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Contents

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Ir. M. Dragosavić

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Preface

This investigation into the structural consequences of gas explosion hazard in high-rise blocks of flats was carried out by the Institute TNO for Building Materials and Building Structures. It had the financial backing of the Building Research Foundation (Stichting Bouwresearch) and its results were published in Dutch as SBR Report No. 29 "Constructieve maatregelen tegen aardgasexplosies in hoge woongebouwen", publ. Samsom, Alphen aan den Rijn & Brussels, 1973.

The present research was conducted by Committee B 16 of the Building Research Foundation, which Committee was constituted as follows:

E. J. A. Corsmit, Chairman
M. Dragosavić (Experimental research and reporting)
K. R. Burger
C. J. van Coevorden
A. D. Eekhout
P. Hooftman
P. A. van Leeuwen
F. K. Ligtenberg
J. H. van Loenen
J. Rietberg
P. J. M. Ruyters
J. Siebelink
W. R. de Sitter
T. Th. Slot
O. van Uchelen
J. Witteveen (Members)

Thanks are due to the Building Research Foundation for financing the investigation and to the Committee members for their active support.

The original Dutch report is here presented in an English translation by C. van Amerongen.

Fig. 1. Collapse of Ronan Point, a block of flat, as a results of an explosion of town gas in the corner flat on the 18th floor.

Structural measures against natural-gas explosions in high-rise blocks of flats

1 INTRODUCTION AND SUMMARY

In 1968 a major structural collapse occurred in a high-rise block of flats in London [1] (see fig. 1), initiated by a town gas explosion in one of the flats. This led investigators in a number of countries to seek ways and means of preventing, as far as possible, a recurrence of such a disaster.

In the Netherlands a committee was set up* to investigate the problem. Its work resulted in practical recommendations which can be summarised as follows.

1. Domestic appliances and pipelines from which gas could inadvertently be allowed to escape should be made safe, and efforts to achieve this should be promoted. These are, however, largely outside the direct control of the structural designer.
2. Rooms to which gas may have access should be adequately ventilated in order to obviate accumulation of gas (for a relatively slow rate of gas escape, anyway). Installation of gas pipelines that are not strictly necessary is to be discouraged. Central heating boilers should preferably be located beside or on rather than inside the building. Gas supply pipelines to a building should be made flexible so as to avoid fracture due to differential settlement.
3. A gas explosion may nevertheless occur in a building. In addition, other special loads of varying intensity can possibly occur, as a result of which the loadbearing structure may locally sustain damage. The most effective procedure is to design the structure in such a way that, following the occurrence of local damage, the loadbearing function of a member which has failed can temporarily be performed by the rest of the structure (alternative path), so that progressive collapse is thus avoided. This means that the designer must take account of the – usually very much altered – pattern of forces after structural damage has taken place, as a result of which tensile forces may develop in members and in structural connections which in normal circumstances are loaded in compression only. The structure will have to posses sufficient coherence to resist these incidental forces.
4. In the customary method of construction the "alternative path" design principle often runs into practical difficulties. Besides, there remains the question as to what degree of damage would have to be taken into account. It is therefore recommended that the structural members should, instead, be so designed that the risk of their failure in consequence of special loads is acceptably reduced. The criterion chosen for this, on more or less intuitive grounds, was the explosion of

* See Preface.

natural gas (North Sea gas), which is the domestic gas used most widely in the Netherlands. The explosion loading associated with this is given in fig. 2. It depends largely on the strength and size of the blow-out or venting wall areas, i.e., the relatively weak non-structural walls which may, and must, fail when an explosion occurs and whose failure will not produce serious consequences to the loadbearing structure.

The meaning of the symbols employed in fig. 2 is as follows:

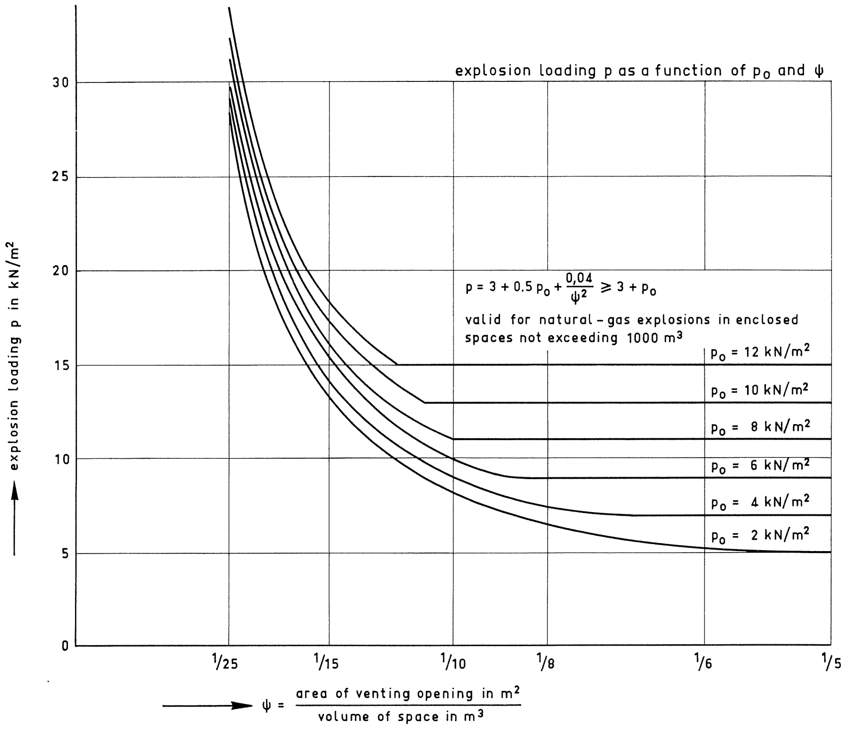


Fig. 2. Explosion loading p plotted as a function of p_0 and ψ.

p = explosion loading, to be regarded as a uniformly distributed static loading on a structural member;

p_0 = uniformly distributed static loading at which failure of the venting wall(s) occurs;

ψ = F/V = ratio of the area F (in m^2) of the venting wall(s) to the volume V (in m^3) of the room in which an explosion may occur.

The considerations and the explosion tests which have led to the determination of the above-mentioned explosion loading are described in detail in this article. The said recommendations and the following description of the investigations have been published (in Dutch) as Report No. 29 of the "Stichting Bouwresearch" ("Building

Research Foundation") entitled: "Constructieve maatregelen tegen aardgasexplosies in hoge woongebouwen" ("Structural measures against natural-gas explosions in high-rise blocks of flats"), published by Uitgeverij Samsom, Alphen aan den Rijn & Brussels, 1973.

2 SCOPE OF THE RESEARCH

2.1 Reason for carrying out the tests

Two of the safety measures referred to in the Introduction, namely, to design the building in such a manner that an "alternative path" for the structural transmission of forces is possible or otherwise to design the loadbearing members so as to withstand the explosion loading, take account of the possibility that an explosion may occur.

In order to design a structural member to withstand explosion loading, or to assess the damage locally affecting the structure in consequence thereof, it is necessary to know the magnitude of such loading. The importance of exceptional loadings, including those due to domestic gas explosions, is being increasingly realised, but little is known concerning the magnitude of those loadings.

For example, the draft of the new Netherlands code of practice "TGB" merely lays down: "The loadbearing structure should be so designed that local damage will not have disastrous effects. Local damage may occur in consequence of fire, explosions, collisions, vibrations, etc." The Netherlands Standard NEN 3028 contains a similar clause with reference to central heating installations. In the Scandinavian countries and within the framework of the Comité Européen du Béton it is likewise being endeavoured to give directives with a view to preventing disasters.

All the above-mentioned efforts confine themselves to stating the requirements in general terms because of lack of knowledge concerning the magnitude of the loadings involved.

The collapse of the block flats in London (fig. 1) and this lack of knowledge, more particularly with regard to the intensity of gas explosions in circumstances such as may arise in a dwelling, were the reasons which prompted the above-mentioned committee to have tests carried out at the Institute TNO for Building Materials and Building Structures.

2.2 Natural-gas explosion as standard criterion of loading

In order to investigate the need for designing a building to withstand possible explosions, etc. and to determine the loading criterion to be applied, it would be necessary to weigh the risk of a disaster and the expected damage against the social usefulness of structural measures applied with the object of limiting the damage. Data for making a statistically justifiable comparison are lacking, however.

Explosions are of rare occurrence and differ in origin and intensity. In dwellings an explosion due to domestic gas is indeed the most likely type, since this fuel is used on most residential premises, but explosions may arise also from other causes (petrol vapour, chemical cleaning agents, chemical experiments), or violent action producing comparable effects (collision, etc.) may occur. The loading to which the structure is subjected in such circumstances is unpredictable and highly variable. A fire may likewise produce disastrous consequences; besides, the risk of an outbreak of fire in a dwelling is many times greater than the risk of an explosion [2].

On the other hand, little is known about the actual capacity of the usual types of construction to absorb and withstand the effects of an explosion, so that the degree of damage that a building can sustain is also difficult to assess.

Since moreover the primary consideration is the personal safety of the occupants, there are, besides the economic factors, also social and psychological factors involved, but these do not lend themselves to statistical treatment.

The Ronan Point collapse did indeed demonstrate that the risk of disasters cannot be entirely ruled out. And that risk becomes greater according as buildings increase in size and more and more dwellings are built as flats in high-rise blocks. So although the need for the adoption of measures to safeguard against exceptional loading cannot be statistically calculated, the importance of such loadings has increased and will go on increasing.

In the absence of data for a statistical approach to the problem, it was decided on more or less intuitive grounds and in response to the Ronan Point disaster, to call for measures aimed at mitigating the consequences of exceptional loadings. For this purpose the *natural-gas explosion* was chosen as the determinative loading, on the basis of the following considerations and assumptions:

a. Natural gas is used in most homes and may inadvertently escape unchecked, so that relatively large quantities of gas-and-air explosive mixture may be formed.

b. Explosions due to other, and possibly even more dangerous, substances cannot of course be ruled out; but the risk that these substances are present in a dwelling in such quantities as to cause even higher pressures than in a natural-gas explosion is to be regarded as very slight.

c. Some other type of violent action (e.g., collision) of greater severity than a gas explosion is likewise rather improbable within a residential building.

d. To cope with loading due to an outbreak of fire other arrangements should be made (e.g., a specified thickness of concrete cover for reinforcement) whereby collapse is prevented or at least deferred for some time. The escape time gained in this way will limit the extent of the disaster to chiefly material damage, as contrasted with an explosion, which allows no escape time.

2.3 Extent of the natural-gas explosion

From the properties of gases and from tests performed in small containers (generally of less than 1 m^3 capacity) it was already known that explosion pressures, besides depending on the type of gas concerned, depend also on the following factors:

a. the percentage of gas in the air;

b. how intimately the gas is mixed with the air;

c. the size and shape of the chamber in which the explosion occurs;

d. the area and strength of the (weakest) walls which are the first to fail in the event of an explosion.

From a perusal of the literature and from discussions with physicists it was not possible, however, to obtain a conclusive answer to the question as to how high are the pressures which occur in a natural-gas explosion in a residential building, since extrapolation of the results of tests performed in small containers to the circumstances of housing construction is not directly justifiable.

The composition and the explosive properties of the natural gas concerned are indicated in Chapter 4. This gas can be ignited and exploded only when it is present in a gas-and-air mixture containing more than 6% and less than 16% of gas. An optimum explosion is obtained if the gas percentage is about 10.5% and the gas is well mixed with the air.

The experience gained with laboratory experiments showed, however, that the ideal gas-and-air mixture is difficult to achieve even with accurate proportioning and mixing. From this it can be inferred that the likelihood of an optimum mixture being present, and exploding, in a room in a residential building is virtually non-existent. In the upper part of the room the (lighter) natural gas will occur in higher concentration, so that possibly only some part of the room is filled with an explosive mixture.

On the basis of these considerations it was decided to consider, as an extremely unfavourable set of circumstances in which a natural-gas explosion may occur in a dwelling, the case where a kitchen or a kitchen and one other room are simultaneously filled with about 10% of gas in the air and that the mixture is ignited at that very instant. The tests were accordingly carried out under those conditions.

2.4 Venting walls

In the case of an optimum explosion of natural gas in a completely closed chamber whose walls can withstand pressures of any magnitude, however high, the pressure will rise to about 7 atm. (gauge pressure), i.e., 700 kN/m^2. Not nearly so high a pressure will develop, however, if the explosion occurs in a chamber whose walls will in part undergo early failure ("blow out"). Because of the relatively low combustion velocity of the gas-and-air mixture, the "vent" (pressure relief aperture) formed in consequence of such failure will enable expansion to take place, so that the pressure exerted upon the other (non-failed) walls will be of limited magnitude.

This property can be utilised in residential building construction by providing an appropriate combination of (stronger) loadbearing and (less strong) non-loadbearing walls. In connection with the function they have to perform in relation to an explosion the members of a structure will here be subdivided into venting walls and loadbearing walls respectively.

