EXPERIMENTAL INVESTIGATION ON THE BEHAVIOUR OF PRESSURE SUPPRESSION CONTAINMENT SYSTEMS BY THE SOPRE-1 FACILITY*

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SUMMARY

The SOPRE-1 test facility is an integral model (scale 1 : 13) of a MARK II pressure suppression containment system. It was set up at the University of Pisa in order to study the pressure-temperature transient in pressure suppression containment systems during LOCAs. Knowledge of this transient is necessary to perform a correct structural analysis of reactor containment.

The containment system behaviour is studied by changing the principal parameters which affect the transient (blow-down mass and energy release, suppression pool water temperature, vent pipe number and submergence, heat transfer coefficients).

The first series of tests involved:

A) 13 tests with break area of 1.8 cm^2,
B) 8 tests with break area of 20.0 cm^2.

The following experimental conditions were changed:

— position of the simulated break (from liquid or steam zone),
— water pressure (20-85 Kg_p/cm^2) and mass (45-70 Kg) in the vessel model.

Tests A): the CONTEMPT codes correctly forecast the pressure-temperature history, both in dry- and in wet-well.

Tests B): the experimental runs have shown that increasing of blow-down flowrate produces dry-well pressure spatial differences and anomalous vent pipe behaviour. This results in damped oscillations of dry- and wet-well pressure, probably due to alternating air bubble over-expansion and collapse, and in vent pipe opening and reclosing.

Dry-well pressure maxima at the end of blow-down are greater than those forecasted by currently applied codes: these codes use an homogeneous model, and do not take into account the above mentioned dynamic phenomena. In some tests other interesting phenomena were observed, such as some local pressure peaks in the suppression pool greater than dry-well pressure maxima at the end of blow-down. At present, all these phenomena are under study; they could be important for the structural analysis of containment systems.

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1. Introduction

The Nuclear Engineering Institute of the University of Pisa proposed in 1971 a research project on the behaviour of pressure suppression containment systems, following a loss-of-coolant-accident (LOCA).

The aim of the initially scheduled series of tests was to investigate in general the phenomena determining the wet-well and dry-well pressure transient, in order to ascertain whether their effects were properly taken into account by the analytical methods currently being applied.

To this end, an experimental facility called SOPRE 1 has been built which represents, in linear scale 1 : 13, the MARK II pressure suppression containment system of a reference nuclear power plant. Fig. 1 is a schematic drawning of the facility, with indication of the measurement points (pressure and temperature transducers). More details about the facility can be found in references [1],[2] . In [1] and in [3] the test procedure is illustrated.

The first tests showed, during the initial phase of blow-down, remarkable pressure oscillations both in dry-well and in wet-well, probably related to venting of dry-well air into the suppression pool.

It may be that similar phenomena caused the accidents which recently have occured in some nuclear power plants during the release of the primary steam in the suppression pool through the relief valve system. Consequently, after a literature survey on the matter we thought of investigating further the above mentioned phenomena.

Eight experimental tests were carried out with blow-down from the liquid zone, through a nozzle of diameter DN = 50 mm (LARGE LOCA), varying water mass and energy in the pressure vessel. These tests completed the first scheduled series [1],[3] .

Thirteen other tests were carried out with a nozzle of diameter DN = 15 mm and with blow-down from the liquid and steam zone; these last tests simulate loss-of-coolant-accidents of less severity (SMALL LOCA). They allow for evaluation of the capability of the CONTEMPT computer codes under a greater range of conditions [4],[5] .

Only eight of these tests have been analysed up to now. Most of these analyses may be found in [1],[2] ; we will mention here only a few of the more important observations.

2. Analysis of experimental results

The experimental tests with outflow from the liquid zone through a 50 mm diameter nozzle are reported and analysed in detail in [5],[7]. Figs. 2 - 5 show pressure transients in runs 50/3 and 85/1. The initial conditions and the main results are reported in Table I (°).

The vent clearing end (first pressure peak in Figs. 2, 3) occurs at different pressures and not simultaneously in all pipes, but at first in those located in the dry-well central zone. The delay of vent clearing compared with the start of blow-down, appears to be indipendent of p_o and M_o values in the test.

