Fire Research Note No 987

GAS EXPLOSIONS IN BUILDINGS PART IV

STRAIN MEASUREMENTS ON THE GAS EXPLOSION CHAMBER

by

M Senior

March 1974

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ABSTRACT

This paper describes the methods employed for the measurement of the dynamic strains occurring in the structure of the large scale explosion test chamber at Cardington, during gas explosions produced within the chamber.

The general considerations for the measurement of strain are discussed and particular reference is made to the choice of resistance foil gauges. Single active element, self temperature compensated gauges have been adopted for use in the experimental work. A limited number of results are presented for illustrative purposes; more comprehensive results will be the subject of a later report. Strains produced within the structure have been extremely small for explosions of non-stoichiometric gas mixtures and vent covers of low bursting strength; much larger values have been obtained for stoichiometric gas mixtures.

Modifications are at present in hand to increase the overall sensitivity of the system.

DEPARTMENT OF THE ENVIRONMENT AND FIRE OFFICES' COMMITTEE
JOINT FIRE RESEARCH ORGANIZATION

CONTENTS

LIST OF SYMBOLS

A	Area
a	Coefficient of thermal expansion
d	Diameter
E	Young's modulus
e	Strain
F	Force
I	Current
I_G	Galvanometer current
k	Strain sensitivity or gauge factor
l	Length
m	Temperature coefficient of gauge factor
R	Resistance
R*	Variable resistance value $(R + \Delta R)$
V_G	Galvanometer voltage
V_I	Bridge supply voltage
α	Coefficient of thermal resistivity
θ	Temperature ^{o}K
ν	Poissons ratio
ρ	Resistivity
σ	Stress

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FOREWORD

Following the Ronan Point disaster and the report of the Investigating Tribunal, it was decided that the Fire Research Station of the Building Research Establishment would undertake a study of gas explosions in large compartments. In particular, the study would cover the factors affecting the development and severity of the explosions and the extent to which the pressures obtained could be relieved by venting.

In the context of the problem as a whole, the study is intended to provide the basic data on the form and magnitude of the transient stresses likely to be experienced by buildings, in the event of gas explosions involving one or more compartments. This information is required as a guide for safe structural design and for any re-appraisal of the relevant parts of the Building Regulations 1972, Part D, England, or Building Standards (Scotland) (consolidation) Regulations 1971.

The study has begun with explosions in a single compartment of realistic dimensions (1000 ft^3, 28 m^3) provided with a single opening of simple configuration, the size of which can be varied and which can be closed with panels having a range of bursting pressures.

In view of the progressive change to natural gas, which is lighter than air, and the probable circumstances of the Ronan Point explosion, special emphasis is placed on the explosion of layered gas/air mixtures and the effects of layer depth, composition and point of ignition.

The principal measurements consist of high-resolution pressure-time records at points both inside and outside the compartment. In general, these pressure records are complex, including both positive and negative pressures, and attention is given to the exclusion of spurious effects due to mechanical vibration and transient heat pulses accompanying the explosion.

The study is to be extended to gas explosions in multiple compartments communicating by door openings and corridors. Here, particular attention will be given to the effects of turbulence generated at openings, bends and obstacles and the possibility of pressures increasing as explosion propagates from one compartment to another.

This series of notes comprises detailed accounts of phases of the work as it proceeds. A project of this magnitude necessarily involves a considerable amount of preliminary work in the development of equipment and procedures all of which needs to be placed on record, but, in isolation, may sometimes appear somewhat remote from the objectives. This foreword is intended to facilitate the presentation of the detailed material with a minimum of introductory matter - no more than is needed to indicate the place of the particular work reported in the project as a whole. Reports of results and conclusions from this study will be included in the series at appropriate stages as the work proceeds and, correspondingly, these will need to contain a minimum of experimental detail.

Reports preceding the present one in the series are:

FR Note 984 Part I Experimental explosion chamber
P S Tonkin and C F J Berlemont

FR Note 985 Part II Measurement of Gas explosion pressures
S A Ames

FR Note 986 Part III A rapid multi-channel chromatographic gas analysis system.
R N Butlin, S A Ames and C F J Berlemont

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1. INTRODUCTION

Measurements of the strain produced within the structure of the test chamber at Cardington, during an explosion, have been obtained to provide information relating to the following problems:

(a) The amplitude and duration of transient strains occurring within the chamber components

(b) The vibration pattern induced within the walls of the chamber

(c) Correlations between vibrations and pressure fluctuations within the chamber

(d) The relative motion of the tying components of the chamber and the concrete base

(e) To obtain practical experience in the use of strain measuring equipment (on large components which may be employed on subsequent work).

It must be emphasized that a detailed strain analysis of the whole chamber has not been attempted. The experimental work is an attempt to produce an overall picture of the movements within the structure of the chamber.

2. GENERAL CONSIDERATIONS FOR STRAIN MEASUREMENT

First, consideration must be given to the type of strain measuring system required. In the present context it is required to measure short term transient strains occurring within the structure; relatively long term strains are not considered at this stage.

