DYNAMIC LOADS ON PRESSURE SUPPRESSION CONTAINMENTS

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SUMMARY

In a Pressure Suppression Containment large quantities of steam may be condensed in a water pool, generally refered to as Wet-Well. A general survey of design, function, and requiements of a PS-Containment was given at the first SMiRT Conference, Paper J3/1*.

The present paper covers the aspect of dynamic loading of the Wet-Well due to pressure suppression. In the past two years, knowledge and understanding of this problem have increased substantially. In addition, a number of experimental programs in this area, such as Marviken and AEG condensation tests, have been performed.

Dynamic loading of the Wet-Well results under two conditions:

1. Loss of coolant accident (LOCA)—pressure suppression;
2. Loss of main heat sink whereby the suppression pool is used for decay heat removal—pressure relief.

For both cases one has to distinguish between two basically different phenomena:

— A transient phase where air is blown into the pool after the water has cleared the vent pipes;
— A steady state phase where only steam is carried down the vent pipes.

In the case of the LOCA, the initial air carried out of the drywell volume might be quite large, causing the water level in the Wet-Well to rise after vent clearing. This level swell continues until the first air bubbles have traversed the distance between vent exit and water surface and escape to the air volume of the Wet-Well. The transient phase ends when the air has been purged from the drywell, at which time the water level has returned to normal and only steam flows through the vents at mass flow rates of 100 kg/m^{2}sec or less.

The level swell by the LOCA sets large masses of water in motion, resulting in pressure pulsations up to 0.5 bar at the bottom of the Wet-Well. The pressure oscillation of condensing and thereby collapsing steam bubbles are localized near the vent pipe exit; they are attenuated to a magnitude below 0.3 bar at the Wet-Well walls.

In case of pressure relief the amount of air initially in the vent pipe is small, however the pressure transient due to the fast opening valves is very steep. The level rise in the pool is insignificant, but the air is expelled at much higher pressures. This results in pulsations due to the oscillating air bubbles.

In the course of a development effort in nozzles for pressure relief vents, it has been shown that the dynamic pressure from air bubble oscillation can be kept below 1 bar and that smooth condensation at high steam flow rates can be achieved up to the boiling point.

Theoretical models have been developed for the effects contributing to dynamic loads.

1. Introduction

In a Pressure Suppression Containment (PS-Containment) large quantities of steam may be condensed in a water pool, generally refered to as wetwell. A general survey of design, function, and requirements of a PS-Containment was given at the first SMiRT conference (Koch et al. /1/). This time the aspect of dynamic loading of the wetwell will be covered in greater detail. In the past two years, knowledge and understanding of this problem has increased substantially. In addition a number of experimental programs have been performed in this area, such as Marviken pressure suppression and KWU condensation tests.

Dynamic loading of the wetwell results under two conditions, (Fig. 1):

1. Loss of coolant accident (LOCA) - pressure suppression;
2. Loss of the main heat sink whereby the suppression pool is used for stored and decay heat removal - pressure relief.

For both cases one has to distinguish between two basically different phenomena:

- a transient phase, where air is blown into the pool after the water has cleared the vent pipes;
- a steady state condensation phase where only steam is carried down the vent pipes.

Both phenomena produce dynamic loads. The more serious ones however are attributed to the air. Therefore the main effort has been to support the experimental investigation with theory especially in this area.

2. Pressure Suppression

2.1 Start of the Pressure Suppression Process

At the onset of a LOCA, a pressure difference between the drywell and wetwell results, and steam with entrained air is carried into the wetwell. To illustrate the process, the upper half of (Fig. 2) shows schematically five progressive stages of the PS-System at typical Design Basis Accident times (DBA times), beginning with the undisturbed system at time zero. The respective pictures below explain the model developed for calculation. During the first second, the reactor coolant flow $\dot{M}_{RC}(t)$ out of the break has built up a drywell pressure high enough to press the water out of the vents. Then drywell air is blown into the pool together with an increasing amount of steam. The steam condenses almost immediately, whereas the air remains in the water in the form of dispersed bubbles. Because of their limited rise velocity (they need about two seconds to traverse an arbitrary distance of 3 m from vent exit to water surface) they cause a level swell. In the mathematical model, the dynamics of the water and bubble rise are separated. This is justified in good approximation because bubble rise is independent of pressure. All the air is assumed below the lumped water mass until the bubble rise model - described in (Fig. 2) - predicts an air flow $\dot{M}_A(t)$ out of the water surface. After this time the level is gradually returning to normal as the air flow from the drywell decreases.

