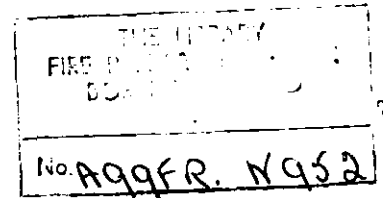


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A PRELIMINARY INVESTIGATION INTO
THE VISUALIZATION OF GAS LAYERS

by

M Senior

December 1972

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ABSTRACT

This paper describes a series of experiments designed to investigate the possibility of the visualization of gas layers using optical methods.

Several optical methods are considered including the possible application of holographic interferometry. Good results have been obtained using schlieren techniques in the visualization of carbon dioxide/air gas layers produced in a tank 1.28 metres in length.

It is felt that double exposure and real time holography will prove to be extremely effective in gas layer visualization due to their inherent high sensitivities and comparatively simple experimental techniques.

KEY WORDS: Holography, Gases, Layers, Visualization.

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CONTENTS

List of symbols
Introduction
Optical methods
Interference methods
Schlieren methods
Shadow methods
Deflection methods
Holographic methods
Summary of optical methods
Experimental methods
Discussion
Acknowledgments
References
Bibliography
Appendix
Figures 1 to 8

LIST OF SYMBOLS

b	Source breadth
B	Intensity
c	Velocity of light in medium
c^*	Velocity of light in vacuo
C	Contrast
f	Focal length
F	Luminous flux
h	Source height
I	Illumination
l	Geometrical path length
m	Magnification
n	Refractive index
s	Fringe shift
S	Contrast sensitivity
δ	Phase difference
λ	Wavelength
ρ	Density
ϵ	Angular deflection
ω	Solid angle
r	Density ratio
α	Height of image of source
L	Path length of test area
x	Distance over which density ratio occurs

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1. Introduction

One problem associated with research into gas explosions involving the use of layered gases, is to obtain information on the location and concentration of the gas layers produced, both at the initiation of the explosion and during the formation of the layers. At the present time layer formation is usually monitored by the analysis of gas samples obtained from various locations within the gas container. While giving accurate assessment of the gas concentration at a given point, the system provides only limited information concerning the spatial and temporal variation of the gas throughout the container. This is due to the limited number of sampling points employed and the rate at which the analysis of any one sample can be performed.

Obviously it would be an advantage to have continuously updated information on the formation of the gas layers. One method of achieving this is to produce a system in which the gas layers, and the incoming gases, are made visible, thus enabling immediate action to be taken over the control of the 'gassing up' process. This report describes the application of existing optical techniques to the problems of gas layer visualization.

The production of gas layers automatically implies a variation of refractive index when light is made to traverse the layer interface. It is the existence of such refractive index variations which allow attempts at layer visualization to be made.

The refractive index may vary across the interface either because different gases are present on either side of the interface, or because the density of the gas is altered by local variations in pressure or temperature. In gases the refractive index n is related to the gas density ρ by the equation

$$n - 1 = k\rho \quad (1)$$

where k is a constant for a particular gas at a particular wavelength.

The variations of refractive index encountered by a beam of light as it passes through a gas layer interface give rise to the production of various optical effects, which may be examined in detail by established optical methods, the results of which, after analysis, produce information on the gas distribution within the layer structure.

There are many optical systems which suggest application within the context of this report, and a comprehensive list of these methods is given in the Appendix. The theory and relative merits of the various methods is considered in Section 2, but it must be emphasized that not all of the known methods are described.

2. Review of optical methods

Consider a beam of light passing through a gas layer interface and eventually reaching a viewing screen. Any variation in the refractive index, in the path of a section of the beam, will produce an alteration in the time of arrival of this section at the screen. This effect is due to the velocity of light c being related to the refractive index n by the equation

$$c = \frac{1}{n} c^* \quad (2)$$

c^* is the velocity in vacuo.

Therefore any system which is capable of measuring the differences in the time of arrival at the screen of the two sections of beam will also produce information related to the refractive index variations. Optical systems which possess the ability to measure these time differences often employ interference techniques.

A. Interference methods

All the information relating to refractive index variations in a 'work area' (the phase object) is contained in the deformation of an originally plane light wave front. The structure of such a wave front can be made visible by interference techniques. The phase differences of the deformed wave, compared with an undeformed reference wave, give rise to changes in intensity as a result of interference. A detailed account of the theory of interference is given by Born and Wolf¹, where it is shown that for two monochromatic waves, initially from the same source, but travelling different paths and which are then combined, bands of illumination are produced which are known as interference fringes.

Intensity maximum occurs if the difference in optical path between the two beams is an even multiple of half the source wavelength. With one beam undisturbed, a change in the optical path length, i.e. the product of the geometrical path length and the refractive index, experienced by the other beam, will produce a fringeshift S such that

$$S = \frac{\Delta n l}{\lambda} \quad (3)$$

In practice two beam interference can be realised by two different means. Firstly the normal two-beam system, an example of which is the Mach-Zehnder interferometer, where one beam passes through the test area and the second beam by-passes the test area. The two beams are then re-combined to produce interference fringes. In the second system, the differential interferometer, both beams are made to pass through the test area and then re-combined to produce interference fringes. Inherent in this technique is the requirement that the phase object must not occupy the whole of the test area. The accuracy obtained for the calculation of refractive index variation with this method is less than that of the by-passed beam method.

Two beam interference systems are often used for the investigation of transparent objects, and there are many variations in the constructional details and degree of sophistication of the different methods employed. The most common system is the Mach-Zehnder interferometer which was developed from the Jamin refractometer in 1890 by both Mach² and Zehnder³. Other forms of interferometer are the Jamin interferometer⁴, Rayleigh interferometer⁵ and the Weinberg-Wood interferometer⁶; the details of these systems are not considered here. All are theoretically suitable for the type of work envisaged in this report.

Consideration has been given to the application of interferometric techniques to gas layer visualization because in many ways they are well suited to the problem. The optical path can be made long and well separated, fringes can be arranged to be in focus anywhere, and a camera can be focused onto the test area. They are extremely sensitive and capable of indicating the region of gas layer formation. These facts have been utilised in such fields as combustion, flame, aerodynamic and plasma research. However, they also have several disadvantages which make them practically unsuitable for this application.