The measurement of transient strain implies the use of a dynamic system in which the main requirement is a large electrical output for a given strain as opposed to the high, long term stability required in a static system. In general most dynamic recording instruments suffer from reduced sensitivity with increase in the frequency of an applied signal.

In order to produce the maximum possible indication of a given strain the transducer itself must have a very high strain sensitivity (gauge factor), and for high frequency work it must possess good temporal strain resolution.

An important requirement here is that the indication of the measured strain, and the equipment employed for recording the measured value, should be remote from the test chamber as the area enclosing the chamber is hazardous.

The environmental conditions prevailing in the proximity of the chamber make excessive demands on all instrumentation, with the effect of water vapour being prevalent. Thus the effects of humidity, and temperature, on the measuring system must be reduced to a minimum.

Mechanical considerations also require that the system must be robust. Constructional details of the test chamber have been described in detail by Tonkin and Berlemont[1] and will not be discussed in the present work.

Finally, the transducer itself should be attached to the test chamber using a bonding method which is completely reliable otherwise erroneous strain measurements could be obtained.

3. THE RESISTANCE STRAIN GAUGE

The strain measurement system which fulfills the requirements laid down in Section 2 is the electrical resistance strain gauge, in particular, the foil strain gauge with the appropriate amplification and recording instruments.

Before entering into details of any particular strain gauge system it is desirable to consider the general theory behind the measurement of strain by the resistance method (Neubert[2], Hetenyi[3]).

Young's modulus E is defined as the ratio of stress σ to strain e, that is

$$E = \frac{\sigma}{e} = \frac{Fl}{A\,\Delta l} \qquad (1)$$

Applying this relationship to a wire of length l, diameter d and area of cross section A, which is stretched by a force F, the change in length Δl (the elongation) is given by

$$\Delta l = \frac{1}{E}\,\frac{Fl}{A} \qquad (2)$$

where it can be seen that E is a measure of the wire's resistance to elongation.

At the same time as the wire is elongated by the applied force, it will be reduced in diameter from d to $d - \Delta d$, depending on the value of Poissons ratio which is defined as

$$\nu = \frac{\Delta d}{d}\,\frac{1}{\Delta l} \qquad (3)$$

Any strain induced in a wire will alter its electrical resistance as the wire becomes elongated and reduced in area. Also an applied strain results in a variation of the resistivity ρ of the wire. Thus the factors Δl, ΔA and $\Delta\rho$ all contribute to a resistance variation ΔR.

For an applied stress variation $d\sigma$ we then have

$$\frac{dR}{d\sigma} = \frac{d(\rho l/A)}{d\sigma} = \frac{\rho}{A}\frac{dl}{d\sigma} - \frac{\rho l}{A^2}\frac{dA}{d\sigma} + \frac{l}{A}\frac{d\rho}{d\sigma} \qquad (4)$$

dividing by $R = \rho l/a$, and using finite increments to replace the differentials, which is possible if $d/d\sigma$ terms are approximately constant in a linear system, then

$$\frac{\Delta R}{R} = \frac{\Delta l}{l} - \frac{\Delta A}{A} + \frac{\Delta \rho}{\rho} \qquad (5)$$

but $$\Delta A/A = 2\Delta d/d \qquad (6)$$

and using Poissons ratio ν from equation (3) we have

$$\frac{\Delta d}{d} = \frac{\nu \Delta l}{l} \qquad (7)$$

Substituting for this in equation (5) then

$$\frac{\Delta R}{R} = \frac{\Delta l}{l}(1 + 2\nu) + \frac{\Delta \rho}{\rho} \qquad (8)$$

Now defining the strain sensitivity or gauge factor k as

$$k = \frac{\Delta R/R}{\Delta l/l} = \frac{\Delta R\, l}{R \Delta l} \qquad (9)$$

and substituting for $\Delta R/R$ from (8) into (9) we have

$$k = 1 + 2\nu + \frac{\Delta \rho}{\rho} \cdot \frac{1}{\Delta l} \qquad (10)$$

From equation (8) and using the value of k in equation (10) we obtain the relation for ΔR

$$\Delta R = \frac{R \Delta l}{l}\left(1 + 2\nu + \frac{\Delta \rho}{\rho}\frac{1}{\Delta l}\right) \qquad (11)$$

which gives

$$\underline{\underline{\Delta R = R\, e\, k}} \qquad (12)$$

Thus a knowledge of gauge factor and the initial and final values of electrical resistance of a section of wire, will enable the calculation of the strain to be carried out. In practice, the only quantity to be measured is ΔR which is usually achieved using an electrical bridge circuit such as

that shown in Figs 1and 2.