2.2 Vent Clearing

The dynamic models used for water motion are explained in more detail (Fig. 3). The water plug initially in a vent pipe is accelerated by the pressure difference caused by the break flow. Its actual length (L-x) is increased by a virtual plug length (L*-L) to account for the motion in the water pool. This virtual length may be estimated with a method presented in /1/ and is, as a rule, equal to half a pipe diameter. The model is in good agreement with experimental results; that is, the neglected momentum of the water escaping from the vent compensates for friction losses, both factors being of minor influence.

The accuracy of the vent clearing model is important, since in general design practice the maximum pressure difference between the two chambers of a PS-Containment occurs with vent clearing.

2.3 Water Level Swell

The one-dimensional, dynamic model for water level swell is given in the lower part of (Fig. 3). The assumption of identical conditions in all vent pipes is a sufficiently good approximation for the Marviken test containment as well as for the KWU PS-Containment, (Fig. 4). The pressure in the drywell can be assumed constant in both cases. Possible pressure waves between the most remote vents can be neglected through an order of magnitude argument; propagation time is some 50 ms, vent clearing time about 1 s. Further the air/steam ratio in the vents cannot differ greatly; in Marviken because of the mixing header, in the KWU PS-Containment because of the missile protection baffles at the vent entrance which prevent a direct jet from entering any one or a number of the vents.

A comparison of experiment and calculation is given in (Fig. 5) on the basis of Marviken test 9. The operating conditions of this test were close to a postulated DBA in a KWU PS-Containment. Data on the Marviken containment and on the pressure measurement in the pool are published in (Appelt et al. /2/,/3/). The calculation accounted for break flow, steam condensation on the drywell walls, and an air entrainment depending on break location. Additional features were a vent flow resistance and the well proven assumption that the air escapes from the pool to the wetwell air volume at water temperature.

The left and right hand side (Fig. 5) show good agreement between the measured and calculated values for wetwell pressure, drywell pressure and level swell. The best agreement is obtained for the first 3 seconds of the blowdown after which the experimental values smooth out. In the theory pressure oscillations around the same mean values persist which shows the pronounced effect of damping. The initial gradients in drywell pressure are in good agreement indicating that steam condensation in the drywell is correctly incorporated in the model. The bubble rise velocity during the aircarry-over determines the level swell and has been properly accounted for.

The discrepancy in the calculated pressure at the vent exit is attributed to local dynamic effects in the water as shown by the rise in measured pool pressure before vent clearing. In the figure the experimental pressure at the pool bottom is compared with calculated pressure at vent exit both adjusted for hydrostatic pressure difference. With this correction the area under the two pressure curves should be identical as long as the wetwell pressures arein agreement and the water below the vent exit is not raised i.l. does not enter into the dynamics of the problem. The analytical model ist presently in the process of further improvement by PSP Ingenieurplanung Munich in close cooperations with the authors.

2.4 Condensation phenomena

PS-Containments are usually designed for steam flow rates through the vents up to about 100 kg/m^2s. At these low mass velocities, condensation under vertical vent pipes occurs in a way that steam bubbles detach from the pipe exit with a high frequency and collapse within a short distance. Each collapse is accompanied by a pressure pulse the amplitude of which decreases with distance from its center. Therefore it is essential to keep condensing steam away from the wetwell walls. With the mass velocities in question this is no problem, however. As a first approximation, the depth to which steam bubbles penetrate the water is limited by the static velocity head of the steam, as it is expended against the hydrostatic pressure of the water. This limit is some 70 cm. In undercooled water, bubbles collapse long before reaching such depths. A general survey of condensation effects under vertical vents is given in (Koch /4/).