The field of view of interferometer systems is limited by the size of the optical elements employed. Most systems employ elements within the region of 0.1 to 0.15 metres diameter, consequently when used for layer visualization any drift in the layer position will obscure the layer from the field of view of the interferometer. For layer work a minimum diameter of 0.3 metres is required, in fact the larger the field of view the better the system becomes, thus enabling the interface to be observed over a much larger region during its formation. This introduces the second disadvantage of interferometry, which is one of cost. All glass plates and mirrors used in interferometry must be optically flat to within 0.1 of the wavelength of light, at least. The cost of producing large scale elements to this accuracy would be considerable.

As a result of the high sensitivity, interferometric systems are extremely susceptible to vibration, which may lead to misalignment. Even walking within the vicinity of an interferometer can produce severe fringe movement. Any misalignment produced is such that realignment is an elaborate and lengthy procedure.

All the disadvantages of interferometry are interdependent. The larger the elements the more prone to vibration they become, at the same time becoming more difficult to align.

These facts render the conventional interferometer unsuitable for large scale gas layer visualization applications but it has been considered as it is the most sensitive optical method of detecting refractive index variations available. Certainly it is possible to both detect and measure the refractive index variations produced during the formation of gas layers. The information obtained from such measurements may then be used to determine gas concentrations.

Since it is not practicable to utilise the high sensitivities of interference methods consideration must be given to other optical properties of the gas layer interface.

B. Schlieren methods.

At the interface of the two gases there is a region of refractive index gradient, over which the refractive index varies from that of the first constituent gas to that of the second. If this refractive index

gradient is normal to a beam of light passing through the interface then some of the beam will be deflected by the refractive index gradient. This is because light travels more slowly in regions of higher refractive index. The amount of deflection is a measure of the first derivative of the gas density with respect to distance, i.e. the density gradient.

The deflection of a light beam from its original path is best observed by 'schlieren methods' which are described here in some detail.

As previously stated the curvature of the ray is proportional to the refractive index gradient normal to the ray.

If the z -axis is the direction of the undisturbed ray, the curvatures in the xz and yz planes are given by

$$\frac{\partial^2 x}{\partial z^2} = \frac{1}{n} \frac{\partial n}{\partial x} \quad (4)$$

$$\frac{\partial^2 y}{\partial z^2} = \frac{1}{n} \frac{\partial n}{\partial y} \quad (5)$$

If the total angular deflections in these planes are denoted by ϵ'_x and ϵ'_y then

$$\epsilon'_x = \int \frac{1}{n} \frac{\partial n}{\partial x} dz \quad (6)$$

$$\epsilon'_y = \int \frac{1}{n} \frac{\partial n}{\partial y} dz \quad (7)$$

For a working medium, such as gas layers, the ray will be deflected on leaving the medium such that

$$n \sin \epsilon' = n_0 \sin \epsilon \quad (8)$$

where n and n_0 are the refractive indices of air and the working section respectively. Thus the final angular deflections are

$$\epsilon_x = \frac{1}{n_0} \int \frac{\partial n}{\partial x} dz \quad (9)$$

$$\epsilon_y = \frac{1}{n_0} \int \frac{\partial n}{\partial y} dz \quad (10)$$

the integrals being taken over the width of the working medium. For a width L these reduce to

$$\epsilon_x = \frac{L}{n_0} \frac{\partial n}{\partial x} \quad (11)$$

$$\epsilon_y = \frac{L}{n_0} \frac{\partial n}{\partial y} \quad (12)$$

the deflection being in the direction of the refractive index gradient. A typical schlieren system, employing mirrors, is shown in Figure 1.

The light source S is positioned at the focus of mirror $M1$, so illuminating the working area with a parallel beam of light. A second mirror $M2$ produces an image of S at its focus K . The lens L produces an image on the screen Q . Between $M1$ and $M2$ each point in the xy plane produces an image of the source, which coincide if there are no refractive index gradients. Any gradient change alters the deflection ϵ , and the image in the focal plane is moved by an amount $f_s \epsilon$. Irrespective of its direction, all light from a point on the object is brought to a focus at the corresponding point on the viewing screen. Thus the image on the screen is also displaced by the refractive index gradient.

In the Toepler method (Schardin)⁷ the displacement of the source image, corresponding to the deflection in the working area, results in a change in the illumination of the image on the screen. For this method a rectangular source is used together with a knife edge placed at the focus K , the latter being adjusted to produce a uniformly reduced illumination of the screen with no disturbance in the test area. A disturbance causing a deflection of the image of the source will then give rise to an increase or decrease in the illumination depending on the direction of the deflection relative to the knife edge.

A brief account of the theory of the Toepler method is given below, which follows that given by Holder and North⁸.

Neglecting light losses, with the knife edge removed the illumination is given with reasonable accuracy by

$$I_0 = \frac{B b h}{m^2 f_1^2} \quad (13)$$

where B is the source intensity and is equal to

$$B = \frac{dF}{dw} \quad (14)$$

where F is illuminous flux

w the solid angle

b and h are the source breadth and height respectively

m is the magnification

and f the focal length of the first mirror.

The dimensions of the imaged source at the image of the source, i.e. at the knife edge, are

$$h' = h \frac{f_2}{f_1} \quad (15)$$

$$b' = b \frac{f_2}{f_1} \quad (16)$$

If all but a height ' a ' of the image is cut off at the knife edge parallel to the source breadth, the illumination falls to a value

$$I = \frac{B b a}{m^2 f_1 f_2} \quad (17)$$

An optical disturbance giving a deflection angle δ_e will cause the source image to be displaced relative to the knife edge by an amount $f_2 \delta_e$. So the change in illumination is now

$$\delta I = \frac{B b \delta_e}{m^2 f_1} \quad (18)$$

The contrast C , with respect to the background is defined as

$$C = \frac{\delta I}{I} = \frac{f_2 \delta_e}{a} \quad (18a)$$

and the contrast sensitivity S is given by

$$S = \frac{dC}{d\epsilon} = \frac{f_2}{a} \quad (19)$$

Equation (18) will not apply when the deflection is large enough to cover the knife edge. The illumination will then be either I_0 or completely dark. Thus there is a maximum range of displacement $\delta_e^{(m)}$ for the retention of sensitivity, this is equal to the height of the image x .

$$x = \frac{f_2 h}{f_1} \quad (20)$$

$$\therefore \delta_e^{(m)} = \frac{x}{f_2} = \frac{h}{f_1} \quad (21)$$

It is usual to operate so that deflections are equal into both the opaque and the transparent regions, when the source height which is not cut off, i.e. 'a', is given by

$$a = f_2 \delta_e^{(m)} \quad (22)$$

and the illumination corresponding to this is

$$I = \frac{1}{2} I_0 \quad (23)$$

Then the sensitivity S is given by

$$S = \frac{f_2}{a} = \frac{2}{\delta_e^{(m)}} \quad (23)$$

so the maximum sensitivity is inversely proportional to the range of displacement and not dependent on the components of the optical system. A more detailed approach to the physical theory of schlieren methods is given by Weinberg⁹.

