Experimental Simulation of Gas Cloud Explosion Effects on a Reactor Containment

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Summary

The loading of a nuclear power plant by pressure waves from an exploding gas cloud involves problems of large complexity. Therefore guidelines have been issued, containing conservative estimates, for the case of a deflagrating gas cloud to facilitate the design praxis.

The actual load due to pressure waves depends on the type of the explosion. A deflagration with its slow burning speed is characterized by a pressure pulse with relatively long duration and low amplitude, whereas a detonation causes a blast wave with a sudden pressure rise and high peak value but short period. In the deflàgration process turbulent flame acceleration also may lead to a blast wave type pressure pulse.

Results of experiments are presented carried out to evaluate the loading of a nuclear power plant by pressure pulses of both characteristics. The configuration of the model and the pulse duration are scaled 1:200. An intricate wave pattern is caused by the reflections and diffractions of the pressure waves due to the complex layout. Many parameters are involved which depend on the type of explosion, e.g. peak pressure, duration of positive and negative phase, rise time.

The pressure waves were simulated in a shock tube with 2.4 m diameter. The resulting pressure-profiles on the surface of the containment were registered by 16 piezo gauges. Measurements of the deflagrative load yielded reflection factors of 1.6 related to the peak overpressure of the free incident wave on a single containment model. With adjacent, obstructing buildings this factor reached a value of 2.6. Under blast load both ratios ranged from 2.4 in the simple case to 4.0 in the complex arrangement.

Scaled graphs are introduced allowing the evaluation of net forces on simply shaped bodies as cylinders and spheres. A transfer of these results to a reference building of original size shows good agreement with direct calculations based on pressure profiles as formulated for deflagration- and detonation-like pulses. The governing parameter in these representations is the ideal, normally reflected pressure. A Fourier-series analysis of the scaled forces yields the result that the main coefficients are contained in the frequency range below 20 Hz.

1. Introduction

Large volumes of flammable liquids and vapors are transported throughout the world. Accidents causing leaks and spills may lead to the formation of explosive clouds in the atmosphere. The potential danger from such clouds extends beyond their boundaries. The aim of this paper is to present experiments on scaled buildings loaded with pressure waves as they originate from an exploding spherical gas cloud.

Depending on the type of the reaction process which shall not be discussed here in detail one expects two types of pressure waves. In the case of deflagration, a pressure wave develops with a finite risetime and a peak pressure of some tenths of one bar. This overpressure phase is followed by an underpressure region of the same magnitude. The detonation of the gas cloud generates a blast wave with sudden pressure rise and a peak value in the order of twenty bar /1/. For some gas mixtures the detonation of an unconfined explosive cloud is in question. But in the real case of an accident partial confinement of the gas or turbulence generated by obstacles may lead to an acceleration of the flame front, thus resulting in the same (detonation-like /2/) type of blast wave.

In the design of nuclear power plants the load due to the effects of external pressure waves has to be considered. For the design praxis in the Federal Republic of Germany a simplified standard load-time function has been issued /3/.

2. Simulation Experiments

The simulation experiments were carried out on a model of a nuclear power plant in the scale 1:200. Accordingly the duration of the pressure waves was reduced on the basis of the Cranz-Hopkinson scaling law. Some calculations of the corresponding original cloud size (dia. 50 m) and the simulation technique for the generation of these types of pressure waves in a shock tube have been presented previously /4/. The effects to be studied in this program were superpositions and interference of the pressure waves thus showing the influence of the building layout.

The typical shape of the simulated pressure time profiles is displayed in Fig. 1 showing a deflagration wave with an amplitude of about 70 mbar and a blast-wave of about 700 mbar. On the surface of the containment model, the pressure distribution is registered by sixteen piezo gauges (Fig. 2). The identification letters A to C together with the channel numbers are used later to distinguish several selected pressure profiles. The model configuration with adjacent buildings of different orientation to the incident pressure wave is illustrated in Fig. 3. In these measurements the instrumented part of the model surface (Fig. 2) is always oriented towards the additional buildings. All pressure time histories are recorded with transient recorders of twelve bit resolution and a channel depth of two thousand words. For data reduction and numerical evaluation these signals are stored on tapes or floppy disks.

A complete survey on the experiments and results is given in a separate report /5/. In this paper only a few main points can be discussed. In Fig. 4 the influence of the obstruction through the adjacent buildings is illustrated. The pressure is normalized by the peak value p_E of the incident wave and the abscissa is scaled by the ratio D/v, i.e. the time interval the wave needs to travel one diameter of the model. Since the presented profiles are taken from different experiments, except channels K4 and K13 in Fig. 4a, their time origins are independent. The channel K4 is positioned on the cylindrical base of the contain-

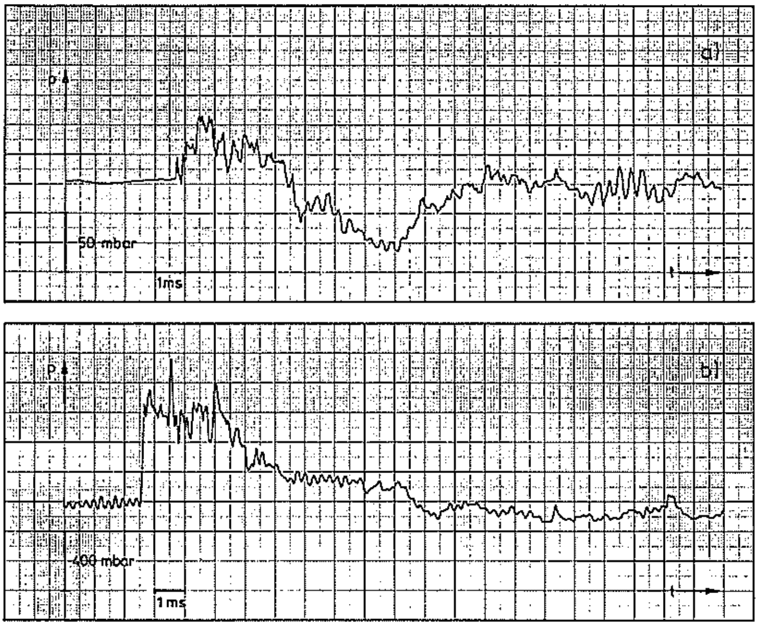

Fig. 1 Simulated pressure-time profiles of incident waves
a) Deflagrative wave: R 17
b) Blast wave : S 8

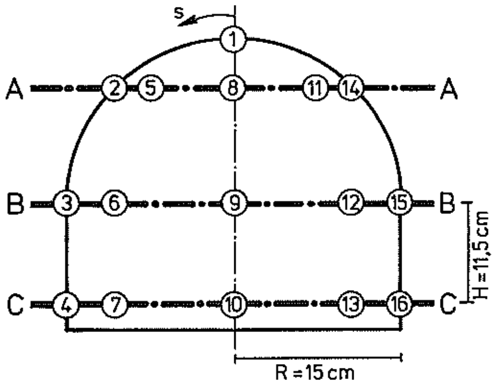

Fig. 2 Position of pressure gauges on the containment surface

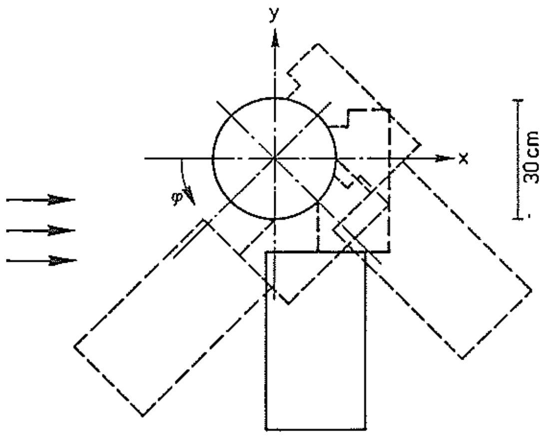

Fig. 3 Plant model configuration

ment and is loaded first by the incident blast wave. The amplitude registered here is the maximum in the case of a simple model. The channel K13 is mounted 135 degrees away from channel K4 where the recess is formed by the annex of the model (Fig. 4b-d). Without obstruction one observes at that point only a pressure amplitude of the same order as the incident wave, whereas in the other case it is increased by a factor of three to four.

An impression of the pressure distribution on the surface of the containment can be obtained by combining the pressure values of the gauges in a selected cross section (Fig. 5a,b). Here the development of the load for different time steps at the base of the containment is presented. The difference caused by the two model configurations can be impressively observed.

3. Calculation of scaled load parameters

The large amount of data resulting from the pressure measurements can be reduced to basic curves which allow in a relatively simple manner to evaluate forces on a containment in original size. The first attempts in this direction already have been presented in a previous paper /4/. This calculation is based on the numerical evaluation of the experimentally determined pressure distribution as it is shown for a single time step in Fig. 6. For the development of the containment surface into a plane the circumferential angle φ and the length s, originating at the top are used (Figs. 2, 3). The projection of the spherical part of the model into this φ-s-plane leads to a partially distorted mapping in the region from 0 to 0.67 of the normalized length s.

The pressure relief (Fig. 6) is set up by the readings obtained at the gauge locations and by calculated values at the points where the shock front crosses between them. Position and amplitude of the shock is interpolated for every time step by using the signals of the adjacent pressure probes. During the numerical processing this time dependent arrangement of data points is divided into triangles the centers of which are loaded by an averaged force computed from the area and the pressure values at the corners of the triangle. In the upper part of the model spherical trigonometry is used for the evaluation of the areas. The forces acting on each triangle are summed up over the whole surface for each time step. A result of this procedure is shown in Fig. 7 for a force component acting on the cylindrical base parallel to the direction of the incident wave. In this plot the time scale is normalized in the same manner as before. The force is scaled by the parameters governing the pressure wave and the geometry of the model. The peak reflected pressure $\hat{p}$ is the value expected for normal reflection at a plane surface, as it can readily be calculated for a given speed or pressure amplitude of an incident blast wave. By applying the reflected pressure in the scaling procedure non-linear effects are taken into account. This results in a single curve representation for forces in the Mach-number range up to three /4/. The normalized momentum $1/2 \int K d\underset{\cdot}{t}$ is also presented in Fig. 7. The factor 1/2 has been introduced to permit the presentation of different components within the same maximum scale reading.

The influence of the obstruction due to one additional building on the y-component is shown in the following for two blast waves incident from different directions, one parallel to the x-axis (Fig. 8), the other under an angle of 45 degrees (Fig. 9). In the symmetrical isolated case the total y-component is zero. Since the components displayed here are calculated only for one half of the cylinder surface, the distance between the two curves is the quantity which marks the effect of the obstruction. In Fig. 8 one observes a magnification

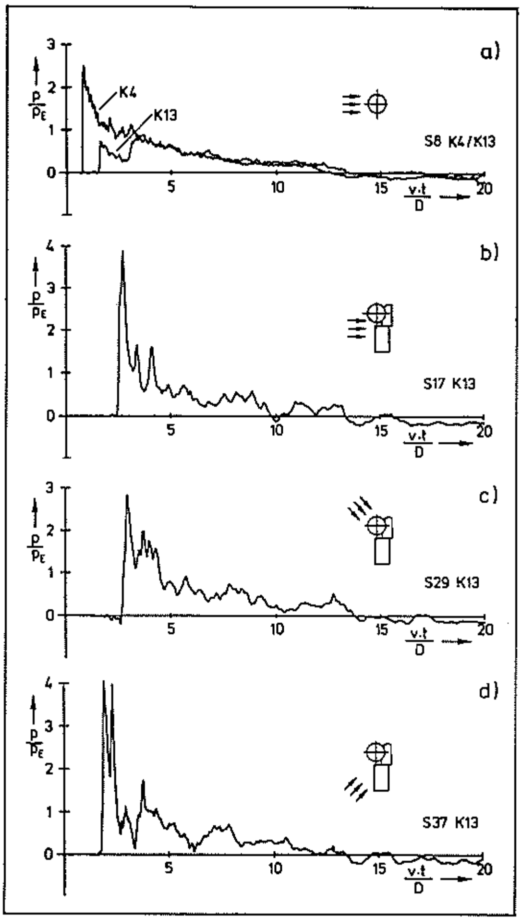

Fig. 4 Influence of obstruction on the pressure profile (test-serie S, gauges K4, K13)

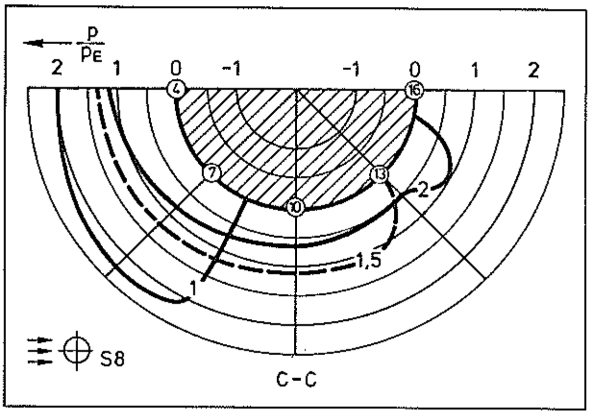

Fig. 5 a Pressure distribution on an isolated model (vt/D= 1, 1.5, 2)

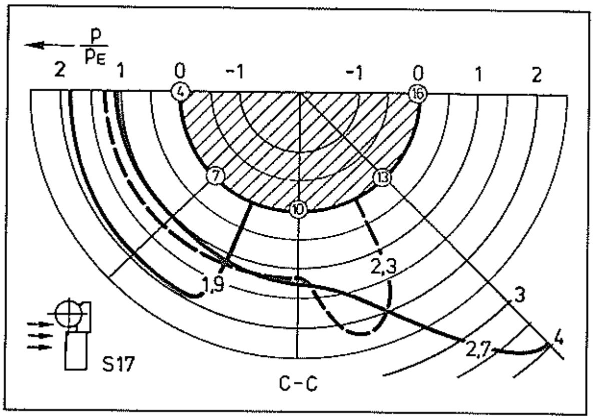

Fig. 5 b Pressure distribution on an obstructed containment (vt/D=1.9, 2.3, 2.7)

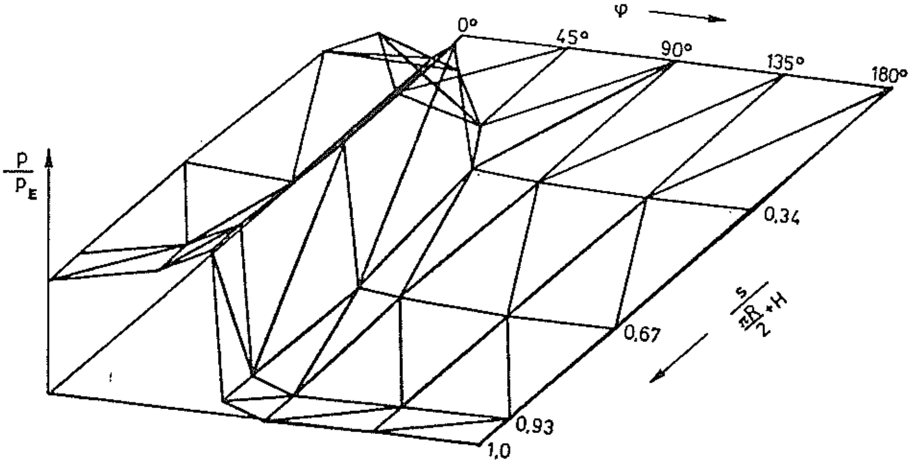

Fig. 6 Pressure distribution on the surface of the containment ($0° \leq \varphi \leq 180°$)

of about 30 % beyond the value for the isolated case during the time interval the blast wave needs to travel one containment diameter. Thereafter for about twice that interval the value falls below in the order of 30 %. In the case of the blast wave incident under 45 degrees (Fig. 9) the positive overshoot shows a marked peak in the order of 75 %.

4. Application to a prototype building

The reduction of pressure measurements to scaled forces for which examples are presented in Fig. 7 - 9 leads to a relatively simple calculation of the load on the reactor model. Since only the geometric dimensions of the model and one blast-wave parameter appear in these graphs an obvious method is offered to estimate the forces on a prototype building in original size. For a pressure pulse with specified peak value of the incident free wave the normally reflected pressure is calculated and, taking the geometric dimensions into consideration, the forces acting on the cylindrical base and the spherical cap are added. The result of this procedure is presented in Fig. 10, together with calculations on a two-dimensional model that have been carried out in another task of the german gasexplosion project /6/. In these calculations load conditions on a reference reactor plant in original size have been evaluated, assuming a socalled detonation-like pressure wave similar to a blast wave /2/. Comparison of the peak values of the two curves shows an extremly well agreement. In the following part the curves deviate from each other since the experimentally realised pulse duration is about twice as long as that of the blast wave on which the numerical calculations are based.

Figure 11 presents a comparison between the resultant forces calculated for two different deflagration waves. The solid curve shows the results obtained for the reference plant loaded by a pulse as specified by the german design guidelines /3, 7/, the other one comprises the scaled forces as obtained for deflagrative load on the model /5/. Since the artificial pulse of the guideline rises rather slow, in this case the normally reflected pressure is approximated by the acoustical solution, i.e. a reflection factor of two. As above positive peak values of the calculated forces agree very well, but a negative phase develops due to the characteristic of the scaled deflagration wave with over- and underpressure region.

The expansion of the scaled forces into Fourier-series yields another interesting outcome. In Fig. 12 a result is presented for the net force on the cylindrical base of the isolated containment under blast wave load. Up to twenty coefficients are calculated which are assumed to contain the most important part of the spectrum. Since the Fourier-expansion in this case is not applied to a periodic process some restrictions have to be considered; however, the approximation is sufficient for the normalized interval ($vt/D = 10$). Transformation of the time scale to the prototype building yields the first harmonic to be in the order of 1 Hz and the main part of the spectrum to be contained in the region below 20 Hz.

A similar result for deflagrative load is illustrated in Fig. 13. In this example the main part of the spectrum is within the frequency range below 6 Hz, the first harmonic being of the order of 0.5 Hz.

The experimental results and their evaluation as has been pointed out here allow to evaluate the load in a complex layout on a reactor containment of original size. In the region of low pressure levels, where linear calculations are still sufficient, the pressure

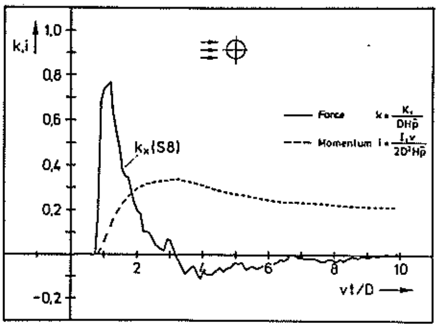

Fig. 7 Resultant scaled force k_x and momentum i_x on the cylindrical base of the containment model (parallel to direction of incident blast wave, test S 8)

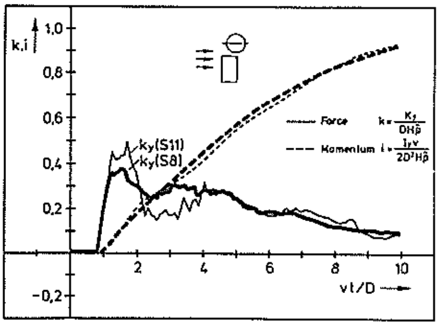

Fig. 8 Influence of obstruction on components k_y, i_y (incident wave φ = 0°)

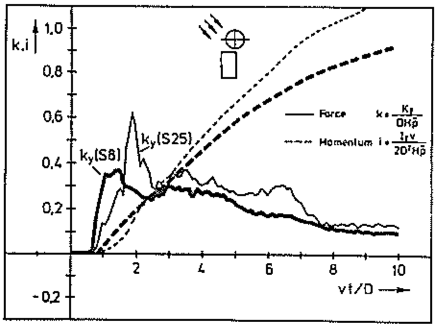

Fig. 9. Influence of obstruction on component k_y, i_y (incident wave: φ = 45°)

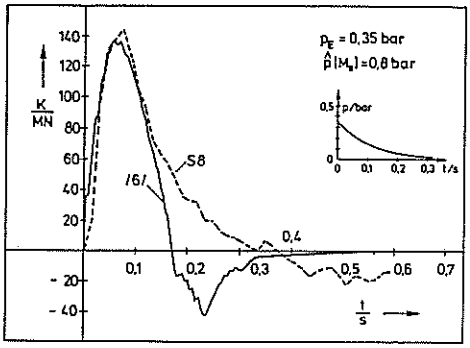

Fig. 10 Comparison of net force K, resulting from experiment (S 8) and calculations /6/

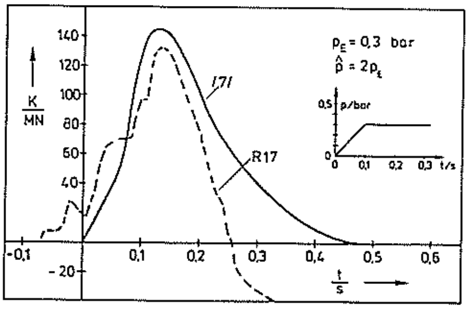

Fig. 11 Comparison of net force K, resulting from experiment (R17) and calculations /7/

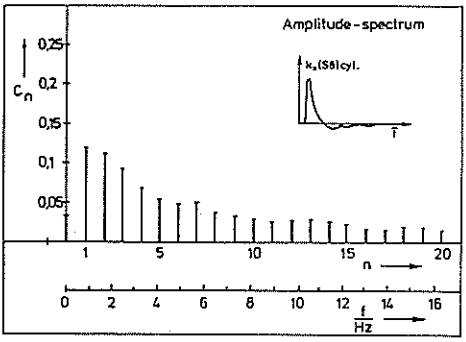

Fig. 12 Scaled amplitude-spectrum applied to prototype building (Blast load)

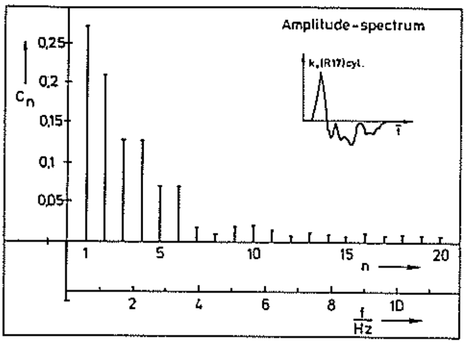

Fig. 13 Scaled Fourier-components applied to prototype building (Deflagrative load)

profile on the surface can be obtained by inserting the dimensions of the prototype, the peak pressure and velocity of the incident wave. For higher levels scaled net forces are calculated which allow for the nonlinearities by introducing the normally reflected pressure. These basic curves give a quick estimation of parameters which characterize load conditions under different types of pressure waves.

5. Acknowledgment

The work presented here has been supported by the german Bundesminister für Forschung und Technologie (BMFT, Grant-Nr. 150 385). The responsibility for the content remains with the author. A particular thank to Mr. K. Heidenreich, whose work in the carrying-out of the experiments is gratefully acknowledged.

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