The vent clearing end occurs, in position P1 (Fig. 1) in all the tests, in 0.06 - 0.09 sec. after the start of blow-down.

However, the first pressure peak increases with increasing test pressure p_o and does not change with water mass M_o.

Going on with the analysis of the results, one can assume (see also [7]) that damping of the pressure oscillations occurs as soon as the dry-well air is transported into the wet-well by the blow-down steam-water mixture; then the steam-water mixture vents into the suppression pool and the steam condenses. The pressure now rises smoothly, both in dry- and wet-well, due to subsequent energy addition and reaches a maximum at the end of blow-down (Figs. 2, 3). Increasing p_o with M_o constant, the pressure maximum at the end of blow-down increases while t_{pMAX} decreases. Increasing M_o (from 55 to 70 Kg), with p_o constant, these pressure maxima and t_{pMAX} increase.

Pressure oscillations in the dry-well generally show a fundamental wave (due to a continuous succession of hydraulic guard openings and closings) to which are superimposed other waves of double frequency or more. The fundamental frequency is about 10 Hz and reaches in runs 50/4 and 70/6 values around 15 Hz.

The maximum amplitude of pressure oscillations in the dry-well rises when the pressure is not greater than 70 Kg_p/cm^2; in runs 70/6 and 85/1 the maximum amplitude is of the same order of magnitude. Oscillatory phenomena are greater in the central zone (Position P1) of the dry-well.

The pressure oscillations in the suppression pool are more regular (Fig.4) and their frequency is always 10 - 15 Hz. The behaviour of the pressure below a vent pipe (P13) is similar to that in the dry-well.

The pressure oscillations in the central zone of the suppression pool have a remarkable amplitude (also of the order of 5 Kg_p/cm^2); some possible hypoteses on the cause of the phenomenon are reported in [7].

In the free volume of the wet-well the oscillations are very irregular; this probably is due to suppression pool swelling; consequently, they are lower near the wet-well walls.

The initial conditions and the main results of the tests with outflow from

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(°) Location of pressure transducers are shown in Fig. 1.

the 15 mm diameter nozzle are given in Tab. II ; Figs. 6 and 7 show the experimental pressure and temperature transients and those calculated from the CONTEMPT LT code in run 70/2.

Increasing p_o, the blow-down time is shorter and the energy addition rate is greater. This affects the pressure peak in the dry-well which rises in bottom outflow tests from 1.07 to 1.55 Kg_p/cm^2 and from 0.78 to 1.3 Kg_p/cm^2 in the corrisponding tests with top outflow. In these last tests the thermohydraulic transient is more affected by thermal exchanges with internal structures and with the external atmosphere.

In the tests with outflow from a DN = 15 mm nozzle, the oscillatory phenomena are absent; this is due to lower blow-down flow rate (one order of magnitude, with reference to previous tests). For the relative slowness of the phenomenon, this can be considered semi-stationary: now the experimental and calculated results are in very good agreement.

3. Conclusions

The results of the first series of tests with outflow diameter DN = 50 mm show remarkable pressure oscillations during the initial phase of the thermohydraulic transient. In this transient the pressure peaks reach values greater than those at the end of blow-down (Table III), particularly in the suppression pool.

The observed pressure oscillations are related to the scale of the model (1 : 13), so that a direct application to a real containment system cannot be taken into consideration. Nevertheless, the experiments performed so far suggest that the assumptions of uniform conditions in each of the two volumes of the containment system and of equal behaviour of all vent pipes should be withdrawn from the current codes, in order to reproduce the test results for the first phase of the pressure transient.

This suggests another line of research: the theoretical study of air bubble expansion and of subsequent pressure oscillations.

Also the maximum pressure values at the end of blow-down predicted by CONTEMPT codes are (for $p_o > 30$ Kg/cm^2) lower than experimental ones, while the theoretical transient drops before the experimental one (Table III).