A *venting wall* may, and indeed must, fail in the event of an explosion. In a residential building the façade front, or part thereof (e.g., only the window glazing), of a nonloadbearing partition wall of relatively light construction can serve as a venting wall. Even a floor or a loadbearing wall may, in principle, be classed as a venting wall if it can (temporarily) be inoperative without causing a hazard of progressive collapse. On the other hand a loadbearing wall is any wall, or floor, which is an essential part of the loadbearing structure and which must be able to withstand the explosion.

The question, however, is: at what pressure do the façade components or other non-loadbearing walls commonly employed in housing construction fail and to what extent will the loading upon the other walls be limited?

In order to answer this question the area and the strength of the venting walls were varied in the tests.

2.5 Loadbearing walls

A structural designer generally has to take account of sustained static loads or loads which, for the purpose of his calculations, can approximately be assumed to be of long duration (e.g., wind loading). The loading developed by an explosion is of very short duration, however, and it is questionable whether a structural member undergoes the effect of such a brief load in the same manner as that of a sustained load of equal magnitude. As will appear from the interpretation of the test results, this will depend to a great extent upon the duration of the various pressure peaks.

In order to obtain some idea of the strength of a loadbearing wall with regard to an explosion of natural gas, a brick wall (1-brick thick) was included in the experimental set-up and was subjected to the loading developed by four explosions. In view of the increasing importance of exceptional loadings and the inadequate knowledge that we possess concerning the behaviour of structures subjected to them, it is advisable to devote more attention to short-duration and dynamic loads acting upon structures.

3 TEST STRUCTURE

For the purpose of experimental research a test structure of reinforced concrete was constructed, comprising two compartments which in respect of shape and size are roughly comparable to a kitchen and a room in a flat (see fig. 3).

The walls and floors, of reinforced concrete construction, were designed for a static loading (at failure) of 350 kN/m^2, so as to be amply capable of withstanding the explosion pressures.

Between the "kitchen" and the "room" was a door opening. In those tests which were performed only in the kitchen or only in the room this opening was closed with

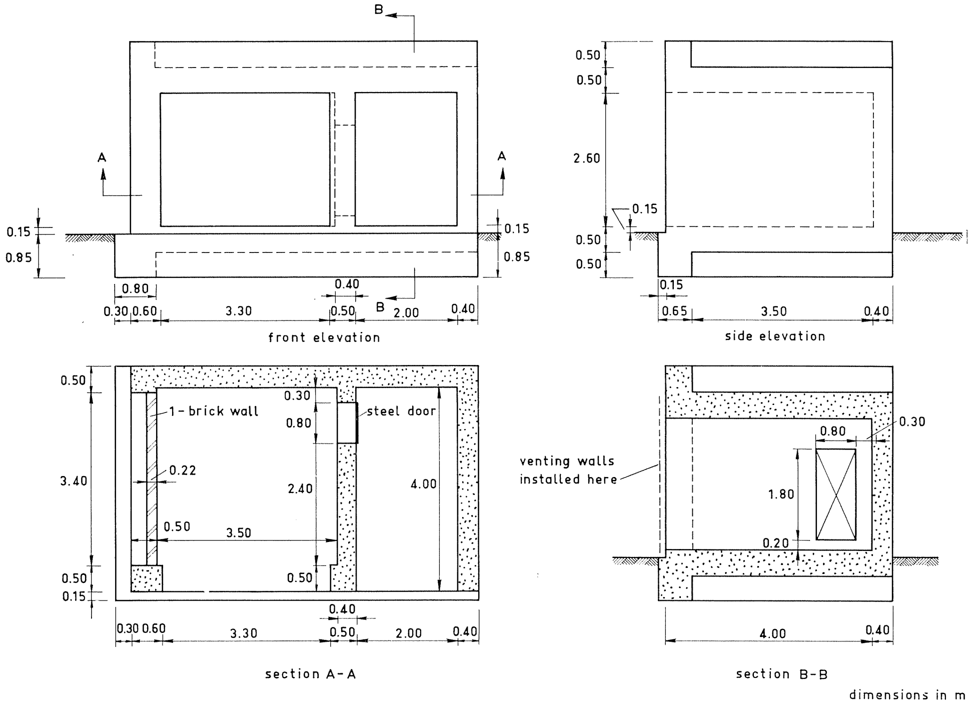


Fig. 3. Test structure.

a steel door. In both compartments of the test structure the front had been left open to enable various types of venting wall to be installed there. The open side face of the room was closed by a 1-brick wall, to be regarded as a (relatively weak) loadbearing wall.

The requisite quantities of natural gas were obtained from a tank of 0.36 m^3 capacity located at a distance of about 50 m from the test structure. The pressure of 150 atm. in the tank was first lowered, by means of a reducing valve, to about 12 atm. (gauge pressure) at the inlet to the supply pipe leading to the test structure.

In tests Nrs. 1 to 7 the gas was discharged into the kitchen through four burners of an ordinary domestic gas cooker or was allowed to escape freely from the supply pipe. In the other tests the gas was fed in through pipes laid along the floor and provided with downward-directed holes (see fig. 4). Since natural gas is lighter than air, good distribution of the gas was obtained even by these arrangements alone. Its mixing with the air was further assisted by a fan suspended from the ceiling (see fig. 4).

The requisite quantity of gas was measured by means of a gas meter and was in most cases additionally checked, before ignition, by means of a gas indicator. Ignition was effected by an electric arc generated by a transformer installed at a height of about 1.30 m above the floor (seen in the centre of fig. 4). In the first seven tests the point of ignition was located beside the wall next to the cooker. In the other tests the point of ignition was in the centre of the kitchen (or of the room).

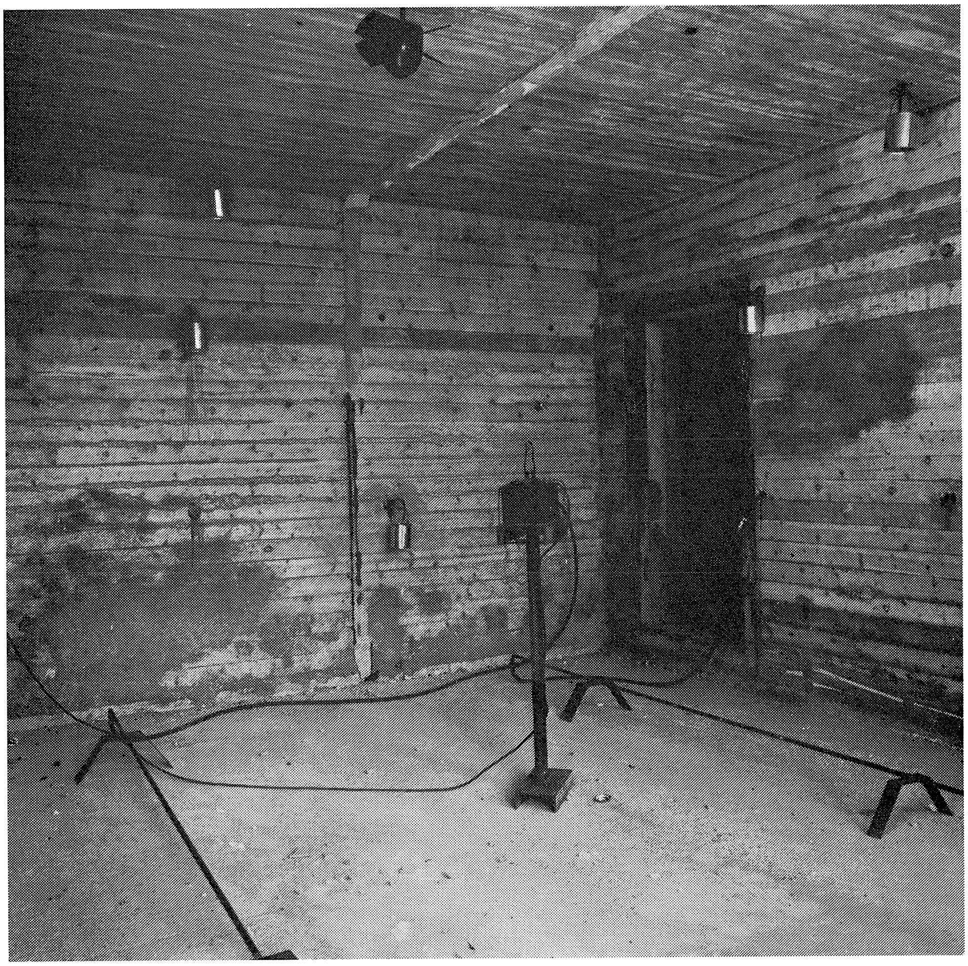
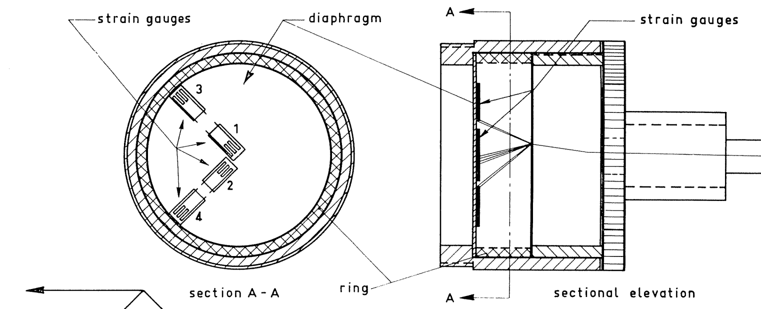
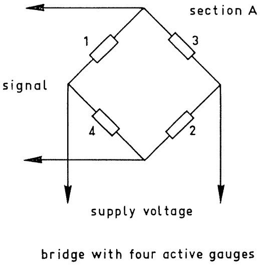


Fig. 4. Pipes with downward-directed outlet holes along the floor and fan suspended from the ceiling.

The explosion pressure was measured by means of pressure transducers disposed on the walls and ceiling. Ten of these transducers had been constructed by the Institute TNO for Building Materials and Building Structures (see fig. 5); in addition, one pressure transducer of the type "American Standard Model 141" was employed (see fig. 6). Fig. 7 shows the measuring instrumentation installed in a small building in the vicinity of the test structure. In order to obtain also a visual record of the explosions for subsequent examination, a colour film of the tests was made at a speed of 48 frames per second. This speed was sufficient to enable the various stages to be distinguished.



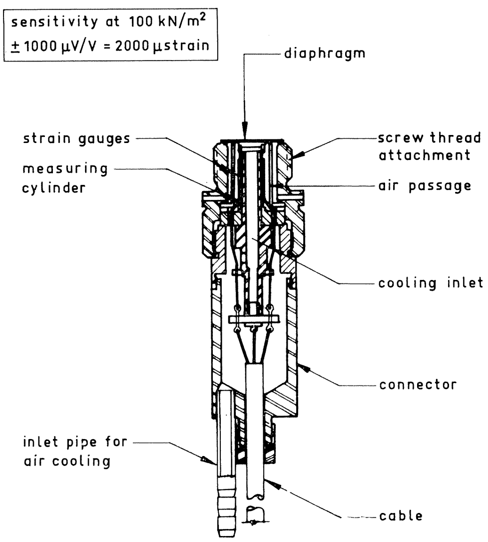


sensitivity at 100 kN/m²	natural frequency	thickness of diaphragm
± 1000 μV/V = 2000 μstrain	25 c/s	0.5 mm
± 300 μV/V = 600 μstrain	50 c/s	1.0 mm

the temperature - sensitive diaphragm is water - cooled

sensitivity approx. ± 0.5 % of full scale

Fig. 5. Pressure transducer with clamped diaphragm to which electrical resistance strain gauges are affixed.



SPECIFICATION

BRIDGE:	four active arms
REPEATABILITY:	within 0,1% of full scale
RESOLUTION:	infinite
ACCELERATION EFFECT:	less than 0,01% F.S. per "G" all planes
VIBRATIONSEFFECT:	intensive from 50 to 2000 C.P.S. to 100 "G" 3 planes
ZEROPRESSURE OUTPUT:	less than ± 2% of F.S.
RESONANT FREQUENCY:	approximately 45000 C.P.S.
PRESSURE LIMIT:	150% F.S. for static pressure full scale for dynamic pressure
NEGATIVE PRESSURE:	useable to full vacuum
BURST PRESSURE:	above 200% F.S.
EXCITATION:	recommended 10 volts DC or AC maximum 17 volts DC or AC
MATERIAL:	347 stainless steel diaphragm and 17.4PH stainless steel body
COOLING AIR	15 to 20 P.S.I.G. clean dry air
RESISTANCE TO GROUND:	500 MEG. Ohms minimum
RESISTANCE OF BRIDGE:	350 OHMS (-34 , ± 10%; -35 , and -36 , ± 1%)

Fig. 6. Section through "American Standard, model 141" pressure transducer.

4 EXPLOSIVE PROPERTIES OF NATURAL GAS

The following data relate to the composition and explosive properties of the natural gas employed in the tests (for comparison, some properties of town gas are also mentioned).