There are many variations on the arrangement of equipment employed in schlieren systems, for example two mirror, two lens, one mirror, one lens employing either parallel or non-parallel light, descriptions of which have been given by Holder and North⁸ and Weinberg⁹. There are also a great many variations in the type of schlieren stop employed, some using graded filters and others using circular cut-off systems where density gradients in all directions are of equal importance. (North^{10,11} and Taylor and Waldrum¹²).

Colour schlieren systems are also available. The simplest method employs a white light source, with a graded colour filter replacing the schlieren stop. (Holder and North¹³)

The schlieren systems so far discussed give no information as to the point at which the disturbance (refractive index gradient) occurs along the beam. To overcome this the sharp focus schlieren system has been developed (Burton¹⁴). The system employs an extended light source illuminating a grid, a second grid is then used to act as a knife edge. This enables a selected region in the test area to be examined in detail by increasing the angle d/fc , where d is the source dimension, decreasing the depth of focus of the system.

The sensitivity of the schlieren system is such that it has been applied with some success in the present context of gas layer visualization, although the sensitivity is much less than that of interferometric systems. Schlieren systems also have the advantage of being relatively simple to set up and adjust and are therefore more suitable than interferometers for this application. The quality required for schlieren optical components is high, in this case high quality is required to alleviate the effects due to lens and mirror aberrations which give rise to image distortion. (Born and Wolf¹). Again the problem of mirror diameter is a limiting factor, the usual size of schlieren mirror being 0.2 to 0.5 metres, the cost increasing rapidly with increase in diameter. It has, however, been proposed by Gates²⁵ to produce large area spherical mirrors by the use of a large number of small mirrors to form a single large mosaic mirror. It is hoped that this method would lead to a reduction in manufacturing costs.

In comparison with the interferometer the schlieren system is a more viable proposition and as such can be used as a reasonable standard of sensitivity by which other methods of visualization may be compared.

C. Shadow methods

Consider once more the interface between two gases taking part in the formation of a gas layer. As well as regions of refractive index gradients, which are observed by schlieren methods, there exist regions of refractive index gradient variations. If these regions are illuminated with a beam of light a shadow pattern of the work area (interface) is obtained. This is caused entirely by the redistribution of light intensity due to ray deflection. For a uniform deflection over the work area all the rays are displaced uniformly, without any redistribution of intensity. The formation of the shadow must be due to gradients in deflections where the light is deflected by varying amounts. Alterations in illumination of this nature can be observed

by the use of the shadow method, where the effects observed are a function of the second derivative of gas density with respect to position.

The simplest method of obtaining shadowgrams is shown in Fig. 4, while Fig. 5 illustrates the formation of the shadows.

The shadow method is the least sensitive of the three main visualization techniques and is the simplest to set up practically. It was first employed by Dvorak¹⁵ in 1880.

The light originally illuminating an area on the screen $dx dy$, after deflection will illuminate an area increased by an amount

$$\Delta I = l dx dy \left(\frac{\partial \epsilon_x}{\partial x} + \frac{\partial \epsilon_y}{\partial y} \right) \quad (25)$$

Therefore the change in illumination on the screen is

$$\frac{\Delta I}{I} = -l \left(\frac{\partial \epsilon_x}{\partial x} + \frac{\partial \epsilon_y}{\partial y} \right) \quad (26)$$

where l is the distance from the screen to the disturbance. Using the relationships obtained in equations (9) and (10) for ϵ_x and ϵ_y

$$\frac{\Delta I}{I} = -\frac{l}{n_0} \int \left(\frac{\partial^2 n}{\partial x^2} + \frac{\partial^2 n}{\partial y^2} \right) dz \quad (27)$$

where the integral is taken over the breadth of the two dimensional disturbance.

Thus the shadow method is proportional to the second derivative of the refractive index, as stated previously.

The shadow method described above was applied to the problem of layer visualization but with no success. It may of course be possible to obtain visualization by increasing the path length l through which the light passes, i.e. use a much larger test area. This was not practicable under the present circumstances.

The interferometer, schlieren and shadow methods provide information on density and the first and second derivatives of density respectively, and therefore they form a complementary "set" of methods, each showing

features of density variation which may not be apparent when either of the other methods are employed. Of the three methods, quantitative measurements have extensively been obtained from interferometry, the schlieren and the shadow methods being employed mainly for visualization techniques. Used in this fashion these two methods require only comparatively simple apparatus to yield a great deal of information.

D. Deflection methods

For the sake of completeness several other methods, mainly belonging to the deflection mapping group, were applied to the problem, all of which proved to be unsatisfactory. A general description of these methods is given below.

Deflection methods employ some form of reference system, usually in the form of a grid or other periodic structure, which is located in the path of an illuminating source. This combination gives rise to a series of individual light rays which are allowed to traverse the working area. Variations of the medium contained in the working area will result in the production of deflections of the individual light rays. When observed on a screen the deflected rays produce a distorted image of the original grid.

The deflection method has three main subdivisions:

- i) A grid is formed by simple wires, opaque and transparent rulings or engraved rulings. (Ronchi¹⁶). These are illuminated by the light source, prior to its traversing the test area. Diffraction effects limit the resolving power of this system. (Weinberg⁹)
- ii) A coherent light source is used to form a series of interference fringes which are then made to pass through the test area. Such fringes can be produced by several methods. The system used in this work is that due to Weinberg¹⁷, in which a helium-neon gas laser, producing a light output at 6328Å, is made to produce fringes by multiple reflection in a glass slide, after being spatially filtered. The fringes are observed through the test area, variations of which cause distortion of the fringe pattern. In this system the sensitivity depends upon the proximity of the test area to the source of the fringe system, this being due to the

divergence of the light beam from the spatial pinhole filter. The visibility of the fringe distortion is very greatly dependent upon the intensity of the laser source. A high power C.W. laser is a necessity for this method, i.e. 10 - 15 m Watts. The sensitivity of this system is inadequate for gas layer visualization.

- (iii) The third method employs two sets of grids set at a small angle to each other. These give rise to the production of Moiré fringes. (Lord Rayleigh¹⁸). In this case variations of the medium within the test area give distortions of the Moiré fringes. Moiré fringes may be produced either by two grids or in a "multipass" system, by one grid and a mirror. (A T.V. scanning raster may also be a source of grid lines). (Review article Oster, and Nishyima¹⁹).

