube from the light water used to simulate the moderator.

The pressure tube and the calandria tube were weakened by milling so that the failure occurred along the desired generatrix. The experiments were conducted with a fuel element mock-up inside the pressure tube.

A summary of the experimental conditions is given in Table I.

As can be seen from fig. 4 the explosions caused a complete opening of the channel over the milled length. An opening of he channel beyond the weakened zone could only be avoided by increasing the channel strength with steel rings at the ends of the milled generatrix.

3.2. Discussion of test results

3.2.1. Pressure measurements

Pressures have been measured with strain gage transducers having a frequency response from 0 - 5000 Hz. These transducers were mounted on the vessel wall. In addition, piezoelectric transducers have been used at different positions in the vessel in order to observe the pressure near the rupture point. The pressure signals were recorded on magnetic tape, the total detectable frequency range being up to 100 kHz.

Fig. 5 shows pressure records taken from transducers mounted in the gas blanket and on the vessel wall.

Analysing these diagrams the following phenomena can be observed :

At the moment of the explosion (due to the rapid vapour release) a pressure wave is produced which propagates in the water but is not transmitted to the gas blanket.
The amplitude of this wave reaches 10 atm and has a width of about $1.5 \cdot 10^{-2}$ sec.

Beginning from the moment of the explosion a gradual increase of the pressure in the gas blanket occurs reaching its maximum value of about 1 atm at about 0.05 seconds after the explosion. This pressure increase is due to the production of vapour in the water which reduces the free gas volume.

Beginning from a time 0.05 seconds after the explosion, the pressure in the gas gradually decreases showing that the vapour volume under water level is also decreasing. The pressure reaches a value of almost zero at about 0.1 seconds after the explosion.

At that time a second pressure pulse occurs in the water, probably because of the collapse of the vapour bubble.

In order to prove this "bubble collapse" interpretation of the results, small scale experiments were performed in which the high temperature coolant was injected into water at temperatures of 50, 80 and 100°C.

The results of these experiments showed that the injection of high temperature coolant into a pool of water at 50°C causes strong pressure peaks whereas at a temperature of 100°C the vapour cannot condense and therefore no pressures are recorded.

Strain gauge measurements performed on the channel during the large scale experiments showed that the pressure peaks caused by recondensation phenomena may cause more damage on the internals than the initial evaporation peak. Therefore a more detailed theoretical study has been undertaken in order to get a theoretical interpretation of phenomena accompanying the fast expansion and recondensation of large vapour quantities in a reactor vessel.

3.3. Calculation of the volume of vapour released in the first tenth of a second after channel rupture.

The assumption has been made that the cover gas in the vessel is isothermally compressed during the expansion of the vapour bubble. With this hypothesis the volume of the bubble can easily be calculated by the expression :

$$p.V = \text{const}$$

where V is the initial cover gas volume and P the pressures measured during the experiments.

Fig. 6 shows the calculated radius of an assumed spherical bubble in experiment 3.

3.4. Calculation of the condensation velocity and collapse pressure of a spherical bubble in an unbounded medium

3.4.1. Mathematical analysis

The general analysis of the collapse of a bubble is quite difficult because of the irregular shape and displacement of the bubble, the perturbation in the adjacent liquid and the possibility of reflections and interactions with walls or obstacles.

It is in fact a three-dimensional fluid-dynamic problem. It is usual to make some simplifying assumptions in order to reduce the mathematical and numerical difficulties of the problem. These assumptions are the following :

a) Spherical symmetry. It is assumed that the bubble has always a spherical shape with a fixed center; that the liquid around the bubble is initially at rest; that the bubble diameter is small relative to the region occupied by the liquid so that reflection phenomena are negligible.

b) Viscosity and thermal conduction in the liquid are negligible; the flow is isentropic.

c) The gas or vapour in the bubble is uniform. The compression and expansion is adiabatic or isothermal. The pressure is a function of the density only and hence a function of the bubble radius.

Under these assumptions we then have the one-dimensional system of equations (in eulerian form) :

$$(1)\quad \begin{cases} \dfrac{\partial \rho}{\partial t} + v\dfrac{\partial \rho}{\partial r} + \rho\dfrac{\partial v}{\partial r} + \dfrac{2\rho v}{r} = 0 & \text{(continuity equation)} \\ \dfrac{\partial v}{\partial t} + \dfrac{v\partial v}{\partial r} + \dfrac{1}{\rho}\dfrac{\partial p}{\partial r} = 0 & \text{(momentum equation)} \\ \dfrac{p+b}{p_\infty + b} = \left(\dfrac{\rho}{\rho_\infty}\right)^n & \text{(state equation)} \end{cases}$$

ρ, p, v are respectively : density, pressure and velocity. In the case of water and if the pressure is measured in atm. $b=3000$ and $n=7$. p_∞, ρ_∞ are the pressure and density in the liquid at rest.