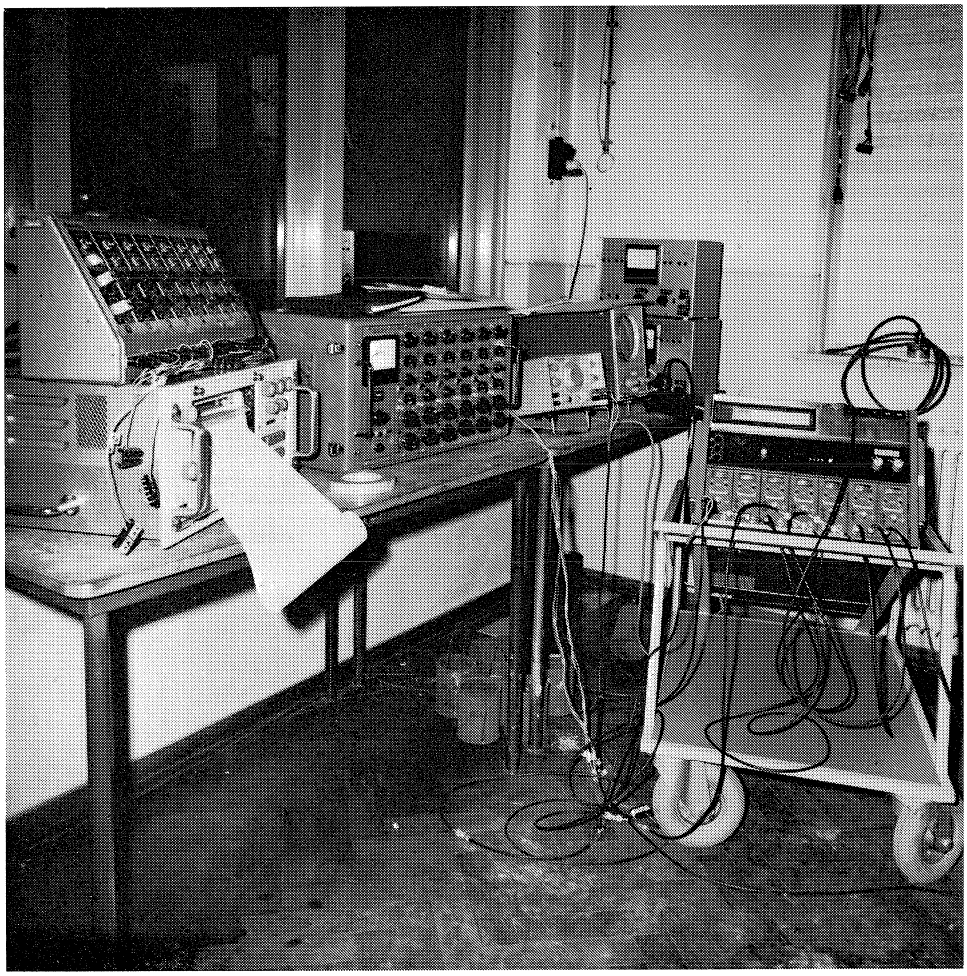


Fig. 7. Recording equipment.

Composition of the gas:

component		% by vol.
oxygen	O_2	0.01
carbon dioxide	CO_2	0.89
nitrogen	N_2	14.35
methane	CH_4	81.30
ethane	C_2H_6	2.85
propane	C_3H_6	0.37
butane	C_4H_{10}	0.14
pentane	C_5H_{12}	0.04
hexane	C_8H_{14}	0.05
and other hydrocarbons		

Explosive properties [3, 4]:

Ignition temperature approx. 670° C. Explosion limits (flammability limits) as percentage by volume of gas in the gas-and-air mixture at 0° C and 1013 mb atmospheric pressure:

minimum approx. 6%
maximum approx. 16%

For complete combustion of 1 m^3 of dry natural gas with dry air or oxygen a quantity of 1.7613 m^3 of oxygen is needed.

For convenience it can be assumed that the air has an average relative humidity of 50% at 20° C temperature and 1.013 atm. pressure and that the composition of this moist air is:

oxygen content	(O_2)	20.7% by vol.
nitrogen content	(N_2)	78.1% by vol.
water content	(H_2O)	1.2% by vol.

The requisite volume of moist air is therefore:

$$\frac{1.7613}{20.7} \times 100 \times 1\ m^3 = 8.509\ m^3$$

of air per 1.0 m^3 of gas.
This corresponds to a natural-gas percentage of:

$$\frac{1}{9.509} \times 100\% = 10.5\%$$

For this proportion of gas in the air an optimum explosion (i.e., with highest combustion velocity and highest explosion pressures) is to be expected. The quantity is then just sufficient to enable combustion of all the gas to take place.

In fig. 8 the combustion velocity is presented as a function of the percentage of gas in the gas-and-air mixture for a number of combustible gases. This velocity, or rate of flame propagation, relates to laminar combustion at atmospheric pressure and normal ambient temperature; it is the velocity with which, at the commencement of an explosion, the radius of the ball of flame in the immediate vicinity of the source of ignition begins to increase. In consequence of turbulence and of pressure and temperature rise the velocity subsequently increases. In spaces of relatively substantial size (5 to 200 m^3) a maximum combustion velocity (the explosion velocity) equal to between 15 and 40 times the values indicated in Fig. 8 can be expected to develop.*

Fig. 8 also reveals some favourable properties of natural gas as compared with town gas (which caused the Ronan Point explosion and which was formerly used in

* In larger spaces, long pipes, etc. the combustion velocity may even exceed the velocity of sound, so that deflagration (= combustion) then becomes detonation.

Holland, too). For one thing, the combustion velocity, and therefore also the explosion velocity, of town gas is higher. Secondly, the explosion limits of town gas are further apart (minimum 6%, maximum 40%), so that there is a higher risk that a mixture situated between these limits will be formed.

If an optimum explosion is produced in a completely closed chamber whose walls can withstand any amount of pressure, the pressure developed in the chamber will

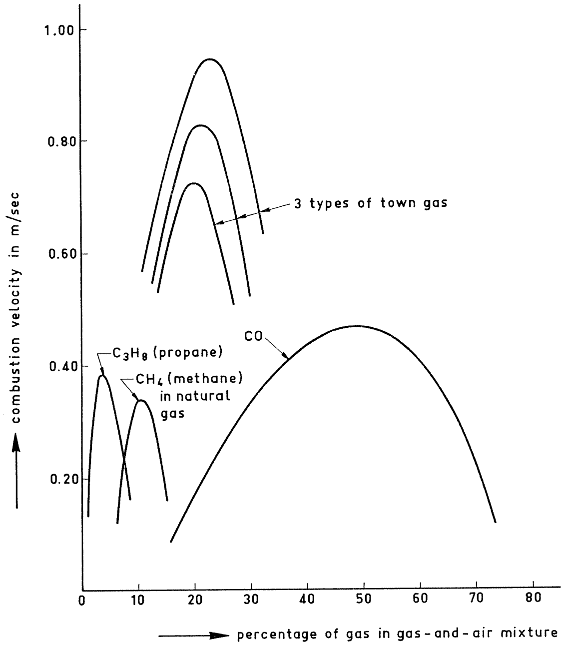


Fig. 8. Explosion velocity of combustible gases.

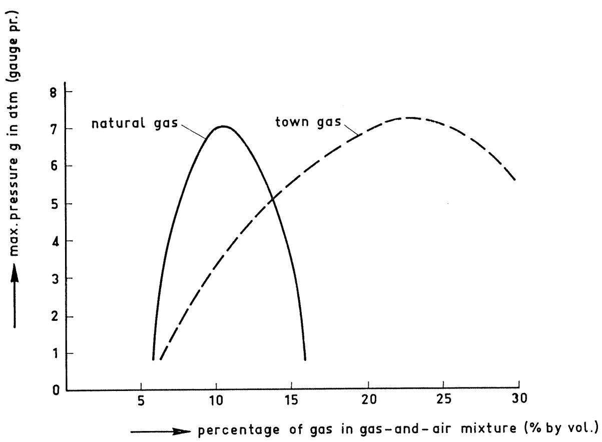


Fig. 9. Maximum pressure (g) attained in a closed chamber depends on the gas percentage.

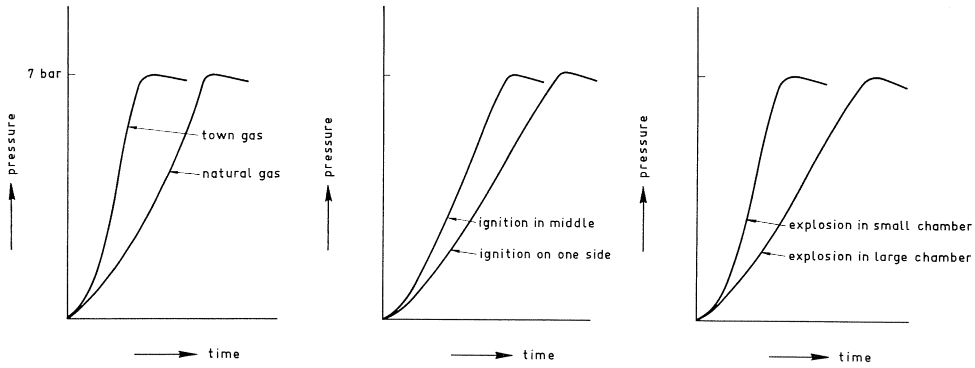


Fig. 10. Schematic diagrams showing pressure build-up in optimum gas explosions in closed chambers: pressure rises to about 7 atm. (gauge pressure) at varying rates.

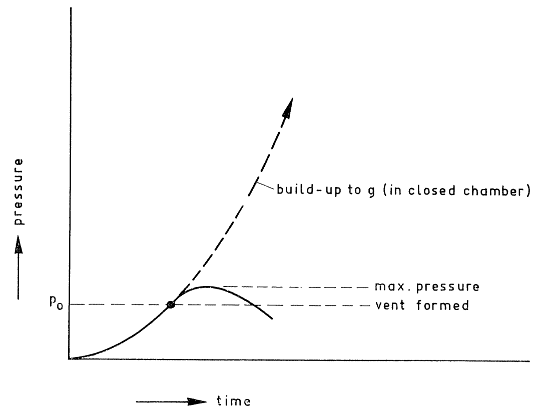


Fig. 11. Schematic diagram showing pressure build-up if a (venting) wall blows out at pressure p_0 and thus forms a vent.

rise to a maximum of about 7 atm. (gauge pressure), i.e., 700 kN/m^2, in a gas explosion, whether of natural gas or of town gas (see fig. 9).

In the town-gas explosion, however, this maximum is reached sooner, as indicated schematically in fig. 10. Also, the maximum is reached sooner when ignition is effected in the middle of the chamber instead of on one side, and sooner in a small than in a large chamber (see fig. 10). After the maximum has been reached, the pressure decreases, this being dependent on the rate of heat dissipation through the walls and the rate of temperature drop within the chamber. If the explosion occurs in a chamber whose walls fail at a pressure much below 700 kN/m^2, expansion beyond the confines of the chamber will take place, and the maximum explosion pressure will in that case be considerably lower. Because of the relatively slow deflagration of the gas-and-air mixture, this will be so also in the case where only a part of the enclosing walls is blown out: if that part thus fails at an early stage, the pressure exerted on the other walls of the chamber will be limited (see fig. 11). The significant question, however, was to what extent the pressure is thus limited under the circumstances occurring in a flat.

To answer this question, 34 explosions in all were produced in the test structure, mostly in the kitchen. In all cases the gas used was natural gas as described above.

5 THE TESTS

The data relating to the conditions in which the individual tests were performed (venting wall, gas percentage, admission and ignition of the gas, etc.) are given in the tables A to H in the Appendix. (The Appendix also contains: the calculated ultimate loading of the glass panes employed in the tests: table I: two examples of the measured pressures; and a series of pictures, from a film, giving some idea of the various stages of an explosion).

Here the information given will confine itself to a short description of each test series.

5.1 Series I: Preliminary tests

The tests Nrs. 1 to 7 were of an exploratory character, in order to obtain some idea of the magnitude of the explosion pressures likely to occur and of the reliability of the equipment. These tests were carried out in the "kitchen" of the test structure, while the venting wall consisted of hardboard or of plywood secured by means of adhesive tape around the edges, which was blown out at very low pressures.

5.2 Series II: Smaller and stronger venting wall

After the preliminary tests, two reinforced concrete spandrel panels, capable of withstanding the explosion pressure, were installed in the front face of the kitchen. In this way the size of the opening was reduced to 2.0 m × 1.8 m, and a wooden window frame was mounted within it, with space for two panes with dimensions of 1.19 m × 1.7 m and 0.73 m × 1.7 m respectively. In tests Nrs. 8 and 9 these latter apertures with closed with hardboard panels, and in tests Nrs. 10 and 11 they were closed 5 mm thick sheet glass.

The photographs in fig. 12 show the situation before and during an explosion. In these tests a gas-and-air mixture containing about 10% of natural gas was exploded in the kitchen.