To calculate the out of balance current flowing in the galvanometer I_G when the strain gauge element changes its resistance from R to $R + \Delta R$, where $\Delta R = R\ e\ k$ from equation (13) and $R + \Delta R = R^*$, we obtain the relationship for the currents I_1 I_2 and I_G in determinant form

$$\text{Determinant } D = \begin{vmatrix} I_1 & I_2 & I_G & 1 \\ -R_1 & (R^* + R_1) & R_G & 0 \\ -R_1 & (R + R_1) & -(R + R_1 + R_G) & 0 \\ R_B & (R + R^*) & -R & V_I \end{vmatrix}$$

This can be solved for I_G, in terms of the applied bridge voltage V_I, therefore

$$I_G = \frac{V_I\ e\ k}{2\ (R+R_1+2\ R_G)} \qquad (14)$$

and so

$$V_G = R_G I_G = \frac{V_I\ e\ k\ R_G}{2(R+R_1+2R_G)} = \frac{V_I\ e\ k}{2(2+(R+R_1)/R_G)} \qquad (15)$$

If the galvanometer is now replaced by a high impedance amplifier, of unit gain, in which $R_G \longrightarrow \infty$, the output voltage is given by

$$V_o = \frac{V_I\ e\ k}{4} \qquad (16)$$

Thus the voltage appearing at the output of a high impedance amplifier is proportional to the bridge supply voltage, strain sensitivity and the strain (also the gain of the amplifier if other than unity).

Variations in the ambient temperature affect the characteristics of strain gauges, in particular variations in gauge resistance due to temperature variation can easily be of the same order of magnitude as those induced by strain.

The relative resistance change $\Delta R/R$ at a given value of strain e and temperature change $\Delta\theta = \theta - \theta_o$ is given by

$$\frac{\Delta R}{R} = e\ k\ o\ (1 + m\ \Delta\theta) + (\alpha + k\ \Delta a)\ \Delta\theta \qquad (17)$$

In the first term of the expression k_o is the conventional gauge factor at temperature θ_o, and m is the temperature coefficient of gauge factor. The second term comprises contributions arising from the thermal coefficient of resistivity α and the product $k(\Delta a)$, where Δa is the difference in coefficient of thermal expansion of the specimen and gauge materials. Thus if the specimen expands more than the gauge for a given temperature change, then the gauge will experience a tensional strain which contributes to the resistance through the $k(\Delta a)$ term. Thus the temperature error of a bonded resistance strain gauge depends on the properties of both gauge and substructure. It is possible to obtain a suitable combination of materials for the gauge and substructure, such that $\Delta R/R = 0$.

4. THE EXPLOSION CHAMBER STRAIN GAUGE SYSTEM

The ease with which estimates of strain value can be obtained when using electrical resistance strain gauges is the most important factor pointing to their use for the measurement of strain in the explosion chamber. In nearly all other respects these devices meet the general requirements of Section 2. In particular the 'foil' type of gauge possesses features which make its use attractive. This device employs a constantan (Ni 45 per cent, Cu 55 per cent) foil of 0.0004 cm thickness, shaped to form a grid, consisting of several parallel lines of metal, Fig.3, giving a total active length of about 10 cm and an electrical resistance in the region of 120 ohms. The grid is mounted on a backing of polyimide film which is tough and creep-resistant, the backing is about 0.003 cm thick.

The layout pattern of the gauge is such that stress concentrations within the element are eliminated. Reversal points on the ends of the grid lines are made wider than the lines themselves to achieve a low value of transverse gauge sensitivity. The copper/nickel foil is only suitable for use to about 250°C; above this temperature the material gradually oxidises and thereby alters its resistance.

Foil gauges are used in conjunction with bridge circuits, consequently the number of active gauges for any given application may be varied, one active gauge giving the quarter bridge, and four the full bridge arrangement. The individual merits of these different arrangements are discussed in Scott[4], Morden[5] and Charles[6].

The quarter bridge has only become feasible with the advent of the self temperature-compensated gauge (s.t.c.). This device is one in which the temperature coefficient of resistance is adjusted so that the resistance change due to temperature is equal in magnitude, but of opposite sign to the resistance

change caused by differential expansion between the gauge and the specimen on which it is mounted. The compensation is restricted to a specific temperature range, but it allows measurements to be made without the need of 'dummy' gauges which were previously required for temperature compensation, i.e. a second gauge was employed in the second arm of the bridge circuit, which was subjected to the same environmental conditions as the main sensing element, but the dummy gauge was mounted in such a way as not to be subjected to any strain. This resulted in changes in resistance caused by thermal effects in the two elements cancelling each other out.

The s.t.c. gauge requires a three-lead wiring system as shown in Fig.1. The overall effect is to cancel resistance effects produced by temperature variations on lead wires. The three-wire, single active s.t.c. gauge system has been adopted for strain measurements on the explosion chamber.

In order to produce a flexible strain measurement system such that the number of strain measuring channels is not limited, a modular system of bridges and amplifiers was obtained. The individual units were manufactured by Strainstall Limited,* these were assembled in conjunction with power supplies, regulators and channel selectors into a rack mounted system, Fig.4. At the present time the system employs five channels but an additional five channels are under preparation. The amplifiers used are of the type 861, designed to operate from a single active element gauge in applications requiring dynamic measurements. They incorporate self-zeroing circuits thus rendering unnecessary the accurate balancing of the bridge circuits. These units are intended to drive medium frequency galvanometer recorders directly, (i.e. 500 Hz to 2 K Hz natural frequency).

A calibration unit is incorporated into the system whose output can be selected to produce a calibration signal in any one of the five channels. The calibration is effected by simulating a known strain level from the momentary placement of a high value resistance in parallel with the active gauge element. This is obtained immediately on connection of the high value resistance, before the self-zero action of the amplifier sets in to reduce the reading towards zero.