The equation of state for the gas in the bubble is :

$$\frac{p}{p_0} = \left(\frac{\rho}{\rho_0}\right)^\gamma$$

$\gamma > 1$ in the adiabatic case, $\gamma = 1$ in the isothermal case.
ρ_0, p_0 are the initial values of ρ, p inside the bubble.

Because of the assumption that the mass of the gas inside the bubble is constant, we have :

$$\rho_0 R_0^3 = \rho R^3$$

hence :

$$p = p_0 \left(\frac{R_0}{R}\right)^{3\gamma}$$

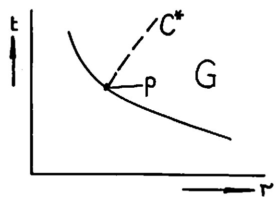
R is the bubble radius. R_o is the initial value of R.
The case of the collapse of an empty spherical bubble has been investigated and solved by Rayleigh [2]. The solution has a singularity since R goes to zero while $\dot{R}$ and the pressure p on the bubble surface tend to infinity.

This singularity is removed if the bubble contains a small amount of gas or vapour.

The problem of the collapse of a spherical bubble containing gas or vapour has been studied and solved by many investigators, see ref. [2, 3, 4, 5, 6, 7].

The solution may be obtained in essentially two ways. The first is to solve system (1) numerically. The second is to introduce the so-called Kirkwood-Bethe hypothesis which makes it possible to substitute for the system (1) of partial differential equations a set of ordinary differential equations and so to reduce the numerical work. We shall outline the second method.

In the r, t plane let R = R (t) be the trajectory of the bubble wall and let G denote the region filled by the liquid ($r \geq R(t)$, $t \geq 0$)



System (1) must be solved in the region G with the initial conditions :

$$\rho = \rho_\infty \;;\quad p = p_\infty \qquad v = o \quad \text{for } t = o$$

and the boundary condition :

$$P(r,t) = P_0 \left(\frac{R_0}{R}\right)^{3\gamma} \qquad \text{at } r \;\; R(t)$$

where $P(R(t), t)$ is the pressure on the bubble wall. We shall write $p [R(t), t] = p(R)$.

This is a free boundary problem since the trajectory R (t) is an unknown of the problem. The problem can be solved numerically. However, a more convenient approximate solution may be obtained the Kirkwood-Bethe hypothesis.

For this, let us consider the enthalpy :

$$h(p) = \int_{p_\infty}^{p} \frac{dp}{\varrho}$$

The Kirkwood-Bethe hypothesis says that the quantity :

$$w = r\,(h + \frac{v^2}{2})$$

is constant along the C^+ characteristics of system (1). By definition these characteristics are the curves tangent to the direction field v + c and hence are solution of the differential equation :

$$\frac{dr}{dt} = v + c$$

Using this hypothesis it is possible to deduce from system (1) the following ordinary differential equation which holds along the trajectory R(t) :

$$(2) \quad -R\,(1 - \frac{V}{C})\,\frac{dV}{dt} + \frac{R}{C}\,(1 - \frac{V}{C})\,\frac{dH}{dt} + (1 + \frac{V}{C})\,(H + \frac{V^2}{2}) - 2V^2 = 0$$

R, V, C, H are the values of r, v, c, h computed on the bubble wall. We refer to ref. [3 to 7] for the motivation of the Kirkwood-Bethe hypothesis and the calculations leading to the ordinary differential equation given above.

V, C, H may be expressed as function of R :

$$P = p(R) = p_0 \left(\frac{R_0}{R}\right)^{3\gamma}$$

$$\varrho(R) = \varrho_\infty \left(\frac{p(R) + b}{p_\infty + b}\right)^{1/n}$$

$$C = c(R) = \sqrt{n\,\frac{p(R) + b}{\varrho(R)}}$$

$$H = h(R) = \frac{c^2(R) - c_\infty^2}{n - 1}$$

$$V = \frac{dR}{dt}$$

Given the initial conditions R and V the differential equation (2) determines the motion of the bubble wall.

It can be proved that :

$$V = \frac{2}{n-1}\left(c(R_0) - c_\infty\right)$$

Using the Kirkwood-Bethe hypothesis it is possible to determine the C^+ characteristics and along them the quantities v, h as solutions of the following system of ordinary differential equations :

$$\frac{dr}{dt} = v + c$$

$$\frac{dv}{dt} = \frac{w}{r^2}\,\frac{c+v}{c-v} - \frac{2c^2 v}{(c-v)r}$$

with :

$$c^2 = (n-1)h + c_\infty^2 \quad \text{and} \quad h = \frac{w}{r}$$

The initial values of r, t, v, w are those relative to the point P on the curve R(t) from which the characteristic starts. If we compute v, p along different characteristics C^+ at the same time t, we get the distribution of velocity. v and pressure p in the liquid at time t.