5.3 Series III: Variation in the strength and area of the venting wall

After series II, the wooden frame was replaced by a steel frame with two apertures with dimensions of 0.6 m × 1.7 m and 1.2 m × 1.7 m respectively. By fitting panes of sheet glass with respective thicknesses of 3, 5 and 8 mm in the smaller, the larger or both of these apertures, a systematic investigation was carried out with regard to the effect of the strength and area of the venting wall (tests Nrs. 12 to 19). In all these

Fig. 12a. Test No. 10: before the explosion.

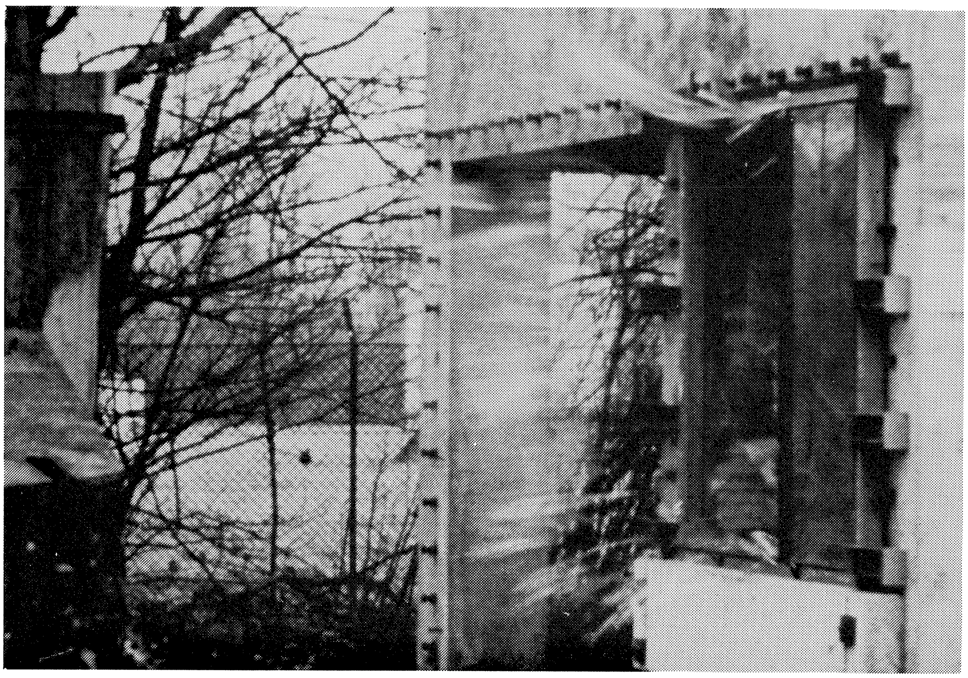


Fig. 12b. Test No. 10: during the explosion.

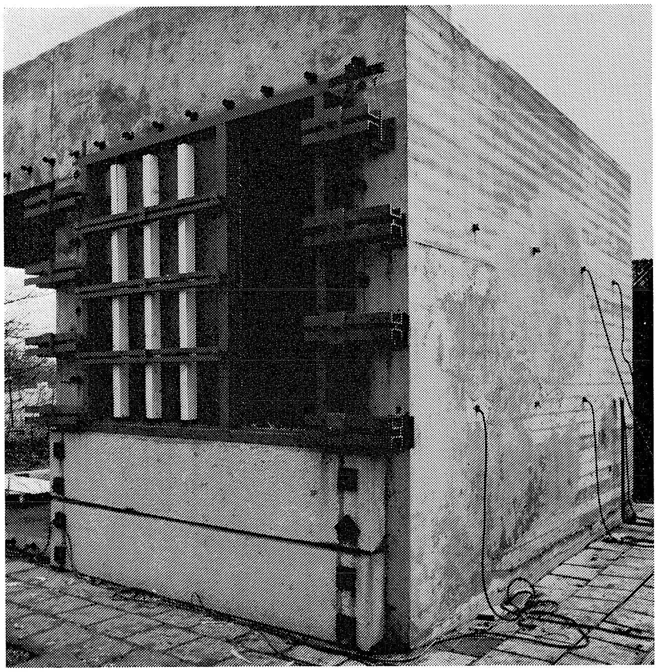


Fig. 13a.
Test No. 13: after the explosion.

Fig. 13b.
Test No. 16: after the explosion

tests a gas-and-air mixture containing about 10% of natural gas was exploded in the kitchen. The situation as observed after tests Nrs. 13 and 16 is seen in fig. 13.

5.4 Series IV: Variation of gas percentage

In tests Nrs. 20 to 24 the percentage of gas in the mixture was varied between 7% and 13% in order to study the effect thereof on the magnitude of the explosion pressure. In all the tests in this series two 8 mm thick glass panes were mounted in the steel window frame.

5.5 Series V: Scatter

This series comprises tests Nrs. 25 to 30, which were repeats of test Nr. 19 and provide a means of assessing the scatter, or variation, which may occur in the explosion pressures despite efforts to ensure the same extreme conditions in all cases (approx. 10.5% gas in the mixture).

5.6 Series VI: Size of the room; strength of the usual loadbearing walls and venting walls

The tests Nrs. 31 to 34 contained in this series were performed with a view to investigating the effect of the strength of the commonly employed façade wall constructions (= venting wall), the effect of the volume and shape of the room on the explosion pressure, and the behaviour of a 1-brick wall (= loadbearing wall).

In tests Nrs. 31 and 32 only a part of the room was filled with the 10% natural-gas mixture, a light partition being installed for the purpose. In test Nr. 33 the whole room was filled with the mixture.

Finally test Nr. 34 was performed with the 10% natural-gas mixture filling the kitchen as well as the room, ignition being effected in the kitchen. In this test both compartments were closed by a façade wall of the usual type; the steel door connecting them was replaced by an ordinary internal door.

The façades adopted for the two compartments (kitchen and room) are shown in fig. 14a. The situation after the explosion is seen in fig. 14b. The 1-brick wall which withstood the explosion is visible on the left in fig. 14a. For further particulars see Tables A to H in the Appendix.

6 INTERPRETATION OF THE PRESSURES MEASURED

6.1 Measured values of pressures

In each explosion test the pressure-time diagram was recorded at 10 points located at the walls and ceiling. Thus, in the 34 tests performed, about 340 of such diagrams were obtained (two examples are given in the Appendix).

In the main, all the diagrams so closely resemble the case shown schematised in fig. 15 that it will suffice to discuss this general diagram only.

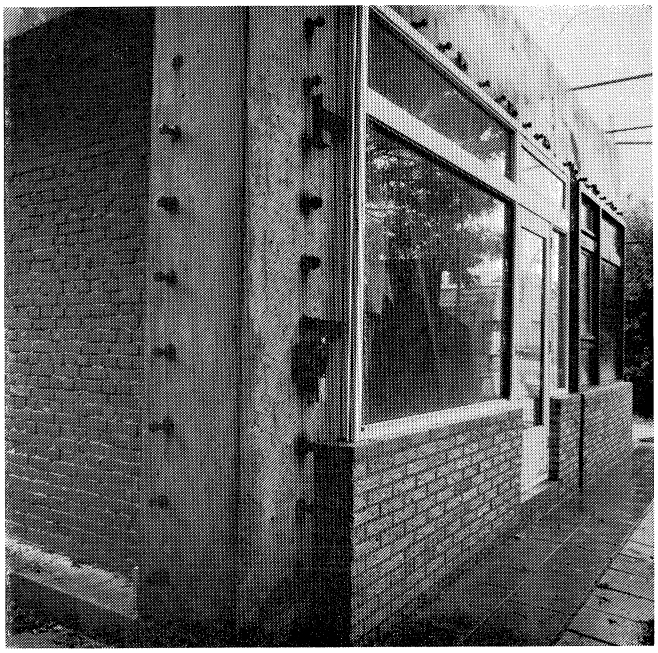


Fig. 14a.
Test No. 34: before the explosion.

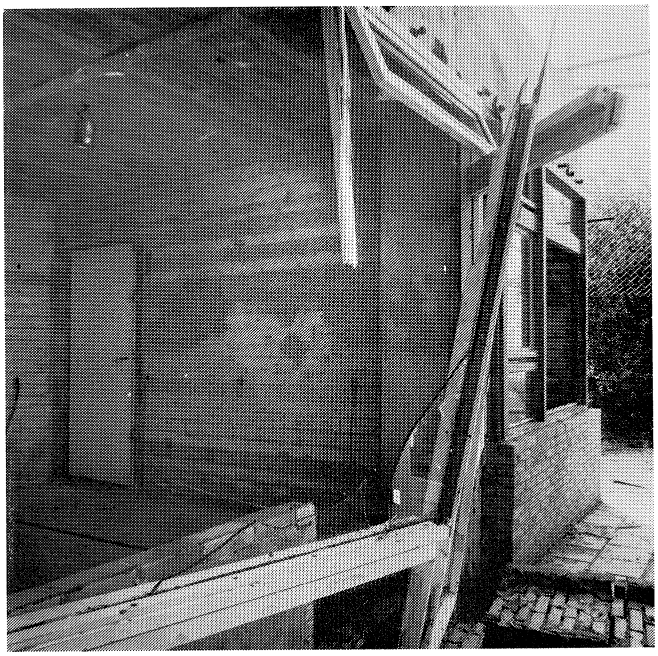


Fig. 14b.
Test No. 34: after the explosion.

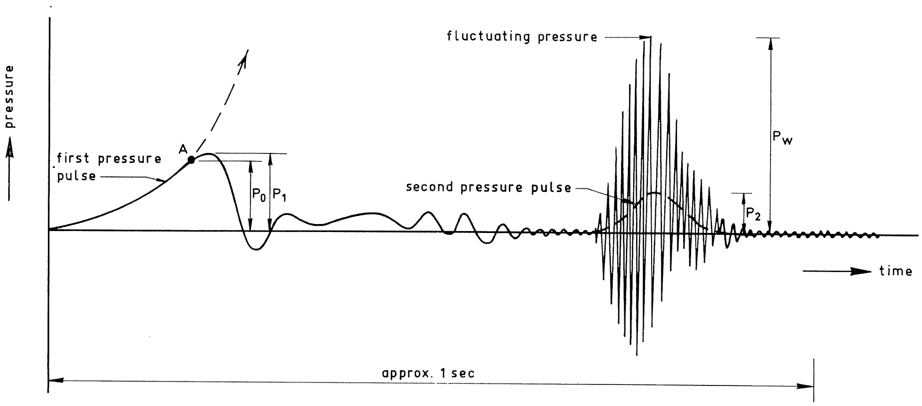


Fig. 15. Diagram showing pressure as a function of time, as observed in most of the tests.

The time measured from the instant of ignition is plotted on the axis of abscissae, the total length of time represented being approximately 1 second. The ordinates represent the pressure developed; the scale on the axis of ordinates has been intentionally omitted, however, as it would have to be different for different tests and is to a great extent dependent on the strength of the venting wall and on the area of the venting opening formed as a result of blow-out of that wall.

As appears from fig. 15, the pressure rises at an accelerated rate to a value at which the venting wall – window(s) or whole façade – blows out. In the diagram this is indicated by point A. After this the pressure in the room undergoes hardly any further increase and then decreases quite rapidly – often down to a negative value. The *peak value* p_1 of this first pressure pulse is given in the tables in the Appendix. After a few minor fluctuations in pressure the explosion appears to have ceased about half a second after ignition. However, further pressure fluctuations occur – probably in consequence of turbulent post-combustion of residual gas – in which the amplitudes attained in most of the tests were substantially in excess of the peak value p_1 of the first pressure pulse.

In this second phenomenon it is necessary to distinguish between the average pressure rise with a *peak value* p_2 (shown dotted in the diagram) and the maximum amplitude p_w of the rapidly alternating pressures. The peak value p_2 and the extreme value p_w measured in the course of each test are likewise presented in the tables.

The pressures p_1, p_2 and p_w are of short duration and should therefore not simply be conceived as a sustained loading such as is usually done in the case of normal loadings. The effect of these pressures on a structural member depends on:

- the above-mentioned amplitudes, but also on:
- the frequency and the number pressure fluctuations;
- the natural frequency of the structural member concerned;
- the strength of the member under loading of short duration.

A dynamic analysis taking account of all these factors is possible but complicated.* A difficulty is that the values of the said factors which have to be introduced into the calculation vary greatly and are imperfectly known. For that reason the measured explosion pressures are here converted to an approximate statically equivalent loading which can, for the purpose of structural analysis, be treated as a sustained loading of that same magnitude.

6.2 Statically equivalent loading

The ratio of the frequency of the pressure fluctuations and the natural frequency of vibration of the loadbearing wall (the resonance frequency) is of considerable influence upon the response of the loadbearing wall to the pressure amplitude to which it is subjected.

If the frequency of the loading is considerably lower than the resonance frequency of the loaded member, the amplitude of the loading will affect the member as though it were a static loading.