The difference between the experimental and theoretical values of pressure at the end of blow-down may be attributed to incomplete condensation of steam in the test suppression pool [7].

In the light of these considerations, the second series of scheduled tests [3],[5] remains valid: the above mentioned hypothesis can be verified by carrying out tests, where the temperature of the suppression pool or the submergence of the vent pipes are changed. Referring to the initial research program, for safety reasons, a smoother increase of suppression pool temperature and some preliminary runs with lower blow-down enthalpy should be planned.

Nomenclature

Abbreviations (also as subscripts)

DN : nominal diameter
DW : dry-well
GI : hydraulic guard (water-head initially present in the vent pipe)
MAX : maximum value of the considered quantity
PIC : peak value of the considered quantity
Pn : position of the nth pressure transducer
RGI : hydraulic guard break (vent clearing end)
Tn : position of the nth temperature transducer
WW : wet-well

Symbols

A (Kg_p/cm^2) : amplitude of pressure oscillations
E_o (Cal) : water energy in the pressure vessel
h (cm) : height
M_o (Kg) : water mass in the pressure vessel
p (Kg_p/cm^2) : pressure
p_o (Kg_p/cm^2) : initial pressure in the vessel
Q (Kg_p/sec) : blow-down flow rate
r (cm) : radius
t (sec) : time
T (°C) : temperature
Ø (mm) : blow-down nozzle diameter
ν (sec) : frequency of pressure oscillations

References

1 MARINELLI M., MAZZINI M., "SOPRE 1: Research on the Pressure Suppression Containment System. First Experiments", Energia Nucleare, Vol. 23, No. 11, November 1976.

2 GUERRINI B., MAZZINI M.,"L'apparecchiatura sperimentale SOPRE 1 per ricerche sui sistemi di contenimento a soppressione di pressione", Istituto di Impianti Nucleari dell'Università di Pisa, RL 203(75).

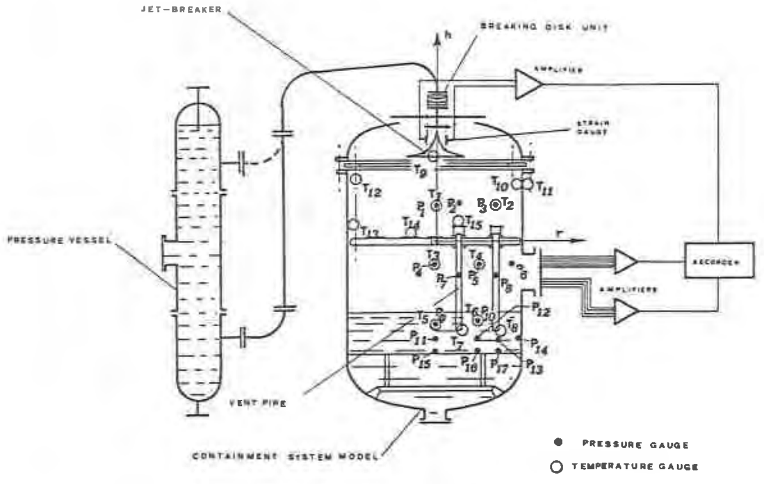
3 MARINELLI M., MAZZINI M., "SOPRE 1: ricerca sul sistema di contenimento a soppressione di pressione. Prime esperienze", Paper presented at the 30th Congress of ATT (Associazione Termotecnica Italiana), Cagliari (Italy), September 24-29, 1975.

4 CARMICHAEL C.F., MARKO S.A., "Contempt-PS, a Digital Computer Code for Predicting the Pressure-Temperature History within a Pressure-Suppression Containment Vessel in Response to a Loss-of-Coolant Accident", IDO-17252, April 1969.

5 WAGNER R.G., WHEAT L.L., "Contempt-LT Users Manual", ANC (Aerojet Nuclear Company), INTERIM REPORT 1-214-74-12-1, August 1973.

6 MARINELLI M., MAZZINI M., MAZZONI A., TODISCO P., "Evoluzione e stato attuale delle conoscenze sui fenomeni termo-fluido-dinamici nei sistemi di contenimento a soppressione di pressione degli Impianti Nucleari tipo BWR", Istituto di Impianti Nucleari dell'Università di Pisa, RL 242(76).