The results obtained with the use of the Kirkwood-Bethe hypothesis and those obtained by solving system (1) numerically are in good agreement ; see [6].

3.4.2. Discussion of results

The code developed on the basis of the preceding theory has been used to calculate the radius of a condensating bubble as a function of time. The initial radius Ro was 49,5 cm, the initial pressure in the bubble was supposed to be 2.10^3 dynes/cm^2 and γ had the value of 1,4. Fig. 6 shows that this theory predicts the condensation velocity with very good accuracy. The assumption that one big bubble expands and recondenses in the vessel during the first 0,1 second after the explosion is confirmed.

There is actually no agreement between measured and calculated pressures. Fig. 7 shows the incident pressure predicted by theory which has to be compared with the pressure record of position 16 in Fig. 5.

It clearly appears that wave reflection on phenomena modify the pressure pulse and therefore have to be considered in the calculation. In order to take into account reflections a first model has been developed which describes the propagation of a plane wave in cylindrical geometry [9]. The work will be continued with the study of the wave equations in r, z geometry.

4. THE RUPTURE OF A CHANNEL IN THE COVER GAS VOLUME

4.1. Description of experiments

The probability of rupture of one channel in the gas blanket can be higher than that of rupture in the moderator. This is due to the fact that the calandria tube is only cooled by the cover gas and not by the moderator.

The experiments were performed in two series :

A - The coolant was injected through an open ended tube. The injection began when an automatic valve at a distance of 3 m from the vessel was opened. The principal aim of this study was to measure the pressure during a long injection period.

B - The rupture of the channel was simulated by the explosion of a rupture disc in the gas blanket. In this way pressures generated during the initial fast evaporation of water could be measured.
A summary of the experimental conditions is given in Table II.

4.2. Discussion of test results

4.2.1. Injection without rupture discs

As indicated in Table II the following parameters have been varied :

- the flow rate from 30 to 45 kg/sec
- the free gas volume from 1.1 to 12 m^3
- the temperature of the moderator.

The most evident result of the experiments is that pressures are kept very low by the condensation of the vapour at the water / vapour interface. Fig. 8 shows that pressures tend to increase when the gas volume is increased from 1,1 m^3 to 2,95 m^3. Only by increasing the volume of the gas blanket to 12 m^3 (which cor - responds to a completely voided vessel) are pressures lower than those measured for smaller gas volumes obtained. The main general conclusion to be drawn from these experiments is that no pressure peaks occur in the vessel when two-phase flow of high enthalpy is established in the vapour blanket from the beginning.

During the first second, the pressure increase to a maximum of about 1 atm gauge. At the same time the temperature reaches maximum values of 100°C. After the first second the pressure changes only as a function of the volume of injected water which gradually reduces the cover gas space. The pressure change can then easily be calculated by the expression :

$$\Delta p(t) = P_o \left(\frac{V_o}{V_o - \Lambda t} - 1 \right)$$

where V indicates the cover gas volume and Λ the flow rate.

4.2.2. Injection through a device of rupture discs

As indicated in Table II the following parameters have been investigated :

- flow rate of the water
- volume of gas blanket
- temperature of the water present in the vessel
- pressure relief systems.

Fig. 9 shows typical pressure records for some of the listed parameters. The results indicate that the transient pressures are almost the same for all investigated test conditions. They are generally not higher than 2 atm gauge for a maximum duration of 0.1 second.

Pressure relief systems have no strong influence on the impulse which acts on the top of the vessel. Small gas volumes will increase the immediate condensation of the vapour by the moderator.

AKNOWLEDGEMENTS

This work has been done in cooperation with CISE (Italy), whose representatives, Messrs. G.Gerini and G.Leoni contributed to the design of the experiments and the discussion of the results.

Special thanks are due to Messrs. E.Soma, W.Schnabel, E.Jorzig, N.Tedeschi and A.Ravelli, who performed the experiments and measurements.

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TABLE I

Experiment	Temperature of saturated water	Axial length of the rupture	Total quantity of injected water	Injection time	Rupture pressure of the channel
1.	263 °C	450 mm	590 KG	28 seconds	40 atm
2.	263 °C	2300 mm	440 kg	21 seconds	30 atm
3.	268 °C	1500 mm	720 kg	34 seconds	54 atm

temperature of the moderator : 50 °C.

TABLE II

Series A : injections without rupture discs - water temperature 264 °C at 50 atm - vessel closed

Experiment	Flow rate (kg/sec)	Gas volume (m^2)	Duration (secs.)	Moderator temp.(°C)
1	30	1,1	11	56
2	30	1,5	10	50
3	30	1,93	47	65
4	30	2,79	41	89
5	45	1,5	5,5	45
6	45	1,26	10	50
7	45	2,79	45	55
8	45	12	63	--
9	45	12	4	--
10	45	12	11	--

Series B : injection through a device of rupture discs - water temperatures 264°C at 50 atm.