Design data for pressure oscillations on wetwell walls are as yet directly taken from representative experiments. The new Marviken data compare well with earlier measurements (Robbins /5/, PG&E /6/) and confirm that for the mass velocities considered

- condensation is very smooth as long as air is mixed with the steam and that
- after the drywell is purged of air, the oscillations are attenuated to a magnitude below ±0,3 bar at the wetwell walls.

As it turns out, neither water temperature nor mass velocity or pipe diameter have an essential influence in the parameter range of interest. Typical pressure traces recorded at the wetwell bottom below a vent pipe exit are published in (Appelt et al. /2/).

3. Pressure Relief

When during normal operation a boiling water reactor is suddenly separated from the main heat sink, the steam generated in the reactor is released via the safety-and pressure relief valves to the condensation pool which then operates as standby condenser, (Fig. 1). From the pool the heat is removed by the residual heat removal system, and cooling water is pumped back into the reactor vessel by the standby water injection system. Basically the same phenomena are responsible for dynamic loads on the wetwell walls during pressure relief, as were discussed with the PS-System. The only difference lies in time scale and magnitudes.

3.1 Vent Clearing

The pressure relief pipe is directly connected to the reactor vessel. Therefore the amount of air initially in the vent pipe is small. However, the pressure transient in the pipe may be rather steep if the relief valves open fast. According to the dynamics of vent clearing as discribed in (Fig. 3), much higher transient pressures are reached. The air as it is expelled out of the vent, is therefore initially at high pressure and begins to expand under water.

As a first approximation, the event can be described as the free motion of a spherical gas bubble in an infinitely expanded water pool. If gravity effects are neglected, equation of motion appears in (Lamb /7/). In the nomenclature of (Fig. 6) we have

$$\frac{\ddot{R}R^2}{r} + 2\,\frac{R\dot{R}^2}{r} - \frac{1}{2}\,\frac{R^4\dot{R}^2}{r^4} = \frac{p(r,t)-p_o}{\varrho_1} \qquad (1)$$

If pressure and volume of the gas bubble are correlated by the adiabatic equation, the above equation yields for the bubble radius

$$R\ddot{R} + \frac{3}{2}\,\dot{R}^2 - \frac{p_i}{\varrho_1}\left(\frac{R_i}{R}\right)^{3\varkappa} = -\frac{p_o}{\varrho_1} \qquad (2),$$

where p_i, R_i are initial values. Integration of equation (2) results in curves as shown in (Fig. 6) in the right, upper part. It can be concluded from equation (1) that the pressure deviation from static pressure $P = (p-p_o)$ is inversely proportional to the radius r from the bubble center, if pressure has reached an extremum:

$$P(R) \cdot R = P(r) \cdot r \qquad (3)$$

Of further interest is the ratio of positive and negative pressure amplitudes in the air bubble. An energy balance gives

$$E_{kin} = \int_{p_o}^{p_{max}} p \; dV + p_o(V_{min}-V_o) = \int_{p_o}^{p_{min}} p \; dV + p_o(V_{max}-V_o) \qquad (4),$$

from which is easily derived

$$\left(\frac{p_o}{p_{max}}\right)^{\frac{1}{\varkappa}} \left[1 + \frac{1}{\varkappa-1} \; \frac{p_{max}}{p_o}\right] = \left(\frac{p_o}{p_{min}}\right)^{\frac{1}{\varkappa}} \left[1 + \frac{1}{\varkappa-1} \; \frac{p_{min}}{p_o}\right] \qquad (5).$$

This relation is also plotted in (Fig. 6). For small amplitudes we have cosine waves:

$$p(R,t) - p_o = \Delta p \cos \omega t \quad , \; \Delta p \ll p_o$$

$$\omega = \frac{1}{R_o} \sqrt{3\varkappa \; \frac{p_o}{\rho_1}} \qquad (6)$$

In the torus-shaped wetwell of the Würgassen power station, which is quite similar to that in (Fig.1), pressure traces were recorded. They show a surprisingly good agreement with the simplified theory presented, as far as curve shape, frequency and pressure propagation is concerned. The latter can be shown to be in good agreement with equation (3) in the circumferential direction, although wall effects are not considered in the theory /7/. In the shape of the torus cross section, the experimental data were not conclusive enough to prove the validity of equation (3).