7 MAZZINI M., MAZZONI A., TODISCO P., "SOPRE 1: Ricerca sul sistema di contenimento a soppressione di pressione. Relazione sulle prime serie di prove", Istituto di Impianti Nucleari dell'Università di Pisa,RL 254(76).



Symbols	Coordinates r	Coordinates h	Notes
P_1, T_1	0	15	central DW
P_2	36	15	middle DW
P_3, T_2	72	15	peripheral DW
P_4, T_3	0	-16	central WW air
P_5, T_4	54	-30	middle WW air
P_6	85	-16	peripheral WW air
P_7	48	-47	middle vent pipe
P_8	72	-47	peripheral vent pipe
P_9, T_5	0	-84	central WW water
P_{10}, T_6	54	-84	middle WW water
T_7	48	-92	bottom vent pipe
T_8	72	-92	bottom vent pipe
P_{11}	0	-97	central WW water
P_{12}	54	-97	middle WW water
P_{13}	72	-97	peripheral WW water
P_{14}	89	-97	WW inter.wall
P_{15}	0	-110	central separ. sheet
P_{16}	54	-110	middle separ. sheet
P_{17}	72	-110	peripheral separ.sheet
T_9	0	70	jet-breaker
T_{10}	89	40	DW inter.wall
T_{11}	90	40	DW exter.wall
T_{12}	85	27	supporting bolt
T_{13}	89	40	DW inter.wall
T_{14}	24	0	tube plate
T_{15}	72	4	deflecting disk

Fig. 1 - Schematic drawning of "SOPRE 1" facility.

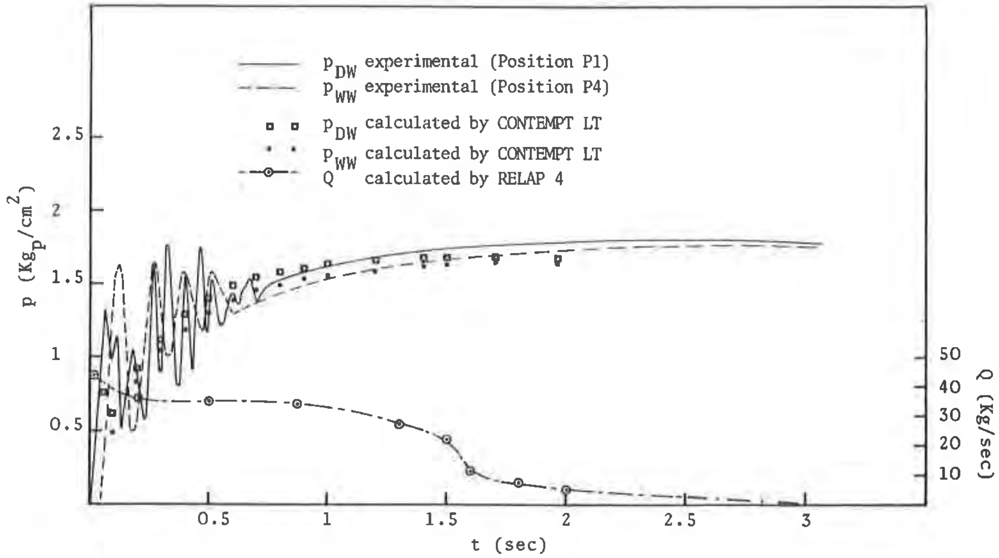


Fig. 2 - Pressure trend in the containment model (test 50/3).