Experiment	Flow rate kg/sec	Gas volume (m^3)	Duration (secs.)	Moderator temp. (°C)	
11	90	0,87	5	50	vessel opened to the air through to 4" diam. pipes
12	90	0,87	2	50	vessel closed
13	90	0,5	1,6	50	" "
14	45	1,5	1,5	50	" "
15	10	0,87	7,7	50	" "
16	45	0,87	24,5	50	" "
17	90	1,5	4	50	" "
18	90	0,87	3,3	50	" "
19	90	0,87	4,4	50	vessel opened to the air through 12" diam. pipe
20	90	0,87	1,65	50	" "
21	90	0,87	1,25	80	" "
22	90	0,87	3,75	80	" "
23	90	1,5	5,4	80	" "
24	50	0,87	3,6	80	" "
25	vapour only	0,87	--	50	vessel closed

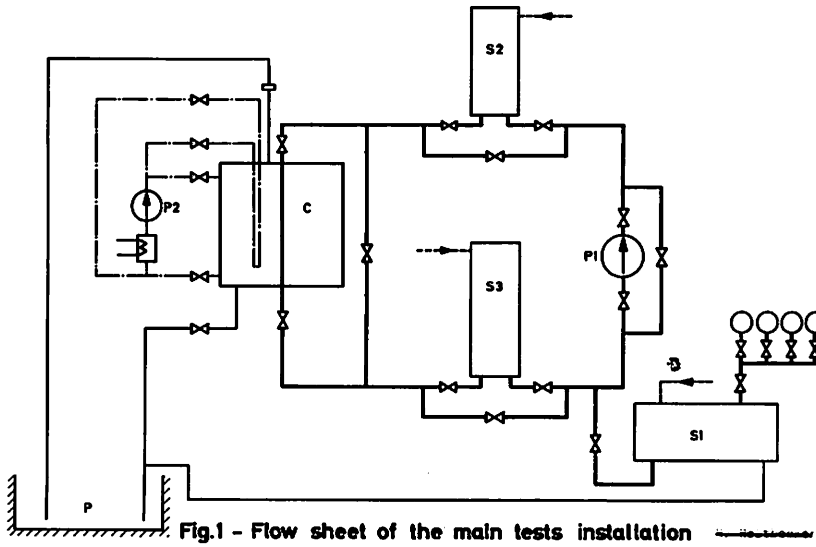


Fig.1 - Flow sheet of the main tests installation

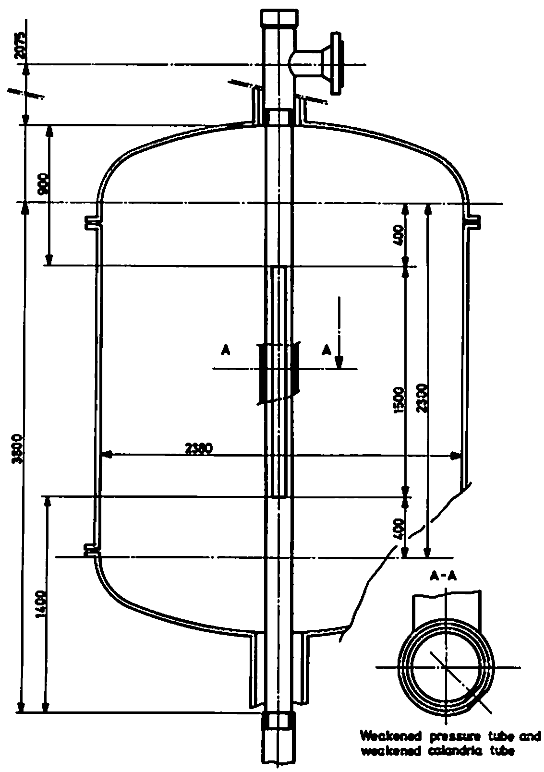


Fig. 2 - Geometry of the vessel

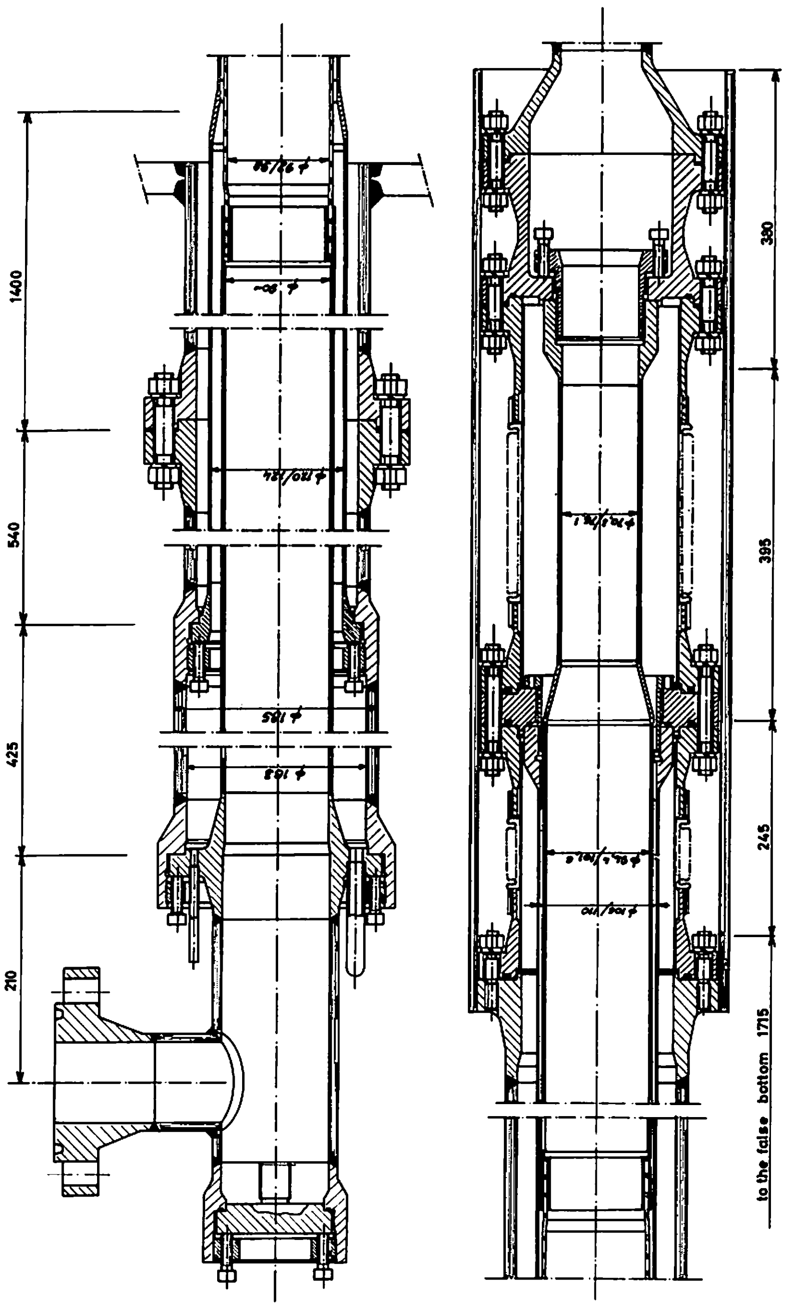


Fig 3 - Channel geometry

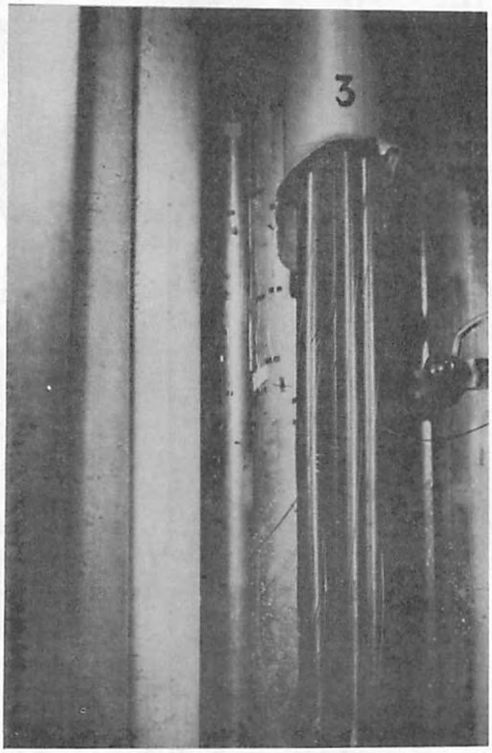