If the pressure fluctuation frequency is close to the resonance frequency of the member, the latter will behave as though loaded by a static loading larger than the actual amplitude.

If the two frequencies are exactly equal, and if the pressure pulse occurs once only, then the loading to be taken into account is π times the pressure amplitude; in the event of continuing pressure fluctuations the member may even fail while the pressure amplitudes are low.

However, if the frequency of the pressure fluctuations is sufficiently higher than the resonance frequency of the member, the pressures will to a great extent be absorbed by the inertia forces, so that the member undergoes much less deformation than it does under static loading of the same magnitude. The comparable static loading is therefore considerably lower than the actual pressure amplitude(s).

The peak values p_1 and p_2 are associated with a "once-only" pressure pulse which lasts about 0.2 to 0.3 second and is attained simultaneously in all parts of the room. These pressure pulses are comparable to a half period of a sine wave with a frequency of the order of 2 c/s.

From the frequency measurements which were carried out in connection with this research on a number of existing buildings it emerged that the resonance frequency of the loadbearing walls and floors is of the order of 30 to 100 c/s (concrete floors approx. 30 c/s; 0.2 m thick concrete walls 70 to 100 c/s; brick walls 60 to 70 c/s).

From the foregoing it is apparent that the peak values p_1 and p_2 of the first and the second pressure pulse, respectively, must be conceived as a static loading of the same magnitude.

On the other hand, this is not the case with the amplitudes of the rapidly fluctuating

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* In certain cases a computer analysis may be used, e.g., for machine foundations and suchlike structures [5, 6, 7]. In principle, this is likewise possible for any structure and loading, provided that the values of the said factors are known.

pressures with p_w as the maximum value. From the frequency analysis [8] of the pressure-time behaviour found in the tests performed in the kitchen it emerged that for the rapidly fluctuating pressure the frequencies of 212 and 160 c/s predominate, the 212 c/s frequency being manifested more particularly at the pressure transducers on a lateral wall and the 160 c/s frequency more particularly at those mounted on the ceiling. In view of these results the pressure fluctuations can be explained in terms of resonance of the mass of air between the two lateral walls, and between ceiling and floor, respectively, this resonance probably being built up by the occurrence of the most intensive post-combustion of the residual gas just at those particular points where the pressures are already highest at any given instant.

There are more reasons why, in converting p_w into statically equivalent loads a substantial reduction can permissibly be applied, namely:

- The frequency of the pressure fluctuations is higher than the above-mentioned resonance frequency of loadbearing walls and floors.
- As contrasted with p_1 and p_2, the pressure p_w is found to manifest phase differences, even at pressure transducers on one and the same wall. This means that p_w does not act simultaneously on the entire surface area of the wall. The comparable uniformly distributed loading is therefore smaller in magnitude.
- The tests were performed in the empty kitchen and/or room. In the presence of furniture, kitchen-dresser, etc. or in an *L*-shaped room the resonance may be considerably slowed down, so that p_w will be reduced or the rapid pressure fluctuations will not occur at all.

For these reasons we may take it that the comparable static loading corresponding to p_w will, generally speaking, be considerably smaller in magnitude than that corresponding to p_1 or p_2 and that therefore only the pressures p_1 and p_2 should be regarded as exercising a real (=static) loading on the structure.

The fact that the explosion pressure constitutes a loading of short duration has not yet been discussed in its implications, considering that in structural analysis it is usual to base oneself on the prolonged presence of the loading and on the associated long-term strength of the material.

For concrete the long-term compressive strength (sustained load strength) is generally taken to be about 0.85 times the strength obtained in a test of short duration [9]. The strength of the steel (reinforcing steel or structural steel) is considered to be reached when the stress attains the 0.2% proof stress. The actual failure strength is substantially higher than this, however. Bearing in mind, too, that the explosion pressure acts for a very much shorter time (one pressure pulse, max. 0.3 sec) than it takes to perform the usual type of short-term test on a structural member, it is safe to assume that with regard to an explosion the structure is about 25% stronger than is commonly allowed for in calculations. After all, the long-term strength is taken as only about 0.8 times the actual strength that the structure possesses in withstanding an explosion. In a calculation for explosive loading we may therefore base ourselves on the values p_1 and p_2 as loading and adopt a 25% higher structural strength than is ordinarily done or, alternatively, we may base ourselves on the usual long-term (sustained load) strength and introduce 80% of the actually occurring pressures as loading. In order to retain the usual procedure for structural analysis, this latter alternative will be adopted, so that as the statically equivalent loading corresponding to the measured pressures should be adopted: 80% of the amplitude of the first and of the second pressure pulse, respectively, i.e., 0.8 p_1 and 0.8 p_2.

It is often supposed that the strength of the material under loading of very short duration is even higher than the strength measured in an ordinary short-term test. It is not clear whether this supposition is based on the favourable influence of the inertia forces on the loading (which aspect has already been discussed and also taken into account, so far as is justified) or the strength of the material itself (i.e., the stresses that it can resist). This latter aspect has not been adequately investigated and it can be doubted whether a significantly higher strength than in an ordinary short-term test would be found if the duration of loading were reduced to 0.2–0.3 sec. This extra strength, if any, will therefore be ignored here.

In Chapter 2 it has already been noted that the explosion pressure, and therefore also the corresponding statically equivalent loading, will depend on the strength and the area of the venting wall. On the basis of tests Nrs. 11 to 19, in which they were varied, it will now be considered how important these factors are, with a view to deriving a formula from which the *explosion loading p* to be introduced into the calculations can be determined.

6.3 Effect of the strength of the venting wall

In tests Nrs. 10 to 19 the vent in all cases was formed as a result of fracture of the window pane(s). The strength of the panes is therefore to be regarded as the strength of the venting wall.

The uniformly distributed loading at which a pane of glass fractures can be calculated approximately by means of the formula which is used also for determining the thickness of glass necessary to withstand wind pressure [10, 11]:

$$d = \beta \cdot b \sqrt{\frac{q\gamma}{f_{kb}}}$$

where: d = thickness of the pane
β = factor depending on the ratio of the length l to the width b of the pane
b = shortest span of the pane, in m
q = wind pressure on the pane, in kN/m²
γ = factor of safety
f_{kb} = ultimate stress (fracturing stress) of the glass, in kN/m²

for l/b =	4	3	2	1.5	1
β =	0.86	0.85	0.78	0.70	0.54

Values normally adopted are: $f_{kb} = 42\ \text{MN/m}^2 = 42{,}000\ \text{kN/m}^2$ and $\gamma = 2.0$. The average ultimate stress of sheet glass is, however, of the order of $2f_{kb} = 84\ \text{MN/m}^2 = 84{,}000\ \text{kN/m}^2$, and the associated factor of safety is $\gamma = 1.0$.

Introducing the average ultimate loading p_0 (i.e., the loading at which the glass fractures), we obtain from the above formula:

$$d = \beta \cdot b \sqrt{\frac{p_0}{84{,}000}}$$

The average ultimate loading is therefore: $p_0 = 84{,}000(d/\beta b)^2$. The values of the ultimate loading for the panes employed in tests Nrs. 11 to 19 are given in table I.

In figs. 16 and 17 the statically equivalent loadings 0.8 p_1 and 0.8 p_2, respectively, for each of these tests have been plotted against the associated value of p_0.

In Chapter 6.1 it has been pointed out that the peak value of the first pressure pulse is not appreciably higher than the pressure at which the venting wall blows out. A definite relationship between the ultimate loading p_0 and the loading 0.8 p_1, as is manifest in fig. 16, is therefore more or less self-evident.

Since the first pressure pulse is a factor determining the conditions under which the second pressure pulse occurs, the value 0.8 p_2 is likewise (though indirectly and to a less extent) found to be dependent on the ultimate loading p_0 (see fig. 17).

6.4 Effect of the area of the venting wall

In general, it is assumed that the ratio ψ of the area F of the vent (= area of venting wall) to the volume V of the gas-and-air mixture that has to expand outwards through the vent when the explosion takes place will determine the magnitude of the pressures developed. In proprotion as the vent is smaller, the flow resistance encountered is higher and the pressures will accordingly be higher also.

In the case of the first pressure pulse this effect was not, or not appreciably, manifest. The results corresponding to the various values of ψ are all located at about the same level in fig. 16; any effect of ψ is within the range of scatter. However, ψ does significantly affect the second pressure pulse, as appears from fig. 17: with decreasing ψ the pressure increases more than proportionally.

6.5 Scatter

It is evident even from the wide scatter of the results indicated in figs. 16 and 17 that it is only possible to make a very rough estimate of the explosion loading. This is even more convincingly demonstrated by figs. 18 and 19, in which the values 0.8 p_1 and 0.8 p_2, as obtained in the test series IV and V, have been plotted against the corresponding gas percentages. It appears from these diagrams that at a gas percentage of about 10.5% the highest pressures were measured, but that these differed very greatly in magnitude in the successive tests.

This wide range of scatter is possibly due to very minor differences in gas percen-

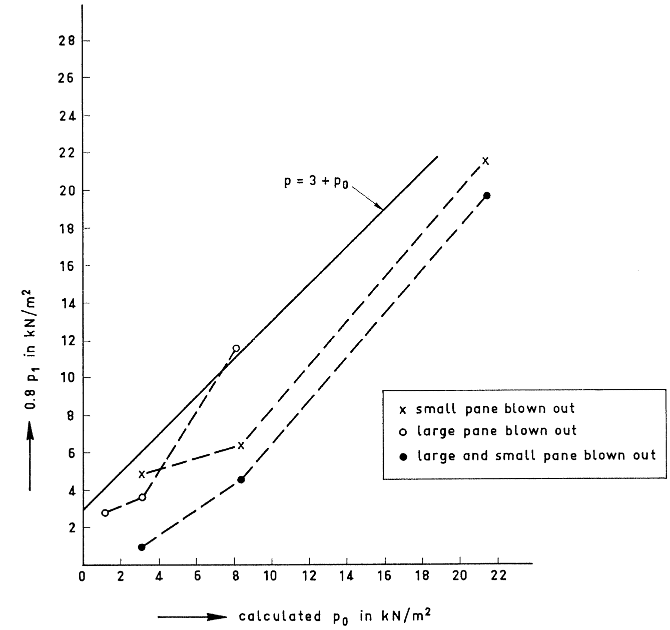

Fig. 16. Effect of strength of venting wall on first pressure pulse.

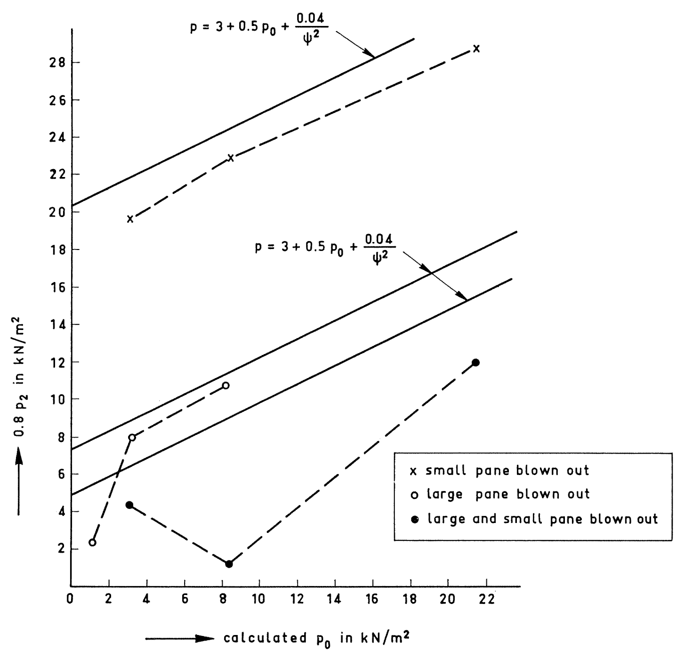

Fig. 17. Effect of strength and area of venting wall on second pressure pulse.

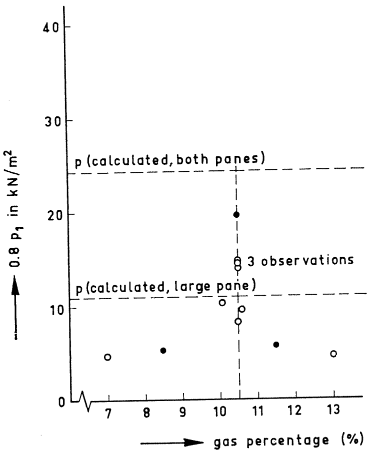

Fig. 18. Effect of gas percentage and scatter (first pressure pulse).

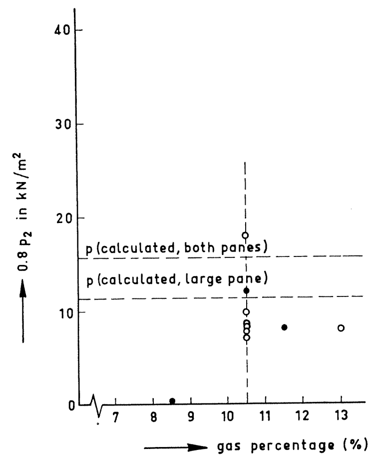

Fig. 19. Effect of gas percentage and scatter (second pressure pulse).

tage in relation to the optimum. In that case the highest measured values could be ignored, because it is unlikely that in actual practice this optimum percentage can be present as accurately as is attainable in a laboratory.