Analysis of the measurements showed that

- the calculated location of the bubble was just below the "steam plume" under the vent, where it would be expected;

- under the assumption that all air is contained in one spherical bubble, the initial air pressure is equal to, or somewhat higher than the vent clearing pressure as would be expected;

- the pressure measured in the bubble volume was considerabely lower than vent clearing pressure.

This observation leads to the conclusion that the mixture of dispersed air and water acts like an idealized "air" bubble of larger radius R and smaller pressure P(R).

At a depth of 2 m below the straight, open ended relief pipe, wetwell wall pressures did not exceed 1,7 bar at valve opening times above 0,5 s (Rupp et al. /8/). Loads like that however, will never occur in the Würgassen wetwell, because the relief vent will be cleared by a separate steam discharged 0,5 s before the actual relief valve action. This reduces the air pressure oscillation on the average to about 25%,in all cases under 50% of the above value.

In an effort to reduce these air pressure loads resulting from vent clearing, by passive means as opposed to steam injection, exit geometries or nozzles for the vent outlets were tested. (Fig. 7) shows the experimental arrangement that produced the best results: a large number of small holes distributed over a cross arrangment of pipes. Generally the observation was made that the reduction from vent clearing pressure to air bubble pressure in the water increased with decreasing characteristic outlet dimension. For the geometry mentioned, that reduction factor is above 10. Data taken in the test stand are shown in the left part of (Fig. 8). The curves have a significant break at valve opening times of about 0,3 s. For opening times below that, vent clearing time is constant some 0,3 s, and vent clearing pressure does not change much.

3.2 Condensation

The 7 to 11 safety-and relief valves of KWU boiling water reactors under construction have a capacity of 600 t/h steam each. This means high condensation rates in a restricted water volume and steam mass velocities of 1000 kg/m^2s and more which is considerably higher than has been standard practice in conventional power plant technology.

A simple, open ended pipe gives smooth and complete condensation whenever the water temperature is below about 50°C and the steam outlet velocity is critical, that is in the operating range of relief vents. At temperatures above 60°C, a pulsating condensation sets in, and at temperatures around 85°C it is usually possible to blow such hard steam jets through the water onto the wetwell walls, resulting in condensation near the walls,

resulting in unacceptable loads on the walls.
With regard to this problem, nozzle geometries offer a further advantage: at high mass flow rates, a smooth condensation is possible at water temperatures up to the boiling point, (Fig. 8), and pressure oscillations measured at the pool walls do not exceed 0,6 bar throughout the whole range of mass flow rates.

4. Closing Remarks

The present state of the art and progress during the last two years can be summarized as follows:

1. Dynamic loads in a PS-Containment were checked in the course of Marviken tests performed with a full size, 58 vent PS-System. Experimental data from full size, 1 vent test have been confirmed.

2. Dynamic loads from pressure relief vents have been studied intensively in a KWU test program. Development of a nozzle geometry for vent exit reduced the air pressure oxillations from vent clearing drastically and extended the pool temperature range for smooth condensation of high steam flow rates up to the boiling point.

3. For the programs under way, the phase of large scale tests is almost concluded. A full documentation of the data is in progress. Dynamic load amplitudes are safely under control. A thorough evaluation of the test data and development of improved and additional analytical models will go on to eliminate empirical methods as far as possible.

L I T E R A T U R E

/1/ KOCH, E.H., KUSCHEL, D.,
"Auslegungskriterien und konstruktive Gestaltung der Sicherheitsumschließung bei Siedewasserreaktoren",
Nucl. Eng. and Design 19(1972)2, P. 291-314.

/2/ APPELT, K.D., KADLEC, J., MÜLLER, R.A., WOLF, E.
"Dynamische Beanspruchung von Druckabbausystemen beim Abblasevorgang", GfK Report, KFK 1702 P. 27-42.