Fig. 4 - Exploded channel experiment 3

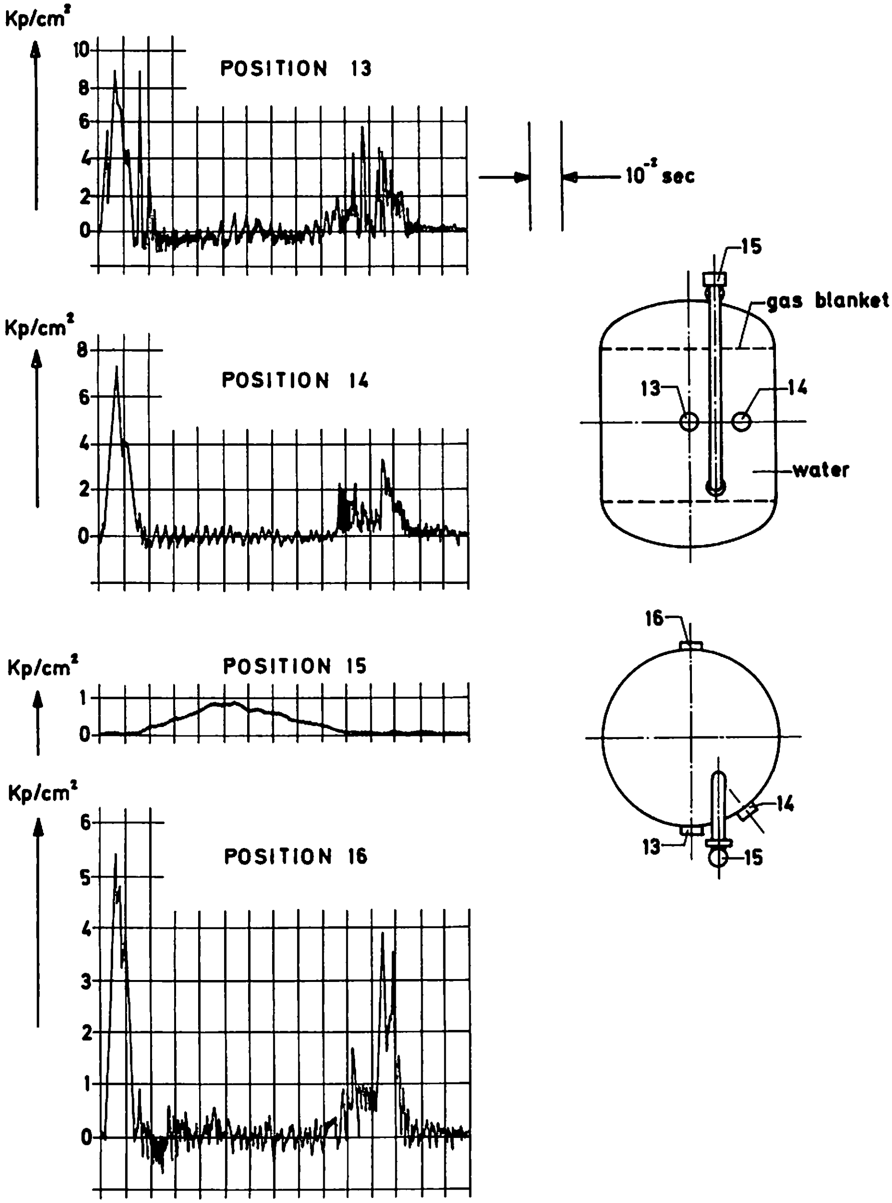
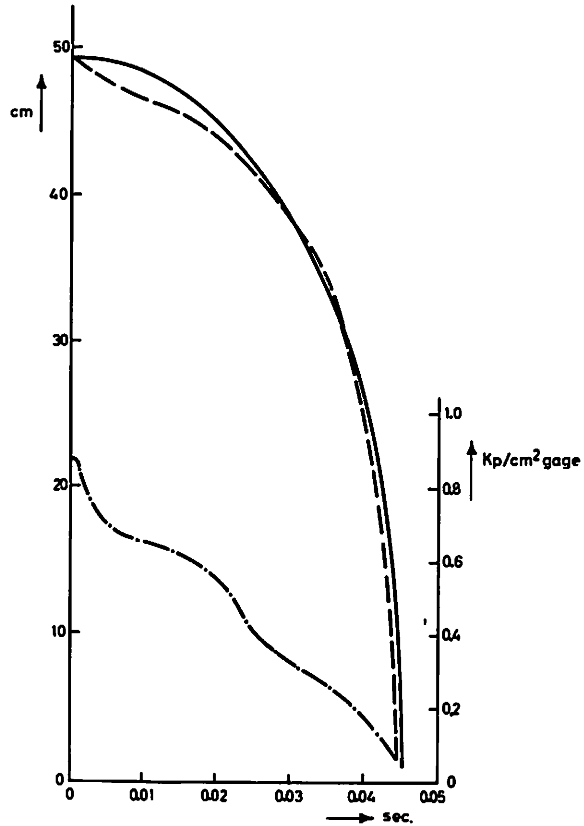


Fig.5 - Records of pressure measurements Experiment 3

Fig.6 Pressure in the gas blanket and radius of the sphe= rical bubble during condensation Experiment 3

-·-·- Pressure curve
——— Calculated radius as indicated in chapter 3.3
– – – " " " " " " 3.4