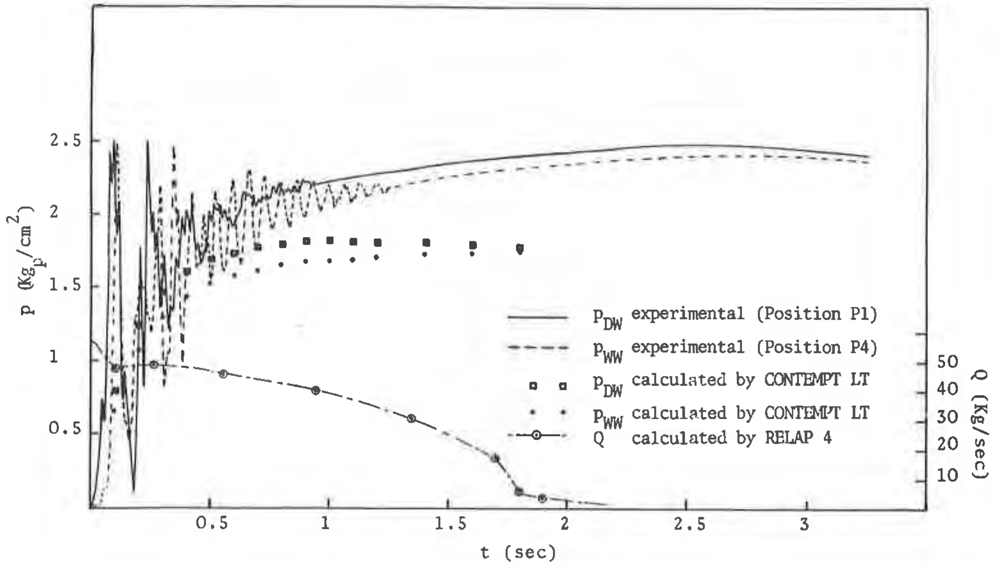


Fig. 3 - Pressure trend in the containment model (test 85/1).

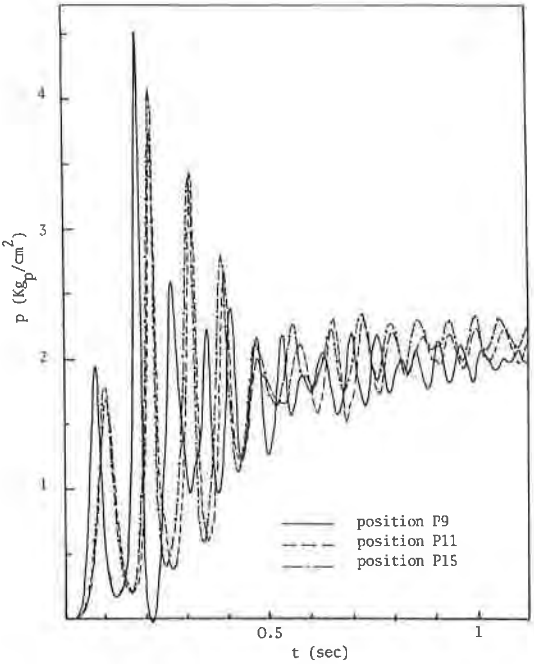


Fig. 4 - Pressure comparative diagrams along the wet-well axis (test 85/1).

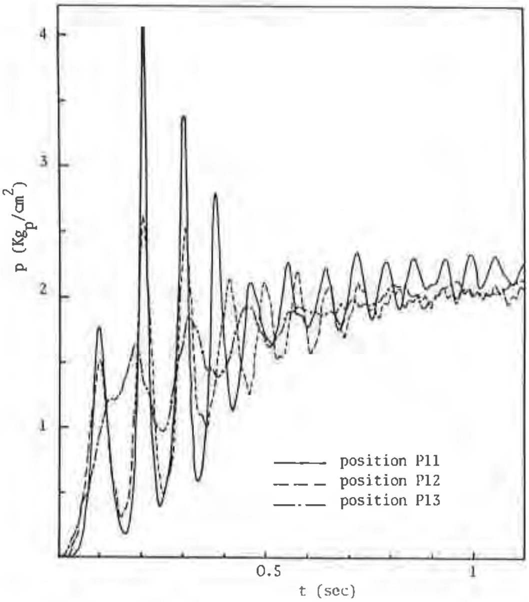


Fig. 5 - Pressure comparative diagrams along a wet-well radius (test 85/1).