/3/ APPELT, K.D., KADLEC, J. WOLF, E.,
" Vorläufige Resultate der Untersuchungen des lokalen Druckpulsationsfeldes bei Blowdown-Versuchen in der Kondensationskammer des Druckabbausystems des Reaktors Marviken", Lecture Reaktortagung 1973, manuscript with ZAED, Kernforschungszentrum Karlsruhe

/4/ KOCH, E.H.
"Beherrschung von Kühlmittelverlusten beim AEG-Siedewasserreaktor, insbesondere Druckabbau",
paper given at Fachseminar Jülich, March 12-16, 1973

/5/ ROBBINS, C.H.
"Tests of a Full Scale 1/48 Segment of the Humboldt Bay Pressure Suppression Containment",
General Electric Report, GEAP-3596, November 1960

/6/ PACIFIC GAS AND ELECTRIC COMPANY
Preliminary Hazards Summary Report, Bodega Bay Atomic Park,
Unit No. 1, Decemerber 1962

/7/ LAMB, H.,
Hydrodynamics, 6 th ed., p. 122,
Dover Publications New York, 1945

/8/ RUPP, W., KEMPF, B., KOCH, E.H.,POHL, E., WEISSHÄUPL, H.,
"Messungen zur Kondensation beim Abblasen über ein Entlastungsventil im Kernkraftwerk Würgassen",
Lecture Reaktortagung 1973, manuscript with ZAED,
Kernforschungszentrum Karlsruhe

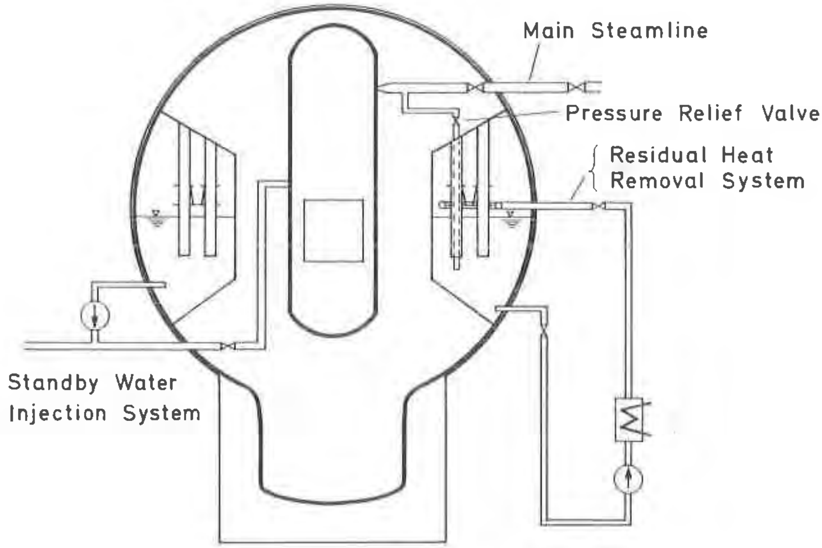


Fig. 1: Containment Pressure Suppression and Reactor Pressure Relief

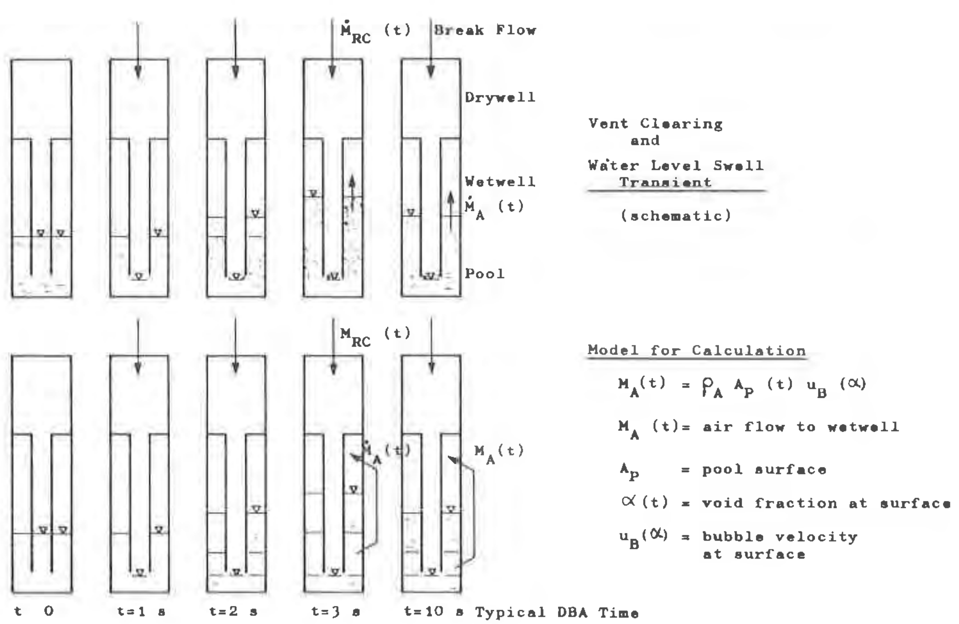
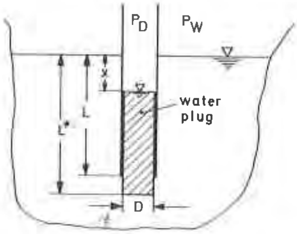
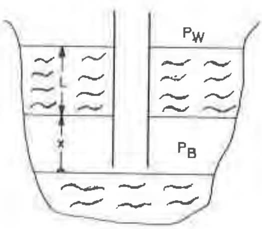