A schematic diagram of a single strain channel is shown in Fig.5.

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*In this note reference is made here and elsewhere to the trade names of the components used. This does not imply a preference for these products but simply reflects the availability and compatability of the various components at the time they were required.

5. FOIL GAUGE SELECTION

There are a number of factors to be taken into consideration when choosing a foil gauge for a particular purpose, and selection problems are discussed in 'An introduction to strain gauges'(WINDOW)[7]. For the application considered here a measurement of dynamic strain is required in which the expected values of strain will be relatively small. The system will be required to operate over an expected temperature range of -5 to +50°C, but the temperature change during any given explosion will be only a few degrees.

The foil gauges are mounted on the steel structure, and on the concrete foundations of the chamber. As the structures are extremely large there is no limitation imposed on the size of gauge which can be used. This permits the use of a dynamic strain system which provides an overall picture of deflections on large surface areas. Special dynamic foil gauges are also available which have higher gauge factors than standard gauges and a much larger fatigue life. This high gauge factor also satisfies the high output requirement.

When using galvanometer recorders impedance matching of the bridge to the galvanometer is important, and also consideration must be given to the maximum value of current which can be tolerated by the galvanometer coil.

The material from which the cell is constructed can affect gauge selection in various ways. Firstly, non-metallic material may require special high elongation gauges. Secondly, the thermal conductivity may well limit the power which can be dissipated by the gauge and so limit the available signal by placing an upper limit on the bridge supply voltage. Finally the coefficient of expansion will determine the temperature compensation value required for a s.t.c. gauge system. In fact, s.t.c. gauges are available for use on steel and concrete.

Consideration of all the points mentioned above led to the choice of the micromeasurements foil gauge EA 06 500 BA 120 which has the following characteristics:

(1) A gauge resistance of 120 $\pm$ 15 per cent to match the Strainstall amplifiers and bridge.

(2) They are open foil gauges with polyimide backing.

(3) Constantan alloy s.t.c. gauges.

(4) Active gauge length of 1.25 cm.

(5) Gauge factor 2.1 $\pm$ 0.5 per cent.

These gauges were employed on initial trials on the Cardington test chamber.

6. GAUGE BONDING METHODS

Efficient operation of a strain measurement system will depend largely upon the mechanical bonding between the gauge and the specimen, as it must enable the gauge to follow exactly the movement of the specimen.

The surface on which the gauge is to be mounted must be free from pits, scratches and all forms of grease. A ground finish is ideal for steel. The removel of oxides and other surface contaminants is usually carried out by lapping the surface with a mild etchant, which must be neutralised after the completion of the lapping process.

Gauges must be mounted on the specimen immediately after surface preparation. Special adhesives are used to ensure good bonding, the choice of which is very important and is specified by the gauge manufacturers depending on the type of surface to which the gauge is bonded. On the explosion chamber, M-Bond 200 was used on the steel structure and M-Bond A5-10/15 on the concrete. (Note: The concrete was prepared by coating the surface with a layer of adhesive and allowing it to cure, before the application of the final adhesive layer and the foil gauge). Curing schedules for the various adhesives must be followed accurately otherwise poor gauge bonding will result.

After bonding has been carried out the electrical wiring must be completed between gauge and amplifier. Care must be taken to route wires through low strain areas and to ensure that they approach the gauge soldering tabs in a low strain direction.

Soldered connections on the gauge must be small, equal in size, and any flux residues must be removed to avoid resistance variation after installation. Only cored solder must be used and corrosive fluxes avoided.

After the initial setting up of the strain system has been carried out, all gauge installations must be protected against mechanical damage, water vapour and oil. (Silicones in particular must be avoided). On the explosion chamber the following protective coatings were applied:

(1) M-coat A, a solvent thinned polyurethane to give general grid protection

(2) M-coat D, to prevent electrical leakage at open wire ends.

(3) M-coat G, provides a rubber-like film for complete mechanical and chemical protection of gauge and lead wires.

A mounted foil gauge is shown in Fig.6.

7. RESULTS FROM STRAIN MEASUREMENTS AT CARDINGTON

Foil gauges were mounted on all the walls and the roof of the chamber. Each gauge was positioned at or near the centre of one of the tank sections which form the main components of the structure of the chamber (Tonkin and Berlemont[1]). Gauges were also positioned on the interface between the steel stanchions and the concrete foundations. Great difficulty was experienced in obtaining good gauge bonding on the concrete surface.

In the immediate vicinity of the chamber three-conductor, flat lead wire was used to connect the foil gauges to a junction box mounted on, and earthed to, the rear of the chamber. From the junction box the connection to the bridges and amplifiers was completed by the use of screened cable, the screen itself being earthed to the cell and the amplifiers. The amplifier output was fed via screened cable to a current limiter which was used to prevent overloading of the recorder galvanometers. The recording output device was a twelve channel U.V. recorder.