A method of visualization which is extensively used is that of gas doping. In this case extremely fine particles of powder, or other foreign bodies, are introduced into the test area. These particles form a suspension at the gas layer interface, depending upon the density of the gases involved. Visualization is obtained by illuminating the particles with the aid of a diffused light source. This method was not considered practicable for this investigation, because interference with the gases must not occur and there is no evidence that the particles will remain entirely in one of the gases forming the layer.

This completes the discussion of the optical methods applied to layer visualization during the course of the preliminary investigation, but it was felt that some form of reference should be produced as to the relative sensitivities of all the methods involved. This was achieved with the aid of a carbon dioxide gas jet and a small gas burner, both of which provide high density gradients and are therefore ideal objects for use in comparisons of different methods. Illustrations of the effects produced are shown in Fig. 6.

E. Holographic methods

The use of a lens to image an object is one of the oldest principles in optics and photography. However, in 1948 Gabor introduced a two step imaging process in which an intermediate record, containing the information necessary to create an image, is formed. This process has

been rapidly developed during the past decade to create the science of holography. It is possible that several of the methods which have emerged during this period could be applied to the problem of gas layer visualization. When these methods are considered three possibilities arise:

- 1) It is possible to produce point holograms of optical elements. This means holograms of schlieren mirrors could be produced in large numbers. These could then be used in place of the actual mirrors in the proximity of an explosion; ideally they could be incorporated into the test rig as windows. If damaged they may be discarded and replaced at moderate cost. Thus the schlieren system becomes a viable proposition in a slightly modified form.
- 2) Double exposure holographic interferometry.
- 3) Real time holographic interferometry.

The theory of holography was first put forward by Gabor^{20,21,22} and a great number of books have since been written on the subject, (Caulfield and Lee²³, Smith²⁴). The theory will not be presented here, only considerations applicable to the possibilities listed above will be given.

Holography and conventional photography both employ a very high resolution photosensitive material as a recording medium. The holographic process is a two step method of optical imaging which can if necessary be made independent of lenses. Complete waveform recording is accomplished so that all the optical information about a subject, phase or reference, is retained, and made available for subsequent retrieval. This does not occur in the photographic process which stores an image by photographic density variation alone, disregarding the phase, which is in fact the most important information carrier.

With the holographic technique a complex object can be examined interferometrically from different perspectives, due to its three-dimensional nature. A single interferometric hologram is equivalent to many observations with a conventional interferometer, and the object can be examined at two separate times. Changes undergone by an object over a period of time can be detected with optical wavelength accuracy.

In the "real time", or single exposure method a hologram of the object is produced, then, after processing, this hologram is accurately replaced in its original position and the object is altered in some way (filling with gas). The hologram is then illuminated with a reference beam and some of this light is scattered from the object. This gives rise to the production of interference fringes which are related to the degree of change in the object. Phenomena in transparent enclosures can be observed regardless of the optical quality of the window material as this is only being compared with its own optical effects. Only changes in the object are detected in so called "real time".

The double exposure method is similar to the real time method in most respects, but accurate registration of the object and hologram is no longer required. The difference between the two lies in the fact that the double exposure method retains as a permanent record the changes in the properties of the object between exposures. This requires the production of two holograms on a single recording medium, one of which yields the primary image including information such as defects in window material, the latter providing information on changes within the object between exposures.

Multiple exposure holograms can be produced giving rise to much sharper fringes. The importance of these methods is again the fact that only photographic recording materials are left in the vicinity of the explosion, and there is no chance of expensive equipment being damaged.

The last three methods described provide a grounding for a whole series of experiments on the visualization of gas layers. The equipment for carrying out such work is available, but experimental work employing holographic technique has not yet been attempted.

Real time holographic methods are most likely to produce the best results, as all the effects relating to the formation of gas layers will be made visible in the form of holographic interference fringes the instant they occur, thus giving instantaneous information on the formation of layers.

Summary of optical methods

Optical method	Sensitivity of system	Limitation due to optical component size	Limitation due to cost of components	Prone to effects of vibration	Result of initial application to visualization problem	Possible determination of gas concentration
1. Mach-Zehnder interferometry	G	L	L.C.	Yes	N.A.	P
2. Weinberg-Wood interferometry	G	L	L.C.	Yes	N.A.	P
3. Two mirror schlieren	G	L	L.C.	No	Good	P
4. Two lens schlieren	G	L	L.C.	No	No result	P
5. Colour schlieren	G	L	L.C.	No	No result	P
6. Schlieren interferometry	G	L	L.C.	Yes	N.A.	P
7. Single mirror shadow	No	No	No	No	No result	No
8. Grid deflection	No	No	No	No	No result	No
9. Interference fringe deflection	No	No	No	No	" "	No
10. Moiré fringe deflection	No	No	No	No	" "	No
11. Particle suspension	No	No	No	No	Yes (*)	P
12. Holography (optical elements)	G	No	No	Yes	N.A.	P
13. Double exposure holography	G	L	No	Yes	N.A.	P
14. Real time holography	G	L	No	Yes	N.A.	P

Key

- 1) G Sensitivity of system can be made high enough to observe layers
- 2) L Limitation on application due to component size
- 3) N.A. Not applied during this investigation
- 4) L.C. Limitation on application due to cost of components
- 5) P Determination of gas concentration is possible
- 6) * Method does not indicate the true position of the layer.

3. Experimental methods

The experimental work described in this report was carried out as a preliminary investigation into the visualization of the formation of gas layers with the possibility of obtaining a practical system which could be employed in large scale experimental work on gas explosions.

The most common gases employed in large scale experimental work are manufactured gas and natural gas, but for reasons of safety the preliminary investigations were carried out using the non-combustible gases carbon dioxide and helium, to form gas layers with air. The difference in density between that of air and that of the two gases is large thereby assisting in the formation of stable gas layers in the situation where thermal effects can be neglected.

In order to investigate the formation of the gas layers, they were produced in a test area with dimensions of 1.28 x 0.30 x 0.58 metres, made of wood with the exception of two end windows which were of 3 millimetre thick perspex sheet. One of the end plates was a sliding fit to allow access to the interior of the container. Provision was made for the test area to be divided into two horizontal sections by the introduction of a false floor; this provided a mechanical interface between the two sections to assist the formation of gas layers. Provision was also made to allow small samples of the gases in the test area to be removed for analysis by gas chromatography. This analysis provided an indication of the formation of the layers and also an indication of the conditions required for visualization to become effective. The sampling points were situated 0.08, 0.17, 0.26, 0.35, 0.44 and 0.5 metres from the floor of the test area. Consideration was given to increasing the number of sampling points in order to increase the accuracy in obtaining the location of the gas layer. This led to an extremely long analysis time over which inconsistent analyses of gas samples were obtained, due to leakage from the syringes which were available for use.