Fig 2: PRESSURE SUPPRESSION SYSTEM; Model for Transient Water Swell



Vent Clearing

$m_P x = P_D - P_W - g\rho_w x$	acceleration of plug
$m_P = \rho_w (L^* - x)$	spez. mass of plug
$L^* - L = O(D/2)$	correction
P_D	drywell pressure
P_W	wetwell pressure

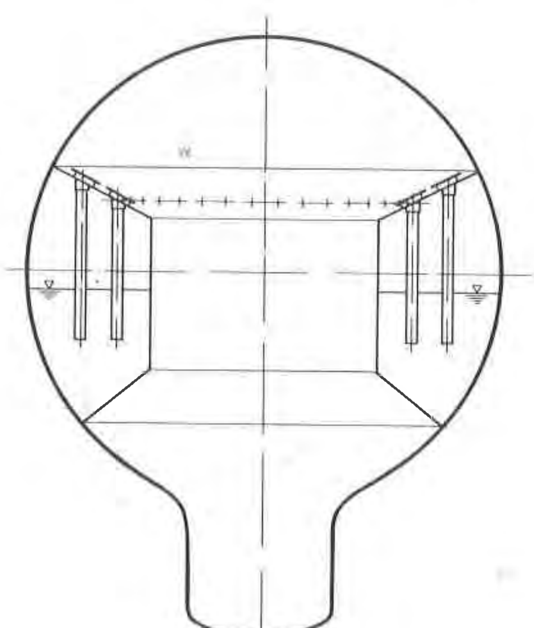


Water Level Swell

$m_N \ddot{x} = P_B - P_W - g\rho_W L$	acceleration of water above vent exit
$m_W = \rho_W L$	spez. mass of water
$P_B = P_D$ - friction loss	pressure in bubble

Fig. 3: PRESSURE SUPPRESSION SYSTEM;
Dynamic Model for Vent Clearing and Water Level Swell