On setting up the system it was found that there was an extremely large 50 Hz noise signal on all channels, resulting from mains frequency pickup on the leads between the chamber and the amplifiers. Two methods of removing this noise were applied simultaneously. One method was the introduction of a unity gain filter unit (with a centre frequency of 50 Hz and bandwidth of 10 Hz at the 3 db down point) into the strain gauge system. At the same time the connecting cables were replaced by cables having a much greater screening efficiency than the existing cable. The overall effect was to reduce greatly the 50 Hz noise signal, but it was found later that the majority of this noise reduction was due to the improved cable and the filter unit was eventually removed from the system, with little adverse effect.

For calibration purposes a 120 k ohms resistance was connected in parallel with each of the strain gauge elements, whose resistance was 120 ohms. Using equation (12) to evaluate the equivalent compressive strain we obtain

$$e = \frac{\Delta R}{RK} \qquad (18)$$

e was calculated to be 476 μ - strain. This was the calibration strain. Each of the channels making up the strain measurement system is calibrated, by the application of the 120 ohm resistance, prior to the commencement of each test. This enables calculations of the strain to be obtained directly from the output recording.

The results so far obtained indicate that the strains occurring within the structure of the chamber are very small, consequently even with the use of maximum amplifier gain the corresponding galvanometer deflections small. This is particularly noticeable for explosions resulting from the ignition of gas mixtures in which the concentrations of gas and air are remote from stoichiometric and with vent covers of low bursting strength. The resulting gas pressures within the chamber are low and hence recorded values of strain are low. For stoichiometric gas mixtures, the increased pressures in the chamber produced acceptable responses from the strain gauges. Typical results are shown in Table 1.

Table 1

Strain Measurements

Experiment number	Internal pressure p.s.i (kN/m^2)	Per cent methane	Strain channel (-strain)				
			1 LHS	2 Roof	3 Rear	4 RHS	5 Concrete
37	0.2 (1.38)	10	25	105	75	20	0
39	0.1 (0.69)	7.5	10	40	20	0	0
41	0.6 (4.137)	10	75	120	110	95	5
46	0.2 (1.38)	10	20	90	65	10	0

Table 1 also shows that even for the same gas concentration in the chamber there is a great variation of pressure resulting from the explosion. This is thought to be due to the variations in the ignition of the gas resulting from variations in the ignition source.

Irregular strain measurements were obtained from recordings made over relatively long periods after an explosion has occurred. After the ignition of the gas, the chamber vibrates for approximately 1.5 seconds with a gradually decaying amplitude; no further signals are recorded for a period of seven seconds. A series of vibrations then occurs for 2.5 seconds, followed by a pause and another series. This occurred throughout the recording period. (Fig.7 illustrates the effect).

8. CONCLUSIONS

Due to the limited number of experiments which have been carried out where strain measurements have been obtained, it is not possible to state definite values as to the amount of strain which can be expected to occur in the chamber for any particular explosion. It is felt that such predictions may become possible as the experimental programme proceeds.

Two points have emerged from the recordings obtained to date. Firstly, the strain system existing presently is not sufficiently sensitive to the

deflections produced in the structure of the chamber as a result of low-pressure explosions. Although the system is generally satisfactory it would be desirable for pressures as low as these to improve the response still further by replacing the foil gauges presently in use with gauges having a larger gauge factor, and employing more sensitive galvanometers in the U.V.recorder.

The second point is one arising from observations of strain recordings obtained for relatively long periods after the explosion.

The information available at the present time is insufficient to make predictions as to the origin of these pulses of vibration, but it is felt that they may be related to the acoustic properties of the 'Airship shed' in which the explosion chamber is situated. More tests must be carried out with recording times of at least thirty seconds, and at the same time obtain external pressure measurements in addition to strain and internal pressure measurements, to enable correlations to be made.

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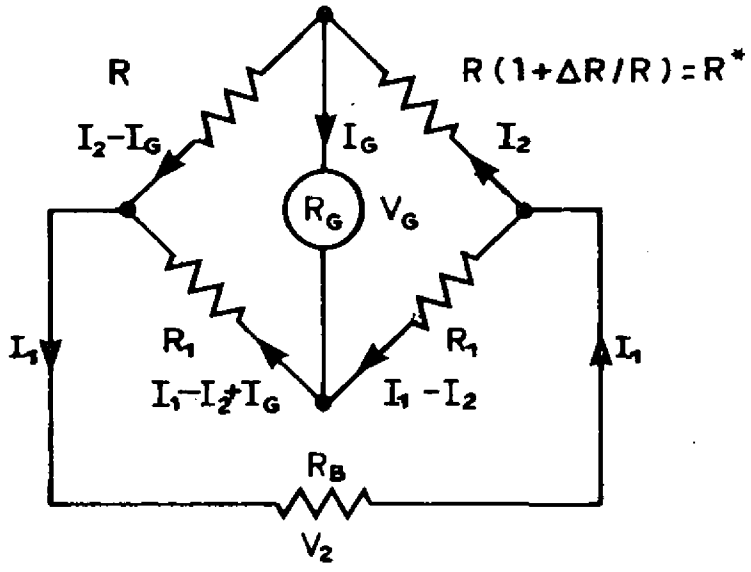