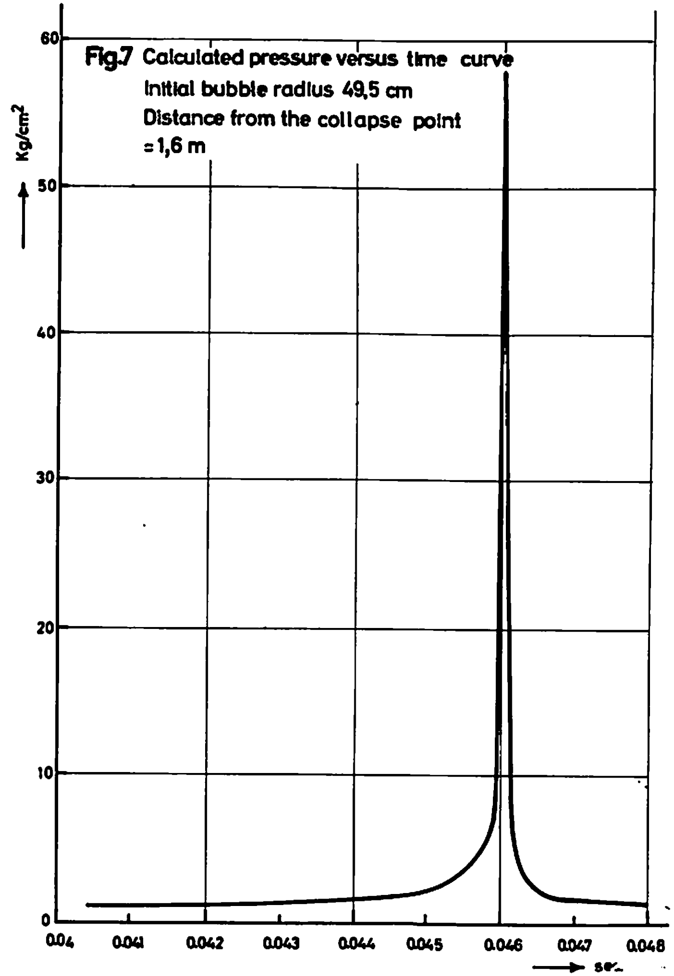


Fig.7 Calculated pressure versus time curve
Initial bubble radius 49,5 cm
Distance from the collapse point
= 1,6 m

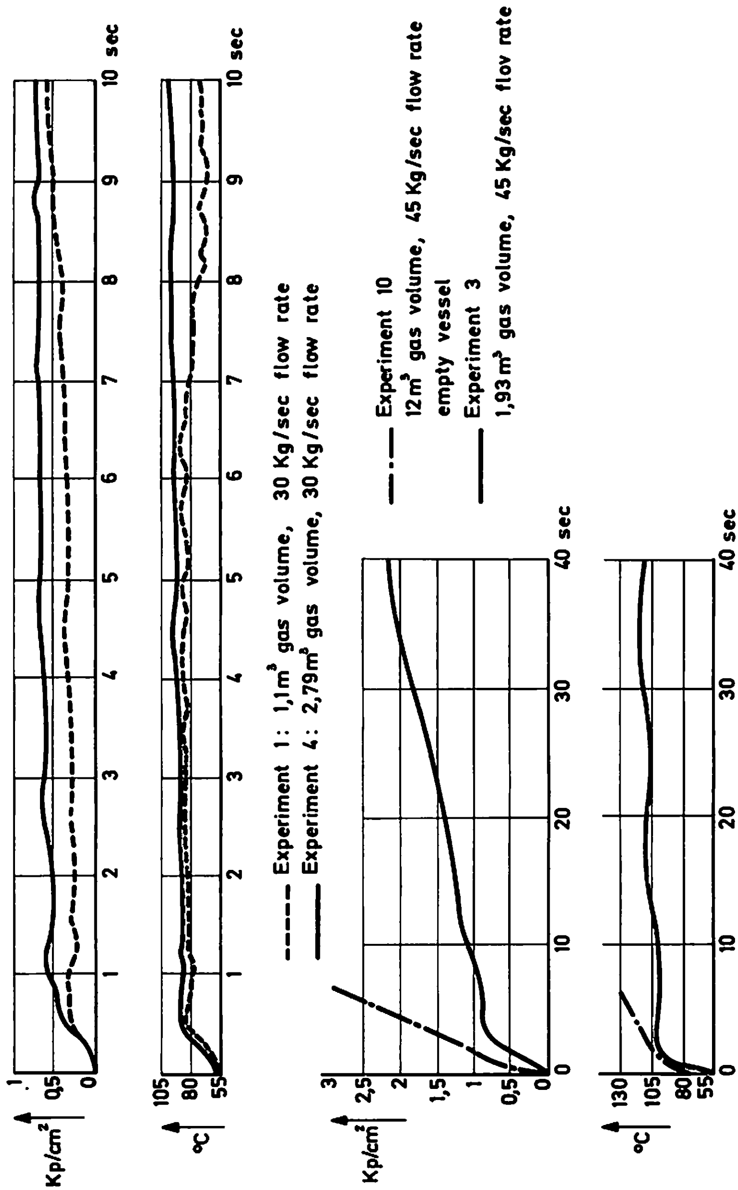


Fig. 8 - Pressure and temperature records.