The gases were introduced into the test area via ports let into the top and bottom surfaces of the container, either as a straight jet or with the aid of various diffusers. The gas flow rate was monitored by the use of a rotameter flowmeter.

Two methods of gas layer formation were investigated. Firstly the gas was allowed to diffuse slowly into the test area, either near the top for helium or near the bottom for carbon dioxide, the gases forming layers with the air

already present. A vent was provided to allow air to leak out at the same rate as the gas was introduced, thus preventing a build up of pressure in the test area. The second method was to insert the false floor into the container and then fill one of the two sections with gas, at the same time allowing the air in that section to be displaced by the incoming gas. After isolating the gas supply, the false floor was then slowly removed leaving a gas air interface at the junction of the two sections. The latter method proved to be the more successful method for the formation of gas layers, but the removal of the false floor introduced some turbulence into the gas/air interface. Rapid removal of the false floor caused sufficient turbulence to destroy the layer.

The optical systems used throughout the investigation were arranged so that the source of light produced a beam which passed symmetrically through the test area in such a way as to be bisected diametrically by the false floor. Each of the various optical methods was applied in turn and the possibility of their use for visualization of gas layers was noted.

4. Experimental results

Of the optical systems applied during this investigation the only method to produce satisfactory results was the schlieren method. Shadowgrams and the various deflection methods (Weinberg's method and Moiré techniques) were insensitive to the gas layers produced in the test area. The holographic techniques described previously have not yet been applied.

The results obtained with the schlieren system are shown in Figs 2 and 3, which were produced from a two-mirror schlieren system. The light source used for this work was a high intensity mercury discharge point source; this was positioned at the focus of the first of two schlieren mirrors of 0.203 metres diameter and focal length 3.05 metres. A parallel beam of light was produced on reflection at the mirror and was directed through the test area onto a second schlieren mirror which brought the beam back to a focus. A schlieren stop (knife edge) was positioned exactly at the point of focus. An image of the test area was then obtained on a screen. Figure 1 illustrates the system.

The series of photographs in Fig. 2 were obtained when the lower section of the container was allowed to fill with carbon dioxide for half an hour; the gas supply was then isolated and the false floor removed. These photographs illustrate the deterioration of the gas layer as the carbon dioxide leaked out of the test area. Figure 3 shows a series of photographs taken as the

test area was being filled with carbon dioxide gas. This time the false floor was not employed; the increase in the concentration of the carbon dioxide can be seen as the height of the interface region increases.

Analysis of the gas within the test area was obtained during the formation of the gas layers in Figs 2 and 3; the results of the analysis are shown in Fig. 7.

Attempts were made to apply the two mirror schlieren system to the visualization of helium gas layers; this proved to be impracticable with all the various test area filling methods previously described. Analysis of the helium within the test area showed that gas layers were not being formed. Instead, a gradual increase in helium concentration was obtained as the point of sampling was moved from the floor of the test area up to the roof. In some cases the helium concentration was found to be higher on the floor and roof of the test area than in the centre. The results of some of the helium analyses are shown in Fig. 8.

5. Discussion

After applying the series of optical methods described in the preceding pages, it became apparent that only the schlieren method would have an immediate application to the problem of gas layer visualization. In the work on carbon dioxide changes in gas concentration of the order of 17 per cent over a distance of 0.09 metres were distinctly visible. In fact, layers were visible at much lower concentration gradients but accurate analysis of these concentrations was not obtained. Work with helium gas was inconclusive; it was not possible to obtain sufficiently good helium layers to be compatible with the schlieren system in use. It has been shown by Holder and North⁸ that the least density ratio which can be detected by schlieren methods is given by

$$\tau = 1 + \frac{C n_0 \alpha x}{k F_2 L \rho_0} \quad (28)$$

(symbols have their usual meanings)

thus implying the need of a small source height a , longer focal length mirrors and longer work area path length and finally a more distinct layer formation to produce better visualization in helium layers. Analysis of the gas indicating concentrations of helium to be of the order of 30 per cent on average, and this only changes to 5 per cent over the whole of the vertical dimension of the test (g) area, and containing no high concentration gradients at all.

It must be pointed out that the object of the work carried out during this project was to examine the possibility of gas layer visualization, and not to perform work relating to the formation of gas layers. The results so far obtained indicate that the problem is double-edged with regards to both the problem of obtaining good gas layers and to that of obtaining highly sensitive optical systems.

Undoubtedly the effects of scaling, i.e. the size of the test area, must play an important part in the formation of the gas layers due to edge effects at the container surfaces. It is suggested that this may be one of the reasons why layers were not obtained with helium. Helium gas has a very low density in comparison with that of air, it is also extremely mobile. Thus the effects due to buoyancy and those due to thermal convection, arising from the properties of the gas, act in opposition in respect to the formation of gas layers. That is the low density assists in layer formation, while the high mobility gives rise to turbulent entrainment of air opposing layer formation. It appears from the results obtained that the latter effect is more dominant, resulting in poor layer formation and instability.

Variations in the temperature of the test area will disrupt the formation of gas layers and may, if sufficiently large, completely obliterate any information obtained from the visualization method. However observation of these thermal effects with the aid of an optical system is important in itself.

The good layer visualization effects obtained with carbon dioxide imply the practicability of layer formation with certain gases and it is proposed to proceed with experimental work using neon. The possible use of freon has also been considered. It is not proposed to employ explosive gases in this work.

Even though the schlieren system has produced good results its large area, expensive mirrors, render the system too sensitive to be used in the vicinity of large scale gas explosion rigs.

Consequently the results of the investigation so far obtained indicate a general inadequacy of the optical methods applied to provide good visualization of gas layers. It must be emphasized that there are several methods which have not been applied up to the present time. In fact the holographic methods described at the end of Section 2 have a definite probability of producing good results for the visualization of gas layers, which is due mainly to the increased sensitivity which they possess over the optical methods so far applied. The work has proved extremely useful in assessing the relative sensitivities of the various methods.