Figure 1 Basic bridge circuit

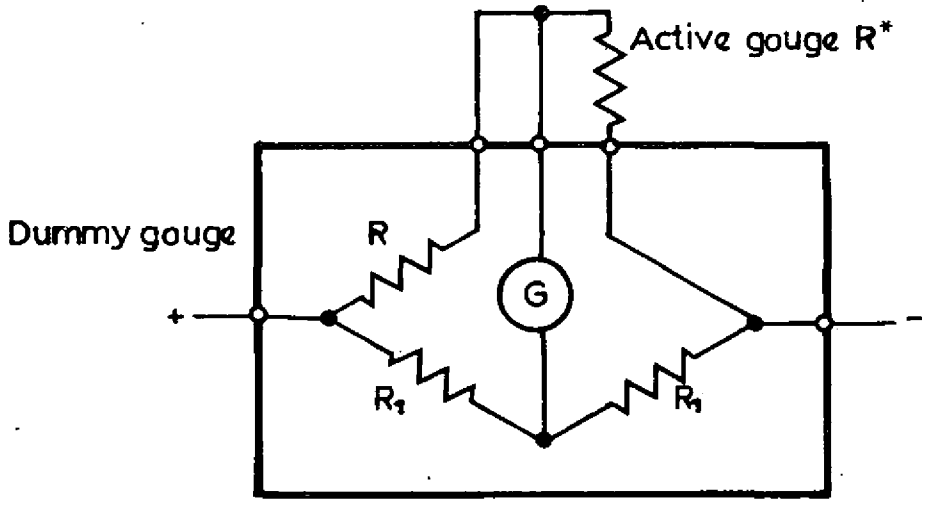

Figure 2 Bridge circuit used for strain measurement

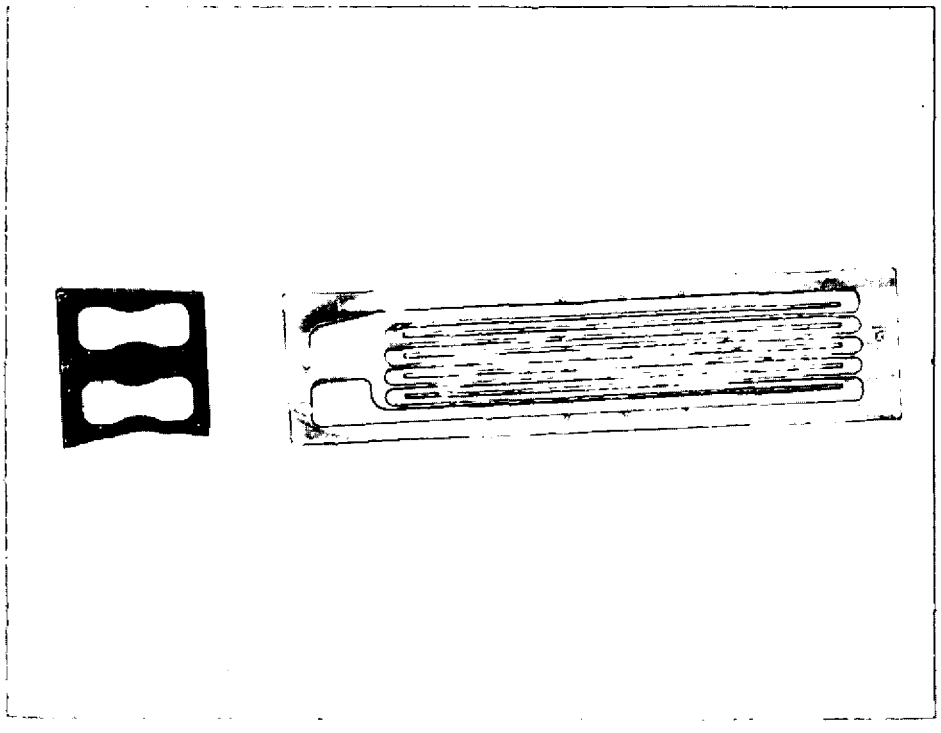

FIG. 3. STRAIN GAUGE TYPE EA06 10CBE 120