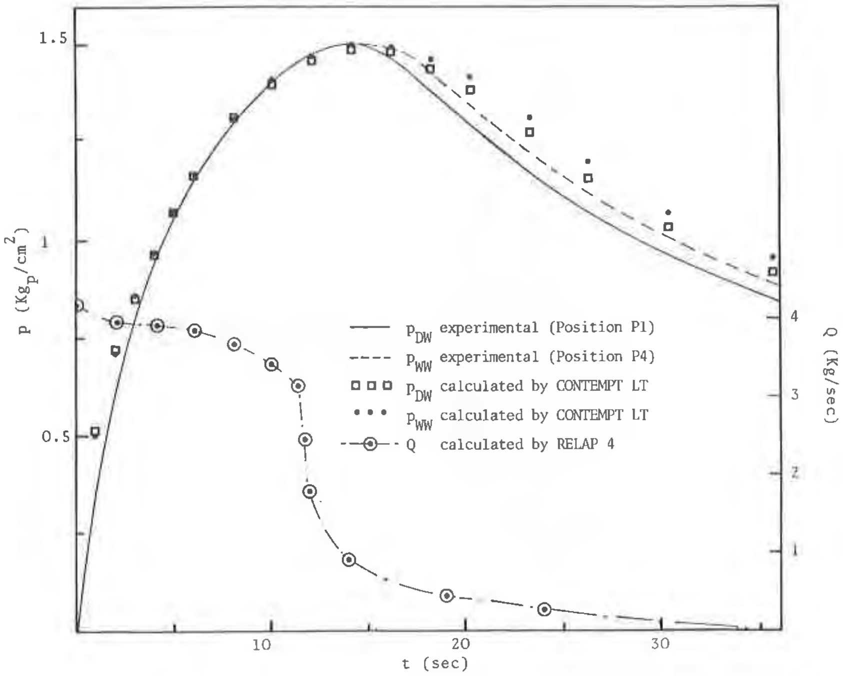


Fig. 6 - Pressure trend in the containment model (test 70/2).

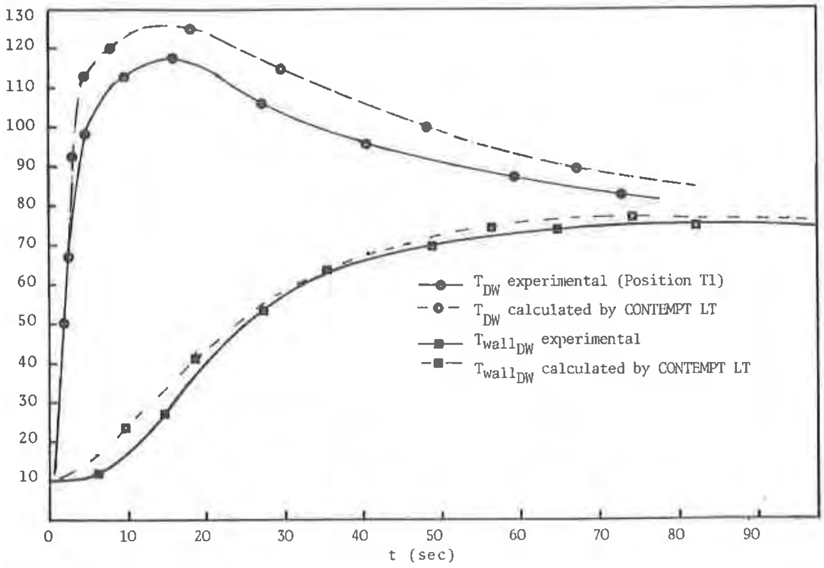


Fig. 7 - Temperature trend in the containment model (test 70/2).

Table I - Initial conditions and main results of the tests with outflow diameter DN = 50 mm.