AEG PS-Containment



Marviken Wetwell

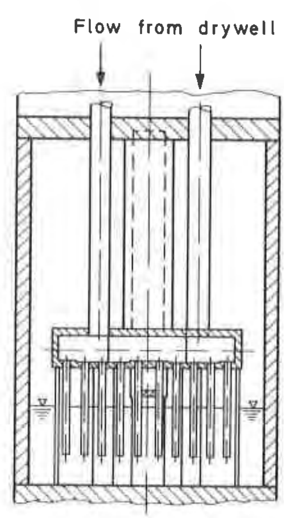


Fig. 4:
Marviken Blowdown Experiment and PS-Containment

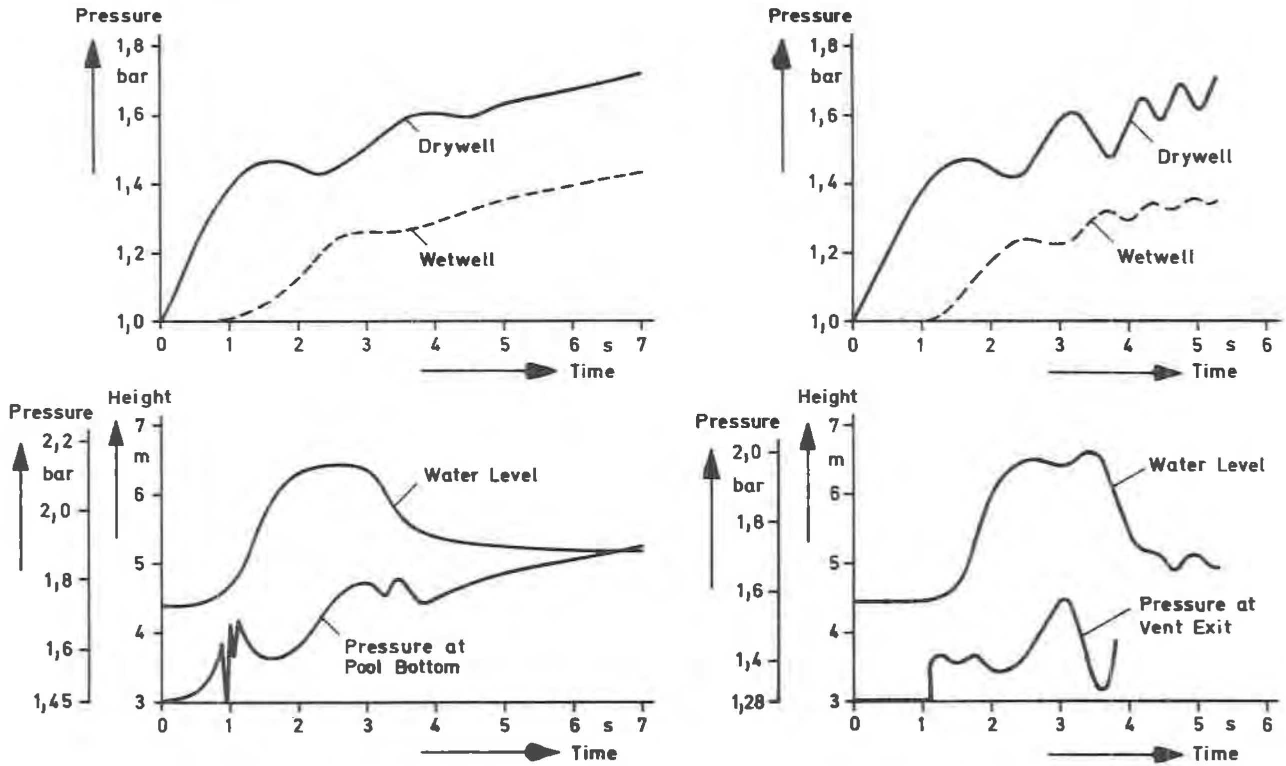


Fig. 5 :
Comparison of Marviken Experiments (left) with Theory (right)