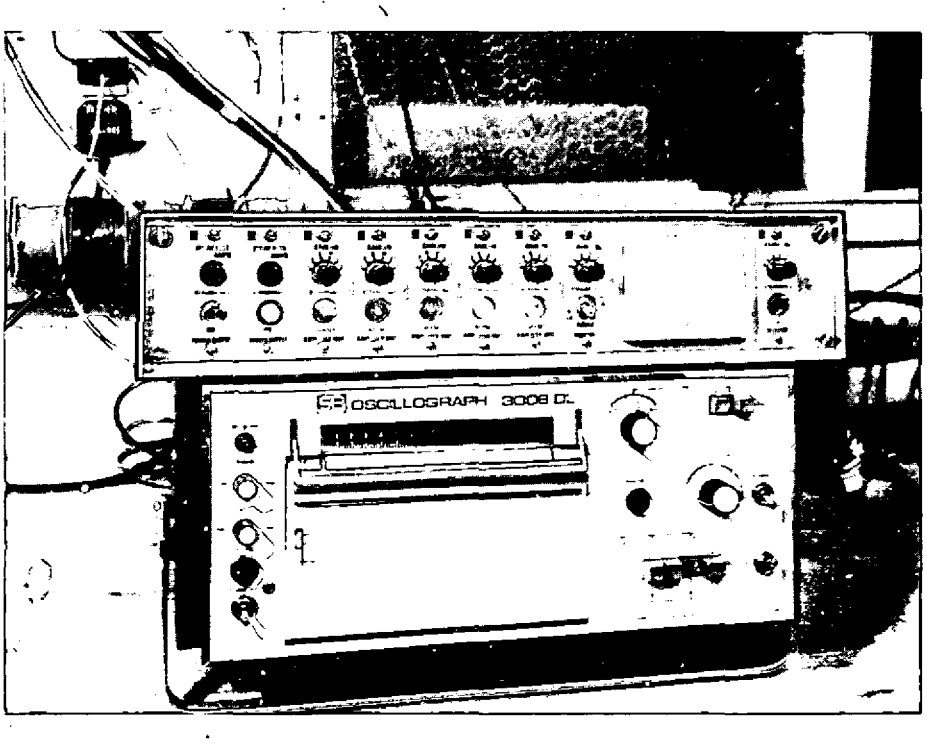

FIG. 4. STRAIN AMPLIFIERS AND RECORDER

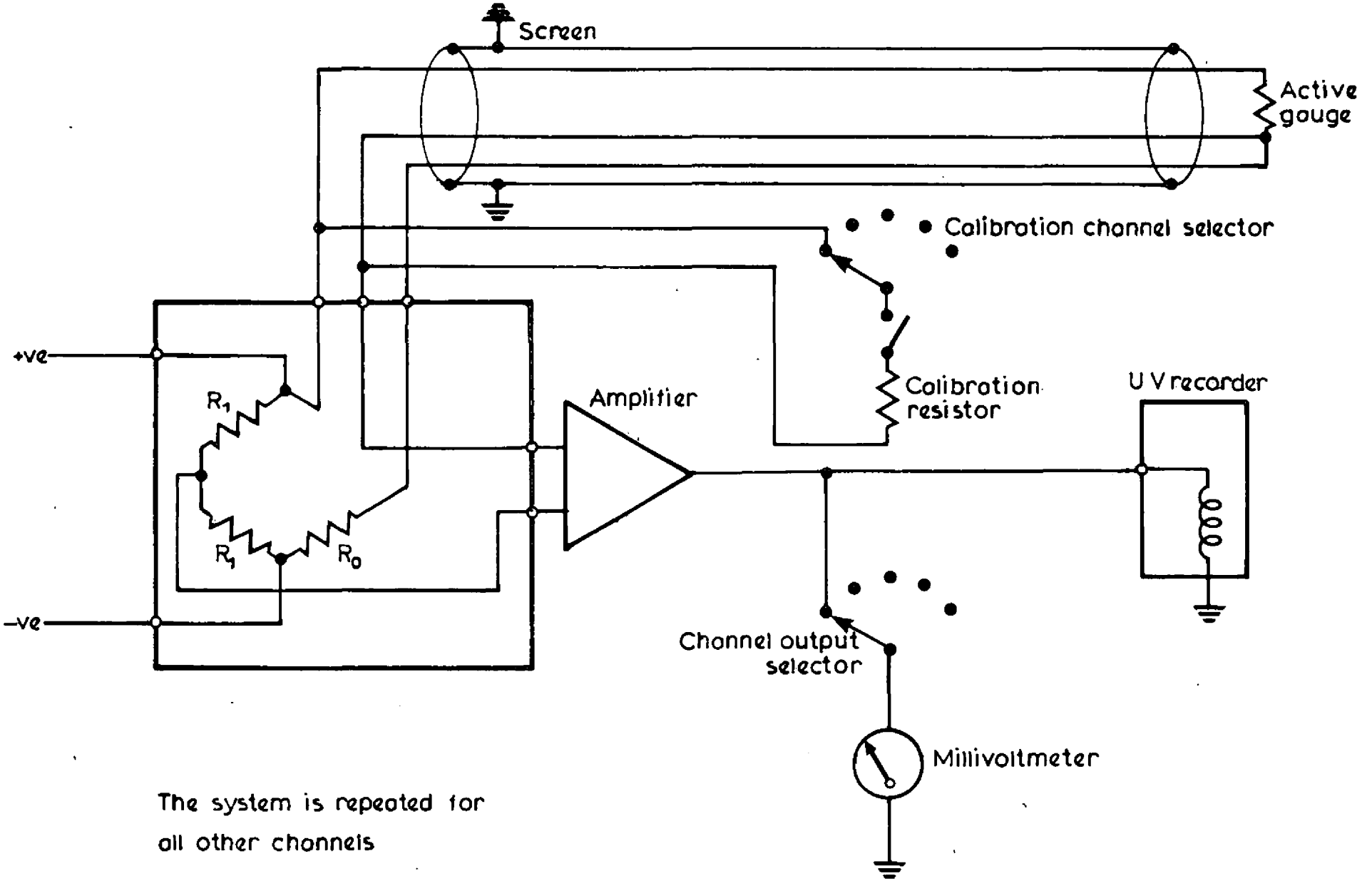

Figure 5 Schematic of single strain channel

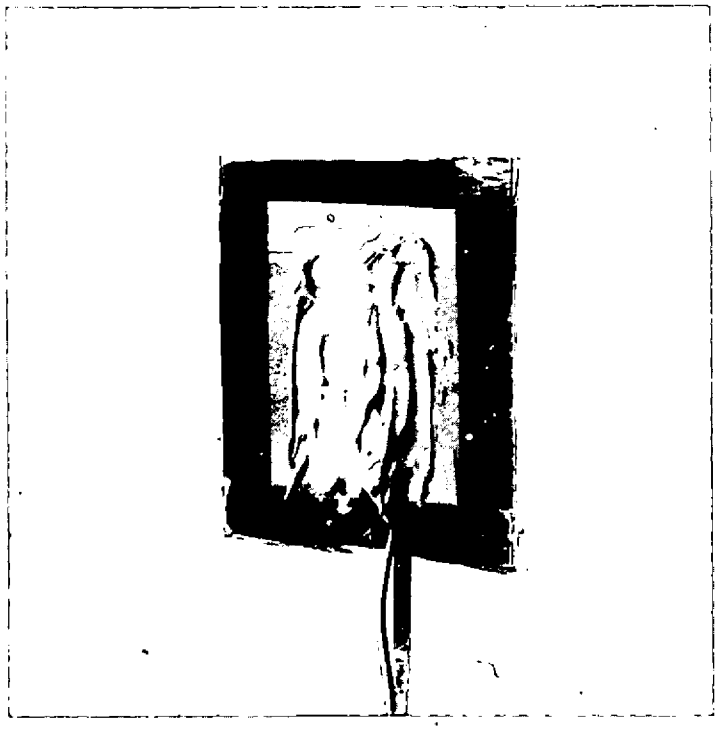