TEST	20/1						30/3					
	INITIAL CONDITIONS						INITIAL CONDITIONS					
	P_o (Kg_p/cm^2)		M_o (Kg)		E_o $(10^3 Cal)$		P_o (Kg_p/cm^2)		M_o (Kg)		E_o $(10^3 Cal)$	
	30		55.1		13.2		30		55		13	
POSITION	P_{RGI} (Kg_p/cm^2)	t_{RGI} (sec)	ν (Hz)	A_{MAX} (Kg_p/cm^2)	P_{PIC} (Kg_p/cm^2)	P_{MAX} (Kg_p/cm^2)	P_{RGI} (Kg_p/cm^2)	t_{RGI} (sec)	ν (Hz)	A_{MAX} (Kg_p/cm^2)	P_{PIC} (Kg_p/cm^2)	P_{MAX} (Kg_p/cm^2)
P1	0.55	0.08	5	0.25	0.6	1.15	0.93	0.08	7	0.7	1.35	1.62
P2	-	-	-	-	-	-	-	-	-	-	-	-
P3	0.60	0.12	-	-	-	-	-	-	-	-	-	-
P5	-	-	-	0.05	0.65	1.13	-	-	6	0.8	1.4	1.57
P11	-	-	-	-	-	-	-	-	-	-	-	-
TEST	30/4						50/3					
	INITIAL CONDITIONS						INITIAL CONDITIONS					
	P_o (Kg_p/cm^2)		M_o (Kg)		E_o $(10^3 Cal)$		P_o (Kg_p/cm^2)		M_o (Kg)		E_o $(10^3 Cal)$	
	30		55		13		50		55		15	
POSITION	P_{RGI} (Kg_p/cm^2)	t_{RGI} (sec)	ν (Hz)	A_{MAX} (Kg_p/cm^2)	P_{PIC} (Kg_p/cm^2)	P_{MAX} (Kg_p/cm^2)	P_{RGI} (Kg_p/cm^2)	t_{RGI} (sec)	ν (Hz)	A_{MAX} (Kg_p/cm^2)	P_{PIC} (Kg_p/cm^2)	P_{MAX} (Kg_p/cm^2)
P1	1.4	0.07	6	0.8	1.4	1.78	1.45	0.07	12	1.0	1.8	1.82
P2	-	-	-	-	-	-	1.7	0.10	8	1.4	1.85	1.86
P3	1.5	0.14	5	0.35	1.3	1.77	1.55	0.13	5	0.65	1.6	1.84
P5	-	-	6	1	1.5	1.75	-	-	6	1.1	1.6	1.86
P11	-	-	14	0.9	1.6	1.8	-	-	12	0.65	1.4	-
TEST	70/3						50/4					
	INITIAL CONDITIONS						INITIAL CONDITIONS					
	P_o (Kg_p/cm^2)		M_o (Kg)		E_o $(10^3 Cal)$		P_o (Kg_p/cm^2)		M_o (Kg)		E_o $(10^3 Cal)$	
	70		55		16.5		50		70		19	
POSITION	P_{RGI} (Kg_p/cm^2)	t_{RGI} (sec)	ν (Hz)	A_{MAX} (Kg_p/cm^2)	P_{PIC} (Kg_p/cm^2)	P_{MAX} (Kg_p/cm^2)	P_{RGI} (Kg_p/cm^2)	t_{RGI} (sec)	ν (Hz)	A_{MAX} (Kg_p/cm^2)	P_{PIC} (Kg_p/cm^2)	P_{MAX} (Kg_p/cm^2)
P1	2.25	0.08	11	1.9	2.25	-	1.5	0.09	15	1.65	1.8	2.16
P2	2.5	0.10	7	2.3	2.65	2.1	1.5	0.10	6	1.1	1.8	2.10
P3	1.6	0.18	5	0.65	1.95	2.05	1.3	0.2	6	0.3	1.6	2.10
P5	-	-	7	1.2	2.25	2.05	-	-	9	1.2	1.9	2.0
P11	-	-	11	5.8	6.0	2.1	-	-	9	1.6	1.9	2.2
TEST	70/6						85/1					
	INITIAL CONDITIONS						INITIAL CONDITIONS					
	P_o (Kg_p/cm^2)		M_o (Kg)		E_o $(10^3 Cal)$		P_o (Kg_p/cm^2)		M_o (Kg)		E_o $(10^3 Cal)$	
	70		70		21		85		70		23	
POSITION	P_{RGI} (Kg_p/cm^2)	t_{RGI} (sec)	ν (Hz)	A_{MAX} (Kg_p/cm^2)	P_{PIC} (Kg_p/cm^2)	P_{MAX} (Kg_p/cm^2)	P_{RGI} (Kg_p/cm^2)	t_{RGI} (sec)	ν (Hz)	A_{MAX} (Kg_p/cm^2)	P_{PIC} (Kg_p/cm^2)	P_{MAX} (Kg_p/cm^2)
P1	1.65	0.06	14	1.3	2.4	2.38	2.5	0.08	8	2.4	2.5	2.4
P2	1.31	0.08	15	1 5	2.4	2.34	2.0	0.10	9	1.5	2.2	2.4
P3	1.7	0.08	15	2.9	3.1	2.4	1.9	0.14	11	1.35	2.3	2.4
P5	-	-	8	1.0	1.9	2.3	-	-	11	3.0	3.2	2.4
P11	-	-	-	-	-	-	-	-	12	3.65	4.1	2.5