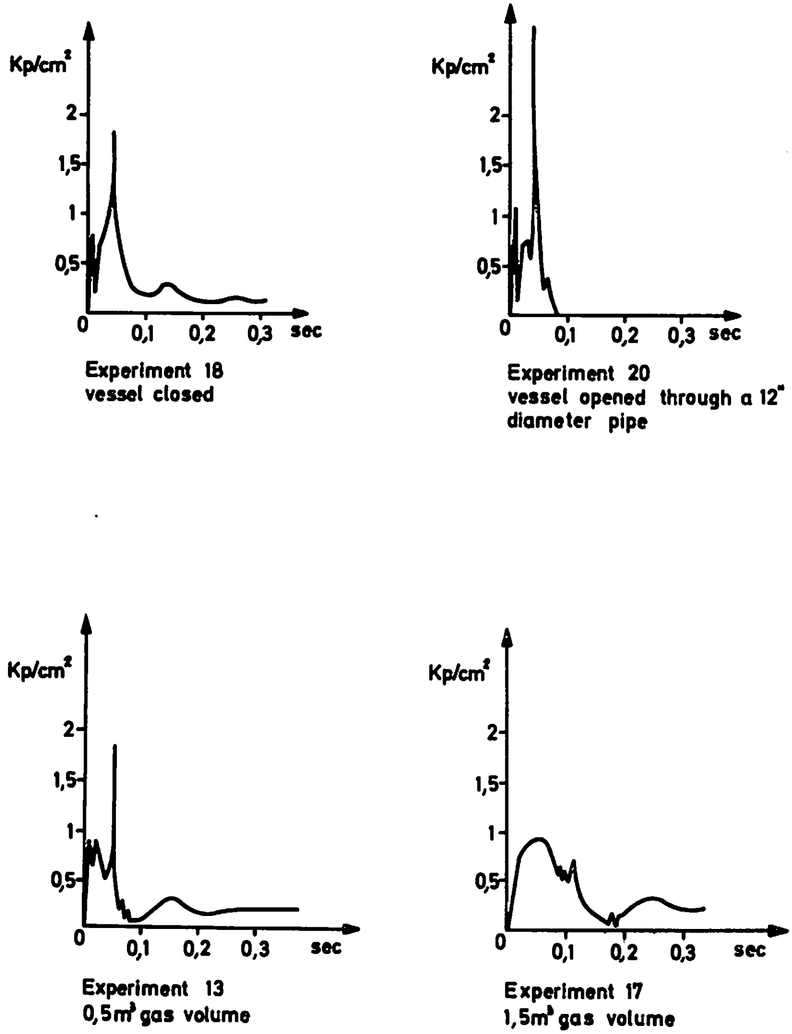


Fig. 9 - Pressures recorded on the top of the vessel

DISCUSSION

Q J. H. BOWEN, U. K.

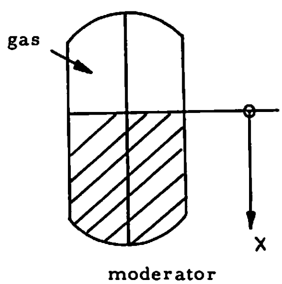
Was damage observed on surrounding tubes which might give a change to real pressure distribution between the tubes ?

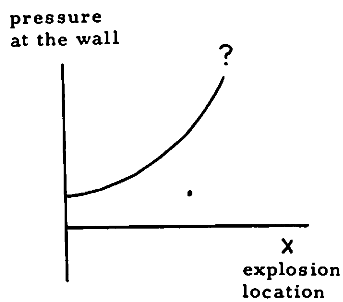
A H. HOLTBECKER, JRC Ispra, Italy

Temperature and strain measurements were performed on the channels but are not reported in the paper. Damage was observed on Al tubes of 2 mm thickness and 108 mm diameter. Pressure measurements were also made directly on the channels inside the moderator.

Q R. HAUSERMANN, Switzerland

1. Are the results strongly dependent whether the explosion is very close the vessel wall or inside the bundle ?
2. Is the axial direction of the explosion influencing the wall pressure ?





A H. HOLTBECKER, JRC Ispra, Italy

2+1. The evaporation (1. peak) and the recondensation (2. peak) have to be evaluated separately.

The rise time of the evaporation pressure peak is rather large and the width of the pulse amounts to some 0.01 second. Therefore the vessel is practically uniformly charged rather independent of the place of the ruptured channel.

The recondensation peak is much sharper and varies as a function of the distance from the recondensation point. Furthermore, no recondensation peak occurs when the bubble escapes towards the gas blanket. This is possible when the channel ruptures beyond the level of the moderator.

Q J.H. BOWEN, U.K.

How was the estimate of 10 atm wall pressure actually made (remembering doubts about calculational assumption - radial flow whereas tubes will interfere) ?

A H. HOLTBECKER, JRC Ispra, Italy

Pressures of about 10 atm were measured on the vessel wall for the recondensation pulse. The shape of the pressure pulse could not be confirmed by the calculation mainly because the code does not take into account reflection phenomena which can only be calculated by a more elaborated code.