6. Acknowledgments

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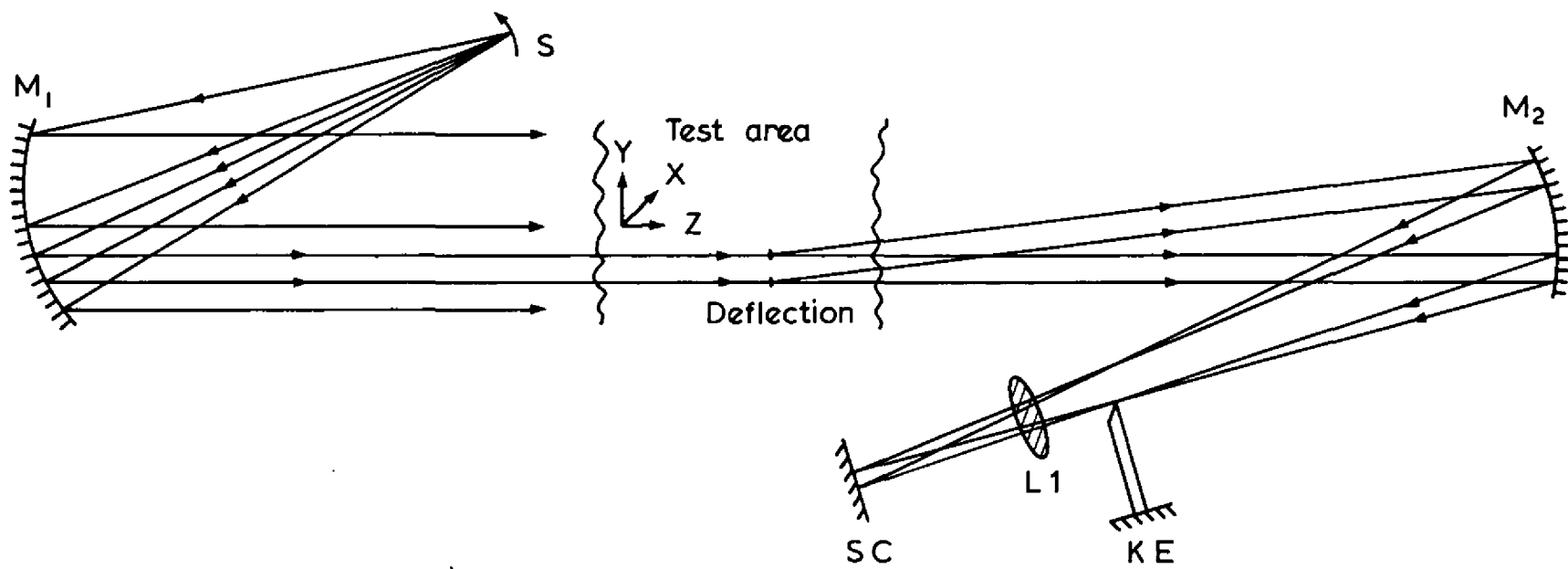


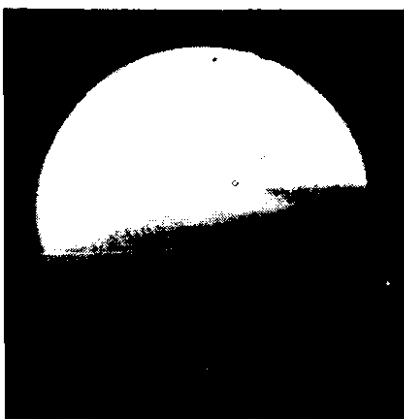
FIG. 1 TYPICAL SCHLIEREN APPARATUS

FIG. 2



Two Mirror Schlieren
Photographs 21 March 1972

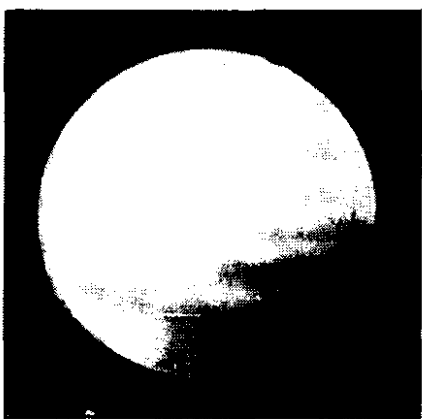
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Dividing Plate in Position