Table II - Experimental and theoretical results in the tests with outflow diameter DN = 15 mm.

	TEST	30/1		50/1		70/2		70/4		70/5		30/2		50/2		70/1	
	OUTLOW FROM	LIQUID ZONE		LIQUID ZONE		LIQUID ZONE		LIQUID ZONE		LIQUID ZONE		STEAM ZONE		STEAM ZONE		STEAM ZONE	
INITIAL CONDITIONS	P_o (Kg_p/cm^2)	30		52.4		71.7		70.9		70.7		31.4		52.7		73	
	M_o (Kg)	55.1		54.4		55		48.7		49		55		55		55	
	E_o (10^3Cal)	13.2		15		16.5		14.7		14.7		13.2		14.9		16.5	
	ϕ (mm)	15.6		15.6		14.8		12.9		12.9		14.8		14.8		14.8	
DRY-WELL		EXPER.	CALCUL.	EXPER.	CALCUL.	EXPER.	CALCUL.	EXPER.	CALCUL.	EXPER.	CALCUL.	EXPER.	CALCUL.	EXPER.	CALCUL.	EXPER.	CALCUL.
	P_{MAX}(Kg_p/cm^2)	1.07	1.19	1.35	1.41	1.51	1.49	1.42	1.46	1.40	1.45	0.78	1.03	1.06	1.29	1.3	1.43
	T_{MAX}(°C)	105	115	-	124	118	126	-	123	-	120	94	113	-	122	114	123
	$T_{wallMAX}$ (°C)	-	-	-	-	76	78	78	84	85	89	-	-	-	-	83	-

Table III - Comparison between the experimental and theoretical values of pressure at the end of blow-down (tests with outflow diameter DN = 50 mm).

	TEST	20/1		30/3		30/4		50/3	
		P_{MAX} (Kg_p/cm^2)	t_{PMAX} (sec)	P_{MAX} (Kg_p/cm^2)	t_{PMAX} (sec)	P_{MAX} (Kg_p/cm^2)	t_{PMAX} (sec)	P_{MAX} (Kg_p/cm^2)	t_{PMAX} (sec)
dry-well	Experimental	1.15	3.5	1.62	2.8	1.75	2.8	1.85	2.1
	Calculated	1.47	-	1.57	-	1.61	2.0	1.7	1.5
	TEST	70/3		50/4		70/6		85/1	
		P_{MAX} (Kg_p/cm^2)	t_{PMAX} (sec)	P_{MAX} (Kg_p/cm^2)	t_{PMAX} (sec)	P_{MAX} (Kg_p/cm^2)	t_{PMAX} (sec)	P_{MAX} (Kg_p/cm^2)	t_{PMAX} (sec)
dry-well	Experimental	2.05	1.8	2.1	3.0	2.35	2.7	2.4	2.5
	Calculated	1.75	1.2	1.78	2.0	1.80	1.4	1.82	1.0