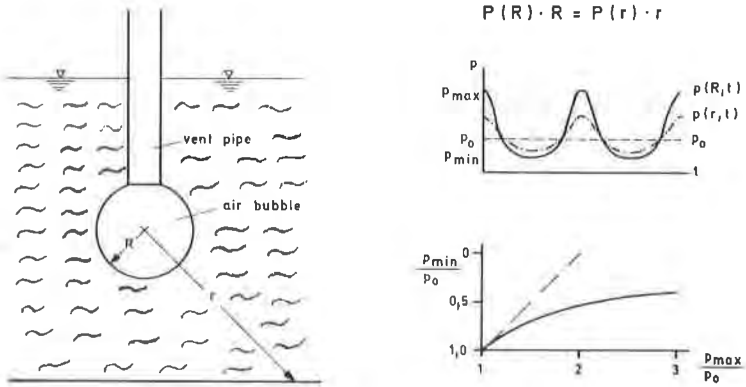


Fig. 6:
The Mechanism of Air Pressure Oscillations under Water

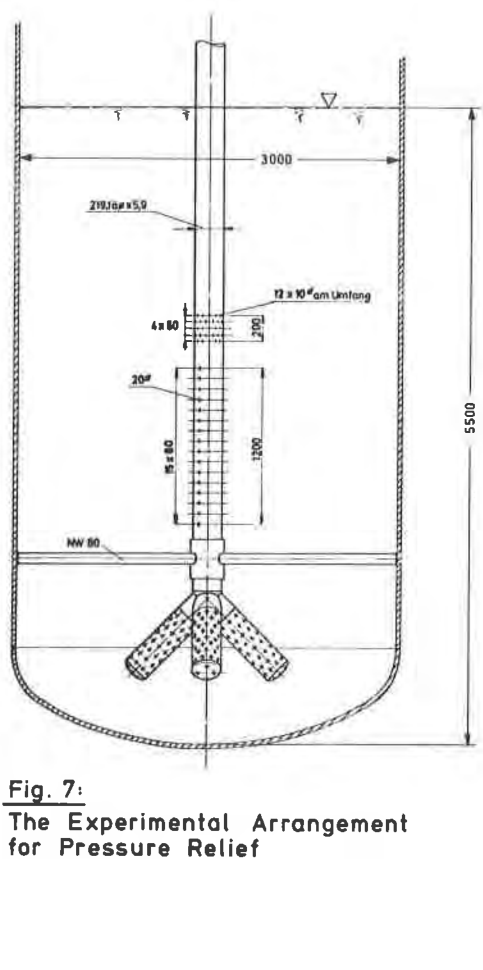


Fig. 7:
The Experimental Arrangement for Pressure Relief

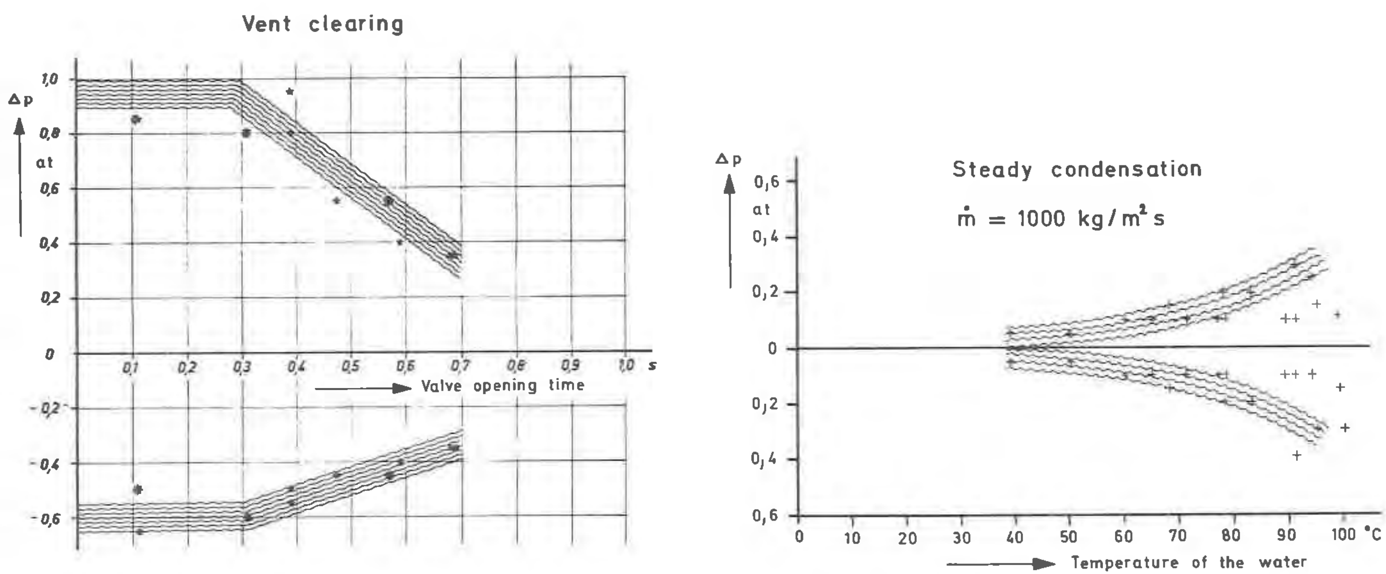


Fig. 8:

Experimental results for Pressure Relief with perforated tube nozzle