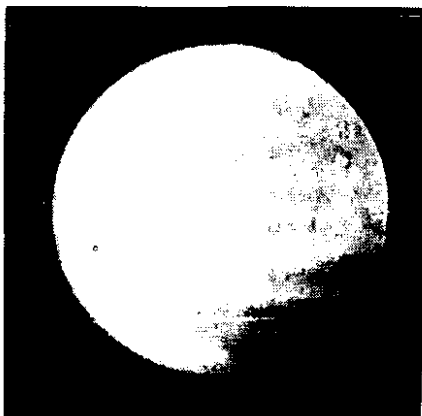
Dividing Plate Removed
Time 0.00 min



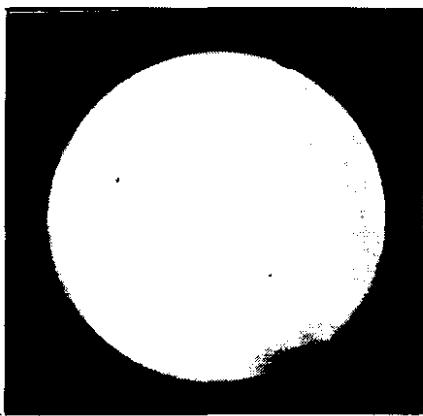
Time + 3.00 min



Time + 4.5 min



Time + 6.00 min

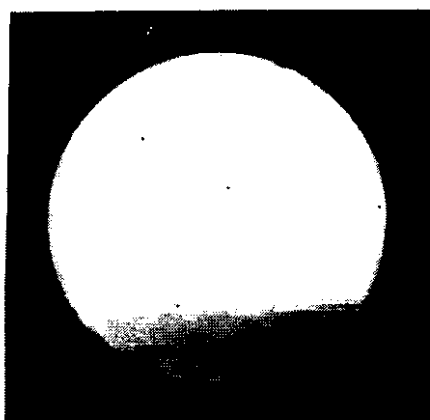


Time + 8.00 min

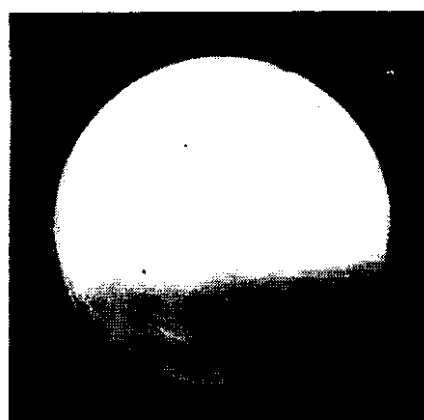
DIVIDING PLATE REMOVED AT TIME 0.00 MIN. CO₂ LEAKING OUT

FIG. 3

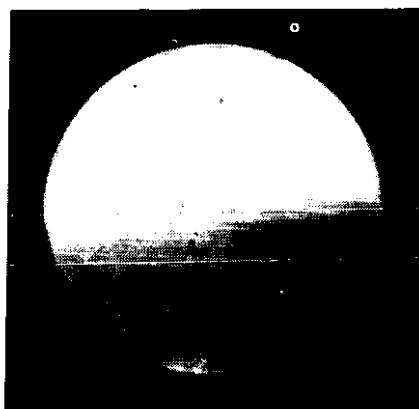
TANK FILLING WITH CO₂. NO DIVIDING PLATE FITTED



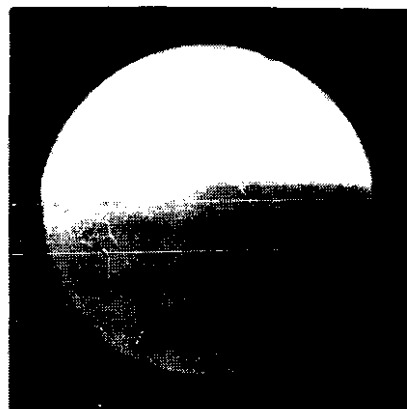
Filling for 3 min



4 min



8 min



15 min

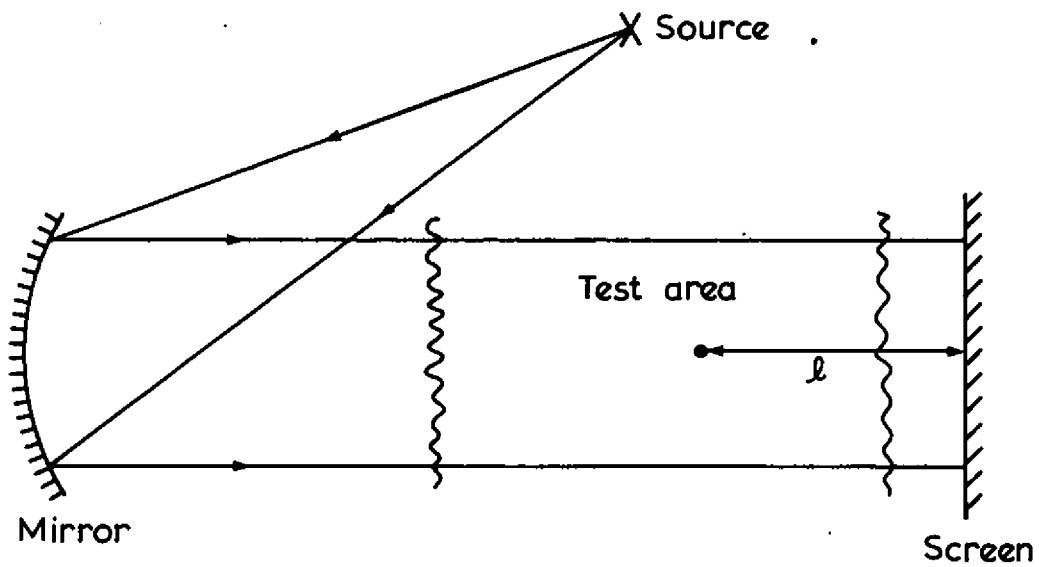


FIG. 4 SHADOW METHOD

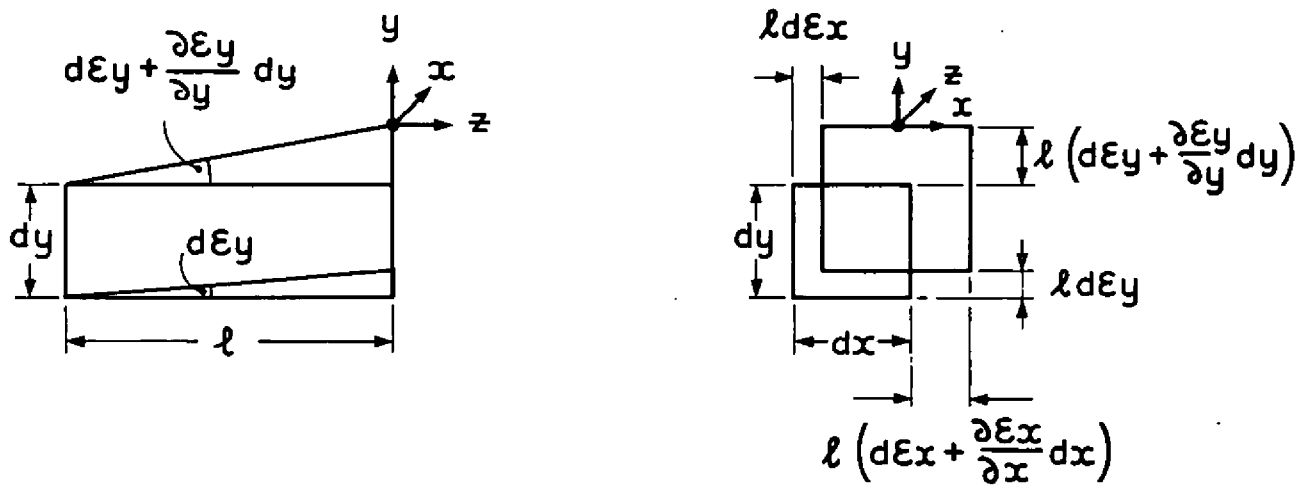
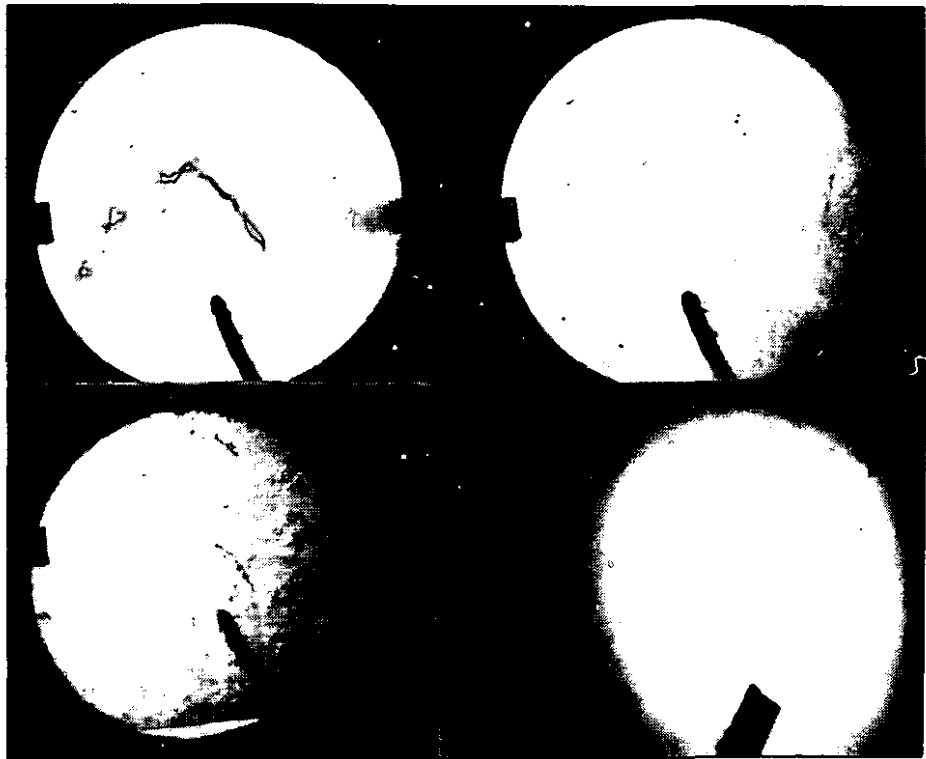