For these reasons the results presented in figs. 16 and 17 are to be regarded as practical extremes, while the scatter is attributable to random circumstances whose influence cannot be expressed in a formula.

6.6 Other results

The results of the preliminary tests (Nrs. 1 to 10) are not included in figs. 16 to 19, as they were obtained under different conditions as regards gas admission, ignition and venting wall. These tests do show, however, that even if the venting wall is of practically negligible strength and of relatively large area a certain minimum pressure is developed (see table A).

The results of the test series VI cannot be plotted in figs. 16 to 19 either, because in those tests the strength of the venting wall was uncertain and probably lower than that of the glass mounted in it; for in those the window frame and the spandrel panel were destroyed also. Broadly speaking, however, it can be inferred from the measured pressures that no new unfavourable effects manifested themselves in the tests of that series, not even when the explosion was produced in both compartments (room and kitchen) simultaneously (test No. 34).

6.7 Explosion loading *p*

With reference to the influencing factors discussed in the foregoing, the information on the explosion loading can be summed up as follows:

a. even with a large venting wall of negligible strength an explosion loading of the order of 3 kN/m^2 is possible;
b. this loading increases proportionally to p_0 in the first pressure pulse and to 0.5 p_0 in the second pressure pulse;
c. a loading increase of $0.04/\psi^2$ occurs in the second pressure pulse.

In this way we obtain for the *explosion loading p* to be adopted in the calculations (see figs. 16 and 17):

for the first pressure pulse: $p = 3 + p_0$
for the second pressure pulse: $p = 3 + 0.5 p_0 + 0.04/\psi^2$

where:

p = explosion loading, in kN/m^2

$$\psi = \frac{F}{V} = \frac{\text{area of venting wall, in m}^2}{\text{volume of the room, in m}^3}$$

p_0 = ultimate loading (blow-out loading) of the venting wall, in kN/m^2

Of the two values of p expressed by the above formulas the larger must of course be adopted, so that we may write:

$$p = 3 + 0.5 p_0 + \frac{0.04}{\psi^2} \geqslant 3 + p_0$$

The explosion loading is indicated in graph form in fig. 2. For any particular combination of p_0 and ψ the explosion loading p can be determined quite simply from that diagram.

If the venting wall consists of glass panes which are all of equal strength, i.e., equal p_0, then the value of p_0 can be readily calculated with the aid of the formula in Section 6.3.

In most cases, however, a façade will contain window panes differing from one another in span and sometimes in thickness. The ultimate loading p_0 (blow-out loading, at which fracture of the glass occurs) will then likewise differ from one pane to another. Obviously, even the strongest pane in the wall will also have to fracture if it is to function as part of the venting system. The highest value of p_0 of any of the panes involved is therefore the deciding value. Sometimes it may, however, be advantageous not to consider the strongest pane(s) as venting elements. This is the case when the total area of all the panes is so large that the favourable effect of the reduced p_0 is not outweighed by the unfavourable effect of the likewise decreased factor ψ. In such circumstances it may, where glazed façades of sufficiently large size are concerned, be advantageous to base oneself on a smaller value for the area F of the venting wall and on the corresponding lower value of p_0.

It may also occur that the panes in themselves are stronger than the glazing bars in which they are mounted. In such a case we may base ourselves on this lower strength of the glazing bars, provided that it is not under-estimated.

Of course the above formula can permissibly also be used in a case where a wall made of a material other than glass serves as a venting wall, provided that the actual strength there of is known.

The last word in regard to the manner in which the essential structural members should be designed to withstand the explosion loading p has not yet been spoken.

The Committee B7, which had this research undertaken, is of the opinion that in the design calculations for the explosion loading p the factor of safety can permissibly be reduced to practically 1.0, because the hazard that in a house or flat a natural-gas explosion will occur with an intensity exceeding that envisaged by the explosion loading p is to be regarded as virtually non-existent.

A structural member designed in this way can be considered capable of withstanding natural-gas explosions.

Exceptions have to be made with regard to large enclosed spaces (e.g., exceeding 1000 m^3 in volume) such as factory sheds and also with regard to long enclosed spaces such as basement corridors, because the pressures which occur under those circumstances have not been investigated and it is possible that they exceed the values obtained from the formulas for p. It is therefore all the more advisable, for example, not to install central heating boilers in basements.

It should be noted that the explosion loading p is so indicated* that the usual material strength laid down in the design code (= long-term or sustained load strength) can be adopted in the structural design calculations. It is therefore not permissible to reckon on a higher material strength because of the short duration of the explosion.

However, in view of the low risk and the short duration of a natural-gas explosion, it is permissible to take account of the tensile strength of stone-like materials if it can be assumed with adequate certainty that this tensile strength has not been nullified in consequence of normally occurring loads, shrinkage, etc.

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* See Section 6.2. The explosion loading p represents $0.8\times$ the static pressure that occurs. The short duration of the stresses acting in the material has already been taken into account in this.

For example, in many instances a loadbearing concrete wall is always subjected to compressive loading. Hence it can reasonably be supposed that the tensile strength of the concrete (in the vertical direction) will be preserved and be available to assist in withstanding an explosion (just as is normally allowed with regard to shear force).

It is more difficult to decide what tensile strength may be assumed for a brick wall normally loaded in compression, since that strength, besides being low, depends to a great extent on the quality of workmanship in constructing the wall. (The brick wall used in the tests withstood four explosions, thanks to its tensile strength and to the incidental fixity at its edges).

It should be noted that the loading p is a loading which, inside the building and in the room concerned, acts in all directions. As a result, tensile forces are produced in the floors, and if there is only a light superimposed loading, the compressive force in the walls may briefly become a tensile force. More particularly in the structural connections between prefabricated components there must be sufficient reinforcement at the connections and the anchorage of such reinforcement must be adequately capable of resisting the tensile force. This reinforcement is also beneficial in ensuring the coherence referred to in Chapter 1.

Finally, it should once again be pointed out that only those members of the loadbearing structure should be designed to withstand the explosion loading p which are liable to initiate progressive collapse in the event of their failure.

Of course, a structural member that can withstand the loading p will also be able to withstand other loadings of comparable type and magnitude, so that thereby the safety with regard to other exceptional loadings is likewise increased.

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Appendix

Table A. Data of test structure and the test results

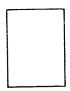
1	2	3	4	5	6	7	8	9	10	11		
		dimensions of chamber	venting wall							measured maximum pressures		
					material			gas	point of			
series	testno.	(kitchen)	diagram	dimensions	type	thickness	fixing	percentage	ignition	P_1	P_2	P_w
		m		m		mm		%		kN/m²	kN/m²	kN/m²
	1			2,00 × 2,60	hardboard	4	adhesive tape	9,8	along	–	–	–
	2			2,00 × 2,60	hardboard	4	adhesive tape	10,5	lateral	0,65	1,00	–
	3			2,00 × 2,60	hardboard	4	adhesive tape	10,5	wall,	–	–	–
I	4	4,00 × 2,00 × 2,60		2,00 × 2,60	hardboard	4	adhesive tape	10,5	approx.	1,08	0,50	1,70
	5			2,00 × 2,60	hardboard	4	adhesive tape	10,5	1 m	–	–	–
	6			2,00 × 2,60	hardboard	4	adhesive tape	10,5	above	1,40	2,50	–
	7			2,00 × 2,60	plywood	4	adhesive tape	10,5	floor	2,20	–	3,20

Table B. Further particulars of the test

1	2	12	13	14	15	16
series	test no.	method of gas admission	admission period	time of mixing gas with air by means of the fan	external temperature during test	particulars
			min		°C	
I	1	two stoves (with four burners in all) along lateral wall, approx. 1 m above floor	110	–	9	In these preliminary tests a number of snags were encountered in connection with regulating the measuring equipment, cooling the pressure transducers, making the test structure gas-tight, mixing the gas with the air, etc. Because of leakage, the gas percentage stated in column 9 was not always attained, and the measured pressures are therefore not representative. These difficulties were overcome before the next series of tests was carried out
	2	,,	110	–	10	
	3	,,	125	–	8	
	4	,,	125	5 minutes after end of gas admission	10	
	5	,,	125	last 70 minutes of admission period	8	
	6	freely from opening No. 53 (see Fig. 17)	13	whole admission period and 4 min. after it	8	
	7	,,	15	whole admission periode and 15 min. after it	4	

Table C. Data of test structure and the test results

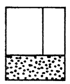
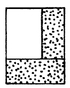
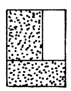
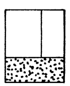
1	2	3	4	5	6	7	8	9	10	11		
		dimensions of chamber	venting wall							measured maximum pressures		
					material			gas	point of			
series	testno.	(kitchen)	diagram	dimensions	type	thickness	fixing	percentage	ignition	P_1	P_2	P_w
		m		m		mm		%		kN/m²	kN/m²	kN/m²
	8			0,73 × 1,70 1,19 × 1,70	hardboard	4	putty	10	along lateral	1,15	0	4,70
II	9	4,00 × 2,00 × 2,60		0,73 × 1,70 1,19 × 1,70	hardboard	4	putty	10	wall, approx.	1,50	0,30	4,00
	10			0,73 × 1,70 1,19 × 1,70	glass	5	glazing bars (wood)	10	1.30 m above floor	5,90	2,80	8,40
	11			0,73 × 1,70 1,19 × 1,70	glass	5	glazing bars (wood)	10	in middle, approx. 1.30 m above floor	5,60	1,50	13,00
	12			1,20 × 1,70	glass	3	glazing bars (steel)	10	in middle, approx.	3,00	3,00	33,00
	13			1,20 × 1,70	glass	5	glazing bars (steel)	10,1	1.30 m above	3,50	10,00	46,50
	14			1,20 × 1,70	glass	8	glazing bars (steel)	10,1	floor	14,50	13,50	57,50
III	15	4,00 × 2,00 × 2,60		0,60 × 1,70	glass	3	glazing bars (steel)	10,1		5,50	24,50	55,00
	16			0,60 × 1,70	glass	5	glazing bars (steel)	10,1		7,75	28,50	59,00
	17			0,60 × 1,70	glass	8	glazing bars (steel)	10,1		27,00	36,00	81,50
	18			0,60 × 1,70 1,20 × 1,70	glass	3	glazing bars (steel)	10,1		1,25	5,50	21,50
	19			0,60 × 1,70 1,20 × 1,70	glass	8	glazing bars (steel)	10,1		13,00	9,00	43,00

Table D. Further particulars of the test

1	2	12	13	14	15	16	17
series	test no.	method of gas admission	admission period	time of mixing gas with air by means of the fan	external temperature during test	panes fractured: small, large or both	particulars
			min		°C		
	8	2 pipes with holes, approx. 0,20 m above floor (see illustr.)	25	last 15 minutes of admission period	1	–	
II	9	,,	25	,,	1	–	
	10	,,	25	,,	2	large	
	11	,,	25	during whole admission period	2	both	
	12	2 pipes with holes, approx.	25	during whole	5	large*	In order to determine the
	13	0,20 m above floor	25	admission period	6,5	large*	precise instant at which
	14	(see illustr.)	25	,,	8	large*	the pane fractured, in this
III	15	,,	25	,,	7,5	small*	series of tests the panes
	16	,,	25	,,	4	small*	were each provided with
	17	,,	25	,,	8	small*	an electrical resistance
	18	,,	25	,,	8	both	strain gauge
	19	,,	25	,,	6,5	large	

* Only one pane provided as a venting element

Table E. Data of test structure and the test results

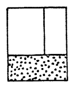
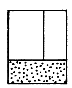
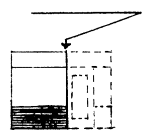
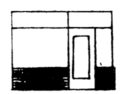
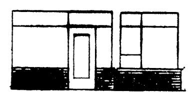
1	2	3	4	5	6	7	8	9	10	11		
		dimensions of chamber	venting wall					gas	point of	measured maximum pressures		
					material							
series	testno.	(kitchen)	diagram	dimensions	type	thickness	fixing	percentage	ignition	P_1	P_2	P_w
		m		m		mm		%		kN/m²	kN/m²	kN/m²
	20			0,60 × 1,70 1,20 × 1,70	glas	8	glazing bars (steel)	7,0	in middle, approx.	–	–	–
	21			0,60 × 1,70 1,20 × 1,70	glas	8	glazing bars (steel)	11,5	1.30 m above	7,07	10,10	12,10
IV	22			0,60 × 1,70 1,20 × 1,70	glas	8	glazing bars (steel)	8,5	floor	6,90	0,50	27,30
	23	4,00 × 2,00 × 2,60		0,60 × 1,70 1,20 × 1,70	glas	8	glazing bars (steel)	13,0		5,90	10,00	34,00
	24			0,60 × 1,70 1,20 × 1,70	glas	8	glazing bars (steel)	7,0		6,00	–	–
V	25	4,00 × 2,00 × 2,60		0,60 × 1,70 1,20 × 1,70	glas	8	glazing bars (steel)	10,5	in middle, approx.	18,00	22,50	58,50
	26			0,60 × 1,70 1,20 × 1,70	glas	8	glazing bars (steel)	10,6	1.30 m above	12,00	10,40	20,40
	27			0,60 × 1,70 1,20 × 1,70	glas	8	glazing bars (steel)	10,5	floor	18,50	12,30	43,10
	28			0,60 × 1,70 1,20 × 1,70	glas	8	glazing bars (steel)	10,5		18,50	11,00	49,80
	29			0,60 × 1,70 1,20 × 1,70	glas	8	glazing bars (steel)	10,5		10,45	10,00	42,00
	30			0,60 × 1,70 1,20 × 1,70	glas	8	glazing bars (steel)	10,5		24,60	15,00	52,50