FIG. 6. GAUGE MOUNTED ON THE EXPLOSION CHAMBER WITH PROTECTIVE COATINGS

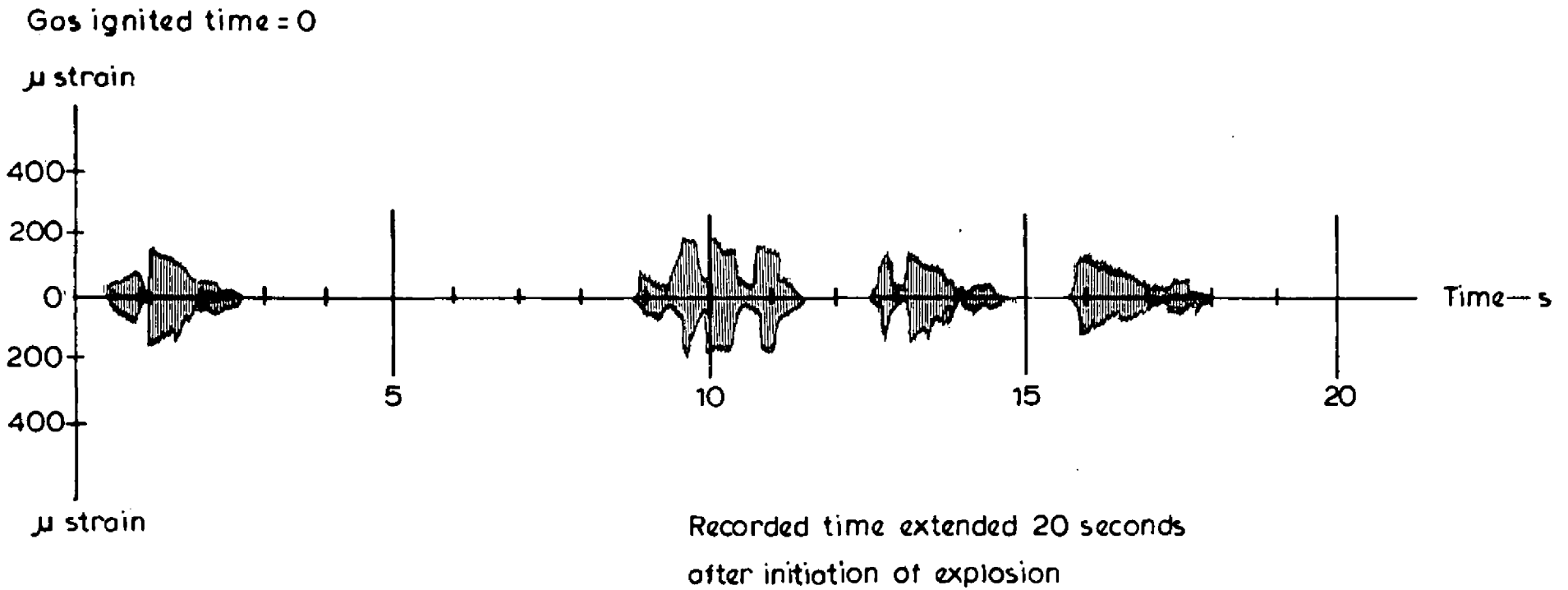

Figure 7 Vibration in chamber structure

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