FIG. 5 GEOMETRY OF SHADOW METHOD

FIG. 6

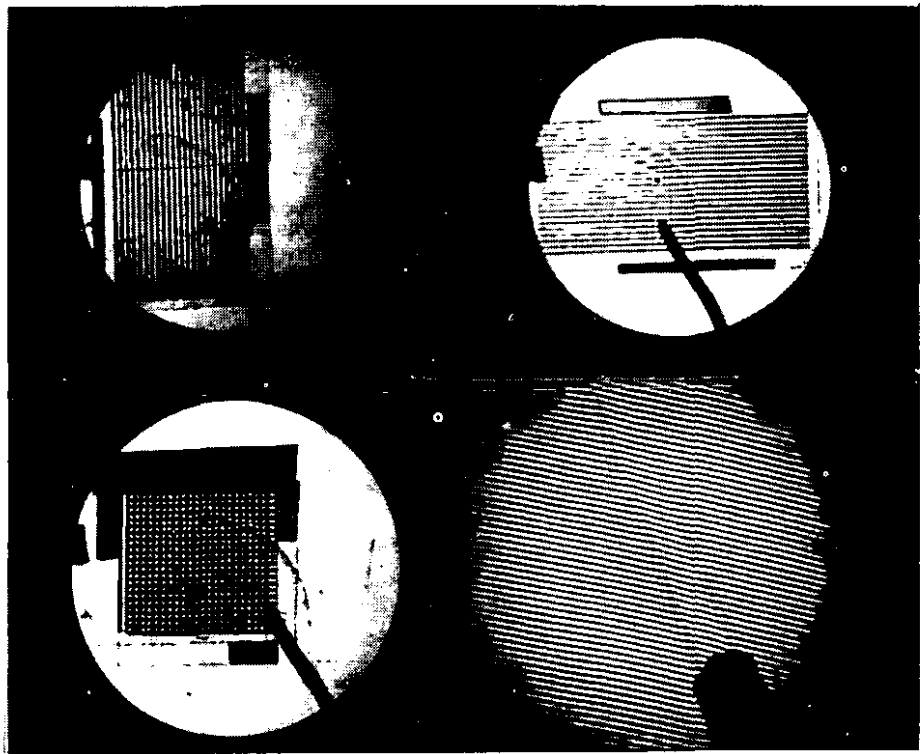


a) Schlieren Method

b) Shadow Method

b) Fine Grid Deflection Method

d) Laser Shadow Method



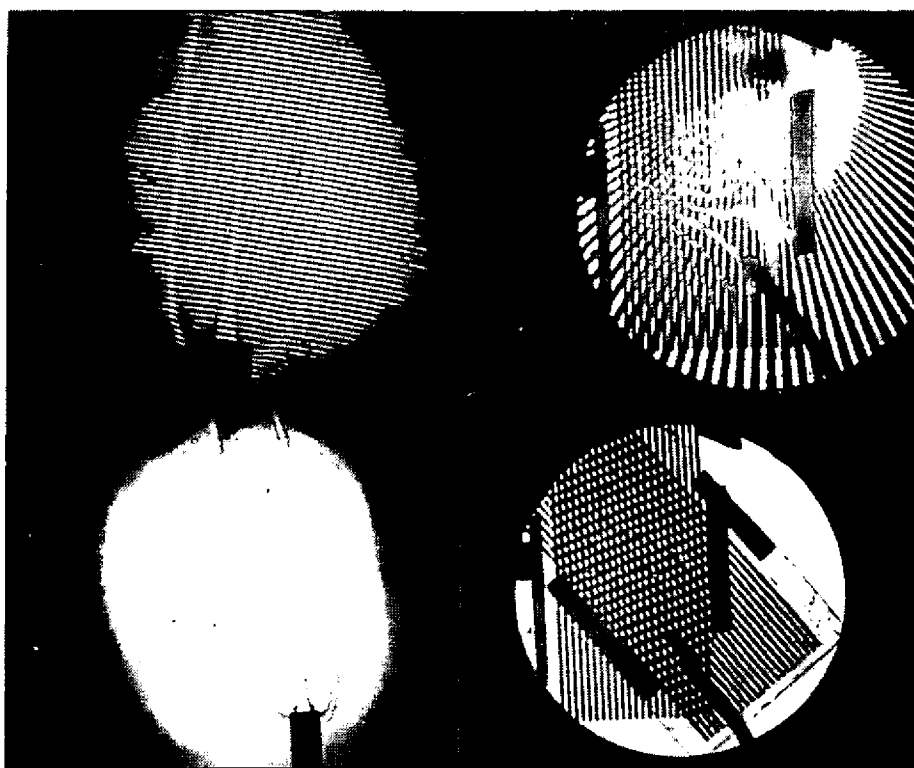
a) Grid Deflection (Vertical)

b) Grid Deflection (Horizontal)

c) Coarse Grid Deflection

d) Weinberg Method

FIG. 6