Table F. Further particulars of the test

1	2	12	13	14	15	16	17
series	test no.	method of gas admission	admission period	time of mixing gas with air by means of the fan	external temperature during test	panes fractured: small, large or both	particulars
			min		°C		
	20	2 pipes with holes, approx. 0,2 m above floor	20	during whole admission period	4,5	large	In test No. 20 the pressure recording equipment was faulty
	21	,,	27	,,	6	both	
IV	22	,,	18	,,	7	both	
	23	,,	30	,,	7	large	
	24	,,	15	,,	10	large	
	25	2 pipes with holes, approx. 0,2 m above floor	23	during whole admission period	10	large	
	26	,,	20	,,	11	large	
V	27	,,	20	,,		large	
	28	,,	20	,,		large	
	29	,,	20	,,		large	
	30	,,	20	10 min		both	

Table G. Data of test structure and the test results

1	2	3	4	5	6	7	8		
			venting wall				measured maximum pressures		
series	test No.	dimensions of the compartment(s)	diagram	material	gas percentage	point of ignition	P_1	P_2	P_w
		m			%		kN/cm²	kN/cm²	kN/cm
VI	31	3,95 × 1,90 × 2,60 (part of room)	position of partition 	facade construction	10,5	in the middle of the relevant	8,00	0	0
	32	,,		as used in practice	10,5	part of the room, approx. 1.30 m above floor	11,00	0	0
	33	3,95 × 3,50 × 2,60 (room)		,,	10,5	in the middle of the room approx. 1.30 m above the floor	5,00	10,00	22,00
	34	3,95 × 2,00 × 2,60 3,95 × 3,50 × 2,60 kitchen and room		,,	10,5	in the middle of the kitch approx. 1.30 m above the floor	4,00* 6,00**	8,00* 0**	10,00* 4,00**

* denotes pressure measured in kitchen
** denotes pressure measured in room

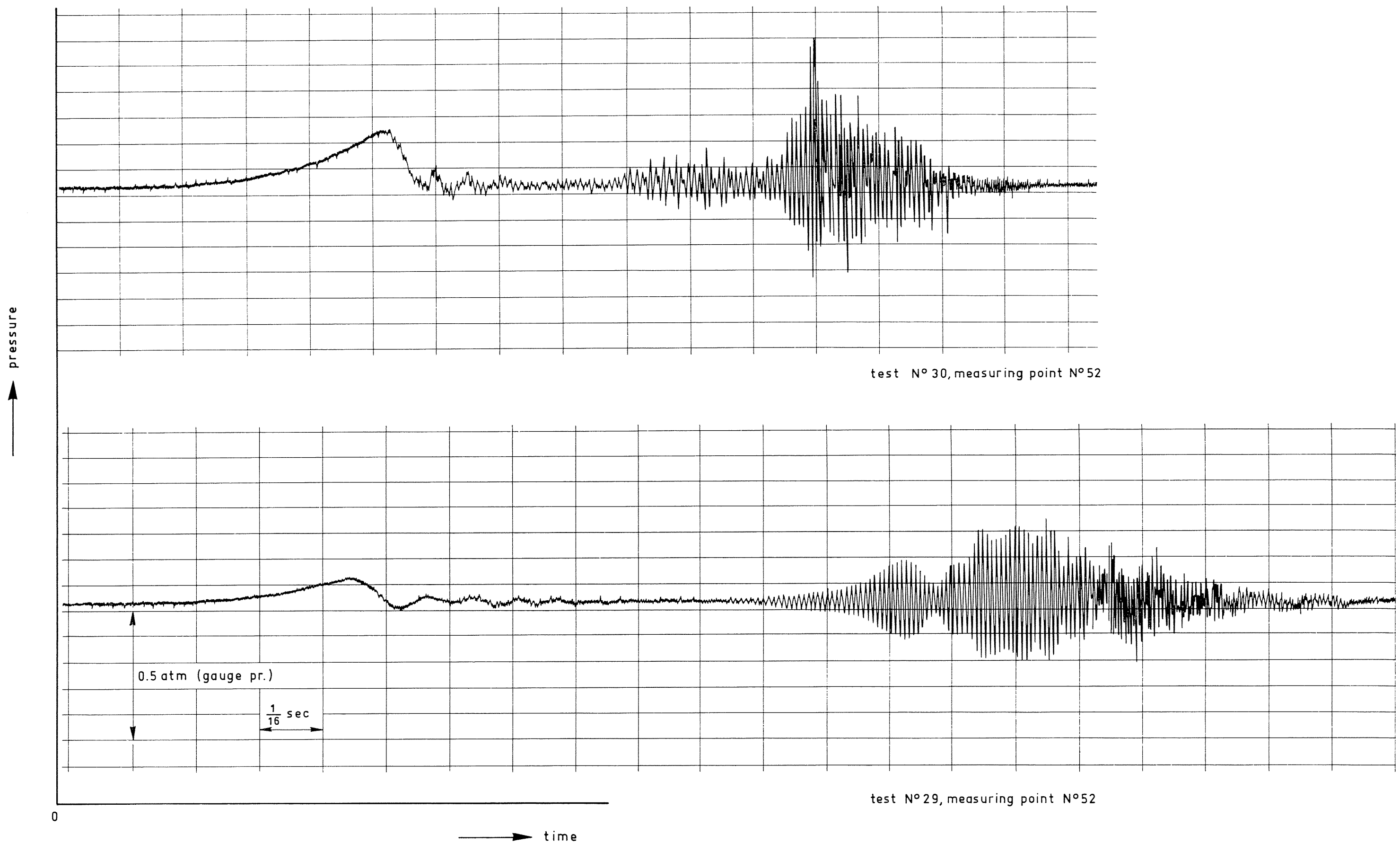
Table H. Further particulars of the test

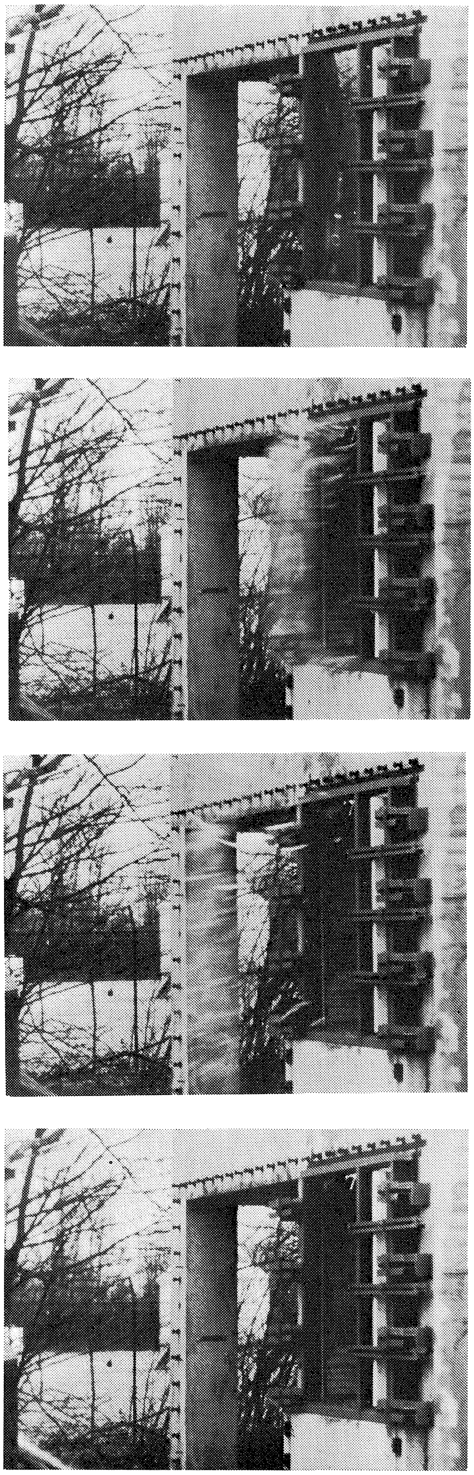
1	2	9	10	11	12	13
series	test No.	method of gas admission	admission period	time of mixing gas with air by means of the fan	external temperature during test	particulars
			min		°C	
	31	2 pipes with holes, approx. 0.2 m above floor	38	during whole admission period	17	The glazing bars were fixed with wire nails every 0.25–0.30 m. The brick external wall (0.22 m thick) and the partition (0.09 m thick aerated concrete) remained intact in the explosion.
VI	32	2 pipes with holes, approx. 0.2 m above floor	43	during whole admission period	16	The glazing bars were fixed with screws every 0.25 m. The pane and the partition failed; the brick wall remained intact.
	33	2 pipes with holes, approx. 0.2 m above floor	48	during whole admission period	23	In the explosion only the door in the façade front was blown open; the rest of the front structure was blown out a very short time afterwards (glass, window frame and outer leaf of spandrel panel); the brick wall remained intact.
	34	1 pipe in the kitchen 2 pipes in the room	36 kitchen 43 (room)	during whole admission period	15	In the explosion the larger window in the kitchen was fractured and then the whole façade front of the room; the brick wall remained intact.

Table I. Calculated strength of glass panes in tests Nos. 12 to 30

dimensions of pane	thickness of pane	calculated ultimate loading
m × m	mm	kN/m^2
1,20 × 1,70	3	1,15
	5	3,20
	8	8,15
0,60 × 1,70	3	3,00
	5	8,40
	8	21,40

Examples of measured time-pressure diagrams



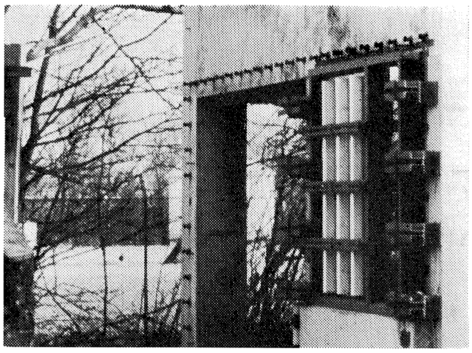


a. before ignition

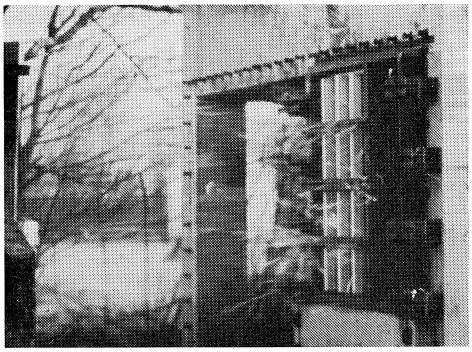
b–c. stages after ignition

d. condition after the explosion

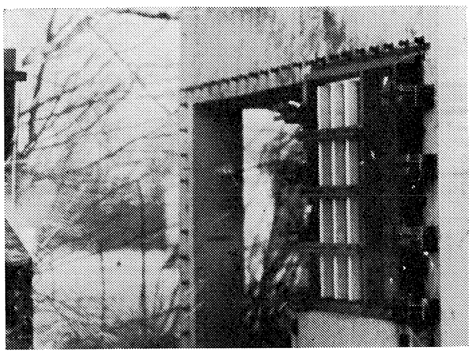
Film image: test No. 12

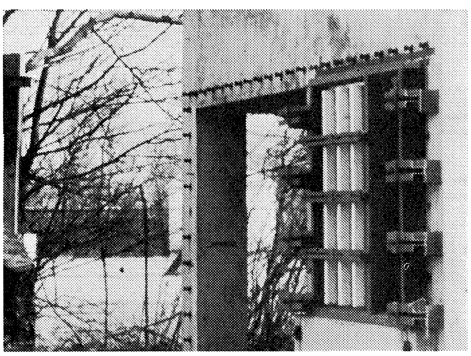


a. before ignition



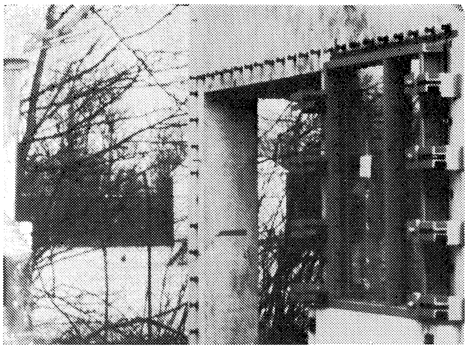
b–c. stages after ignition



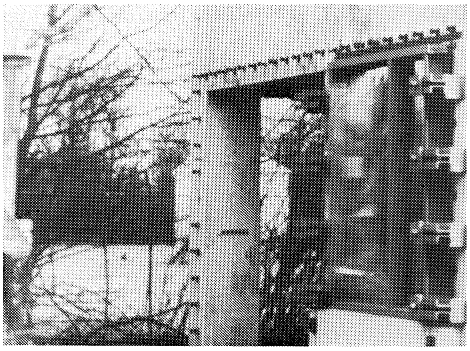


d. condition after the explosion

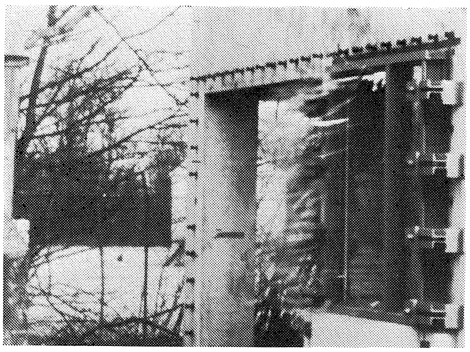
Film image: test No. 17

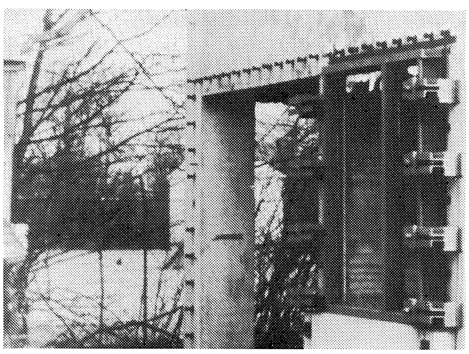


a. before ignition



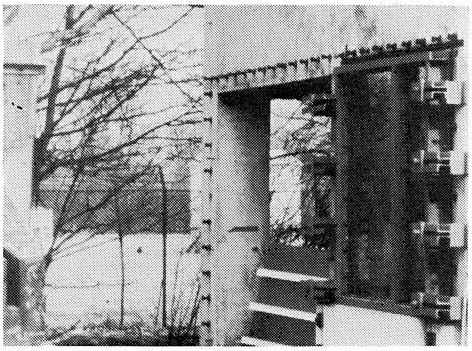
b–c. stages after ignition



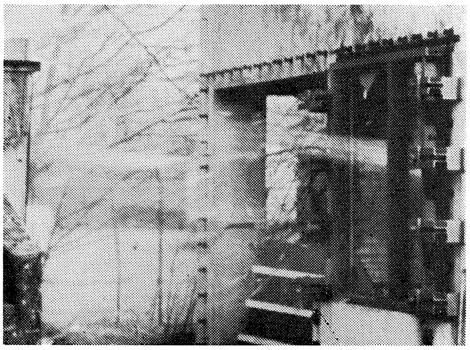


d. condition after the explosion

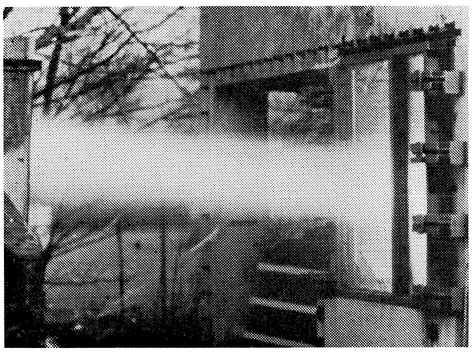
Film image: test No. 18

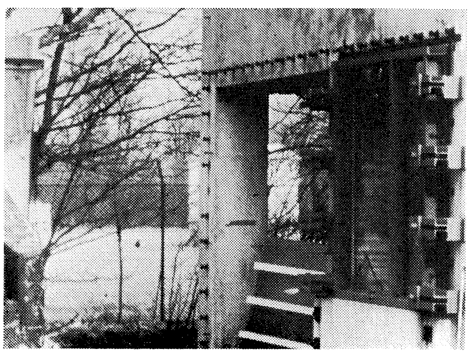


a. before ignition



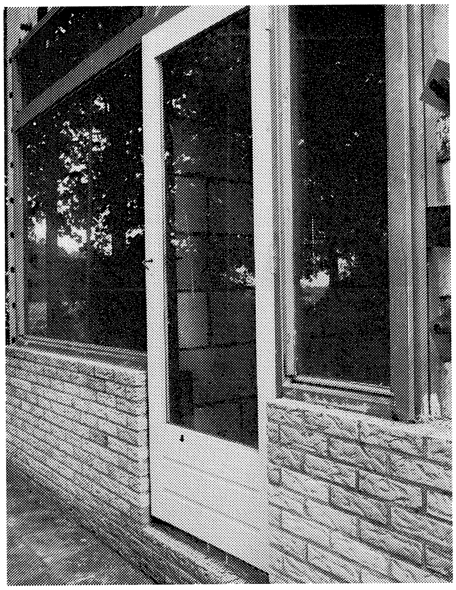
b–c. stages after ignition



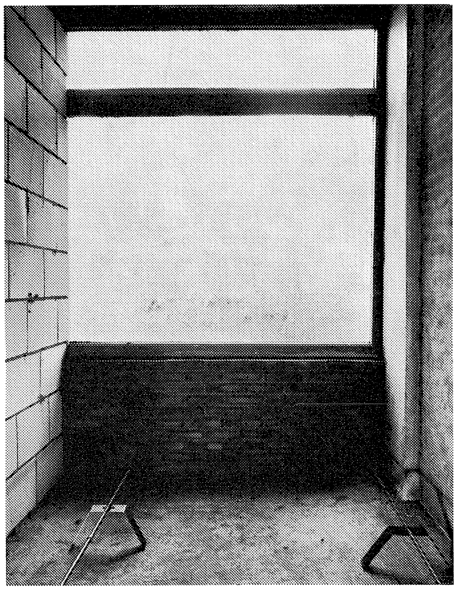


d. condition after the explosion

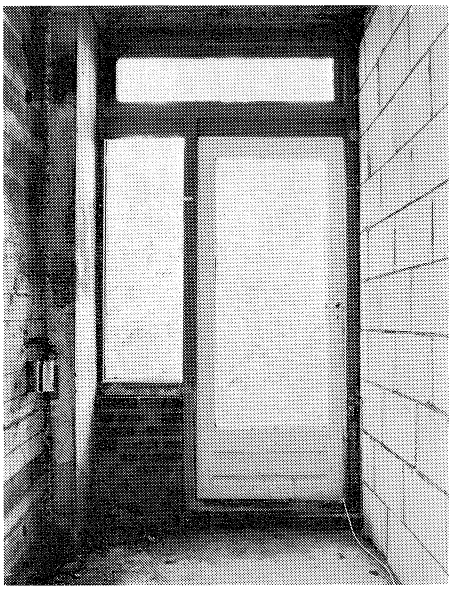
Film image: test No. 23



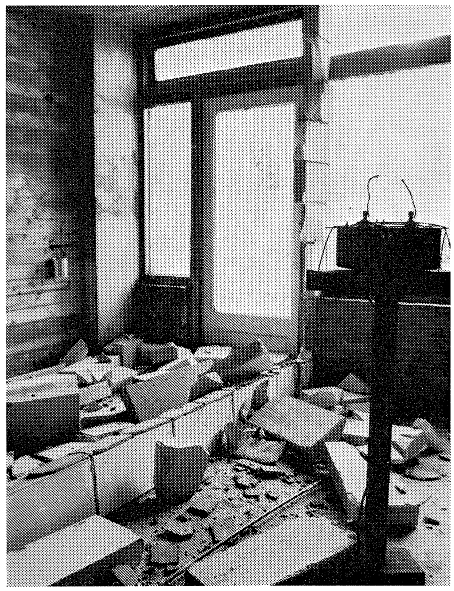
a. exterior view before the test



b. part of room in which gas was exploded (partition wall is seen on the left)



c. other part of room

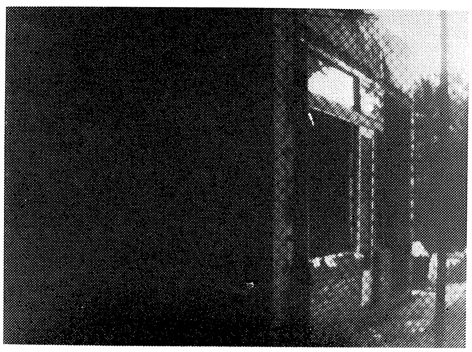


d. condition after the explosion (test No. 32)

Views showing arrangements for tests Nos. 31 and 32.

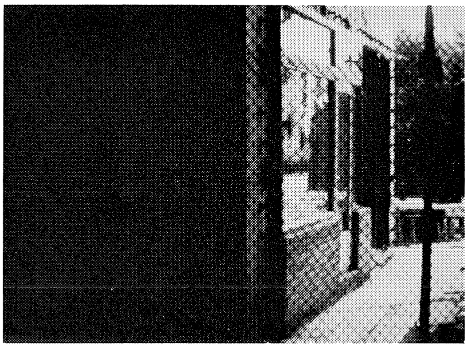
a. before ignition

b–c. stages after ignition

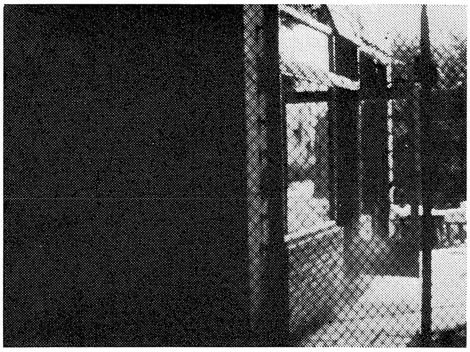


d. condition after the explosion

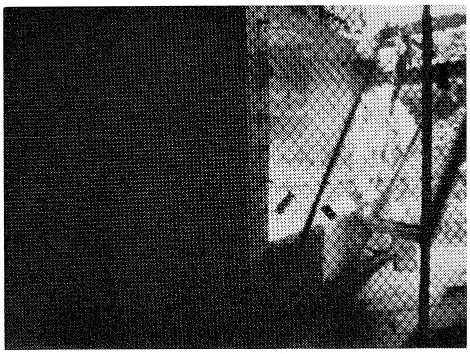
Film image: test No. 32

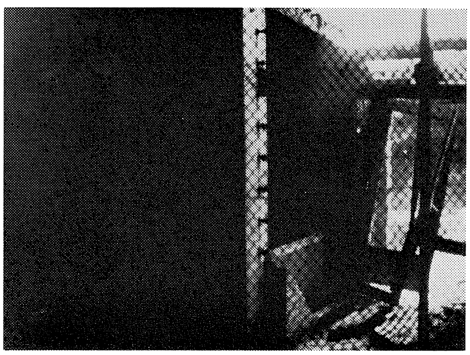


a. before ignition



b–c. stages after ignition

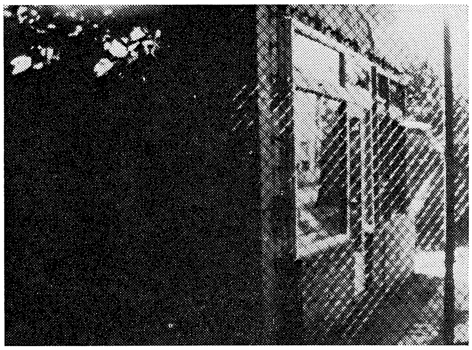




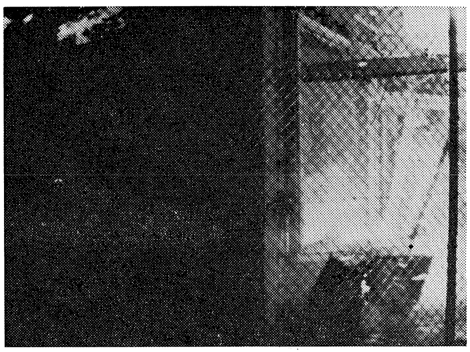
d. condition after the explosion

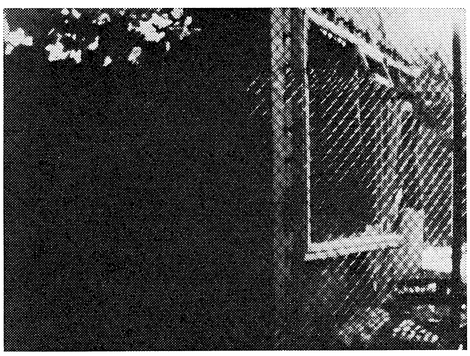
Film image: test No. 33

a. before ignition



b–c. stages after ignition





d. condition after the explosion

Film image: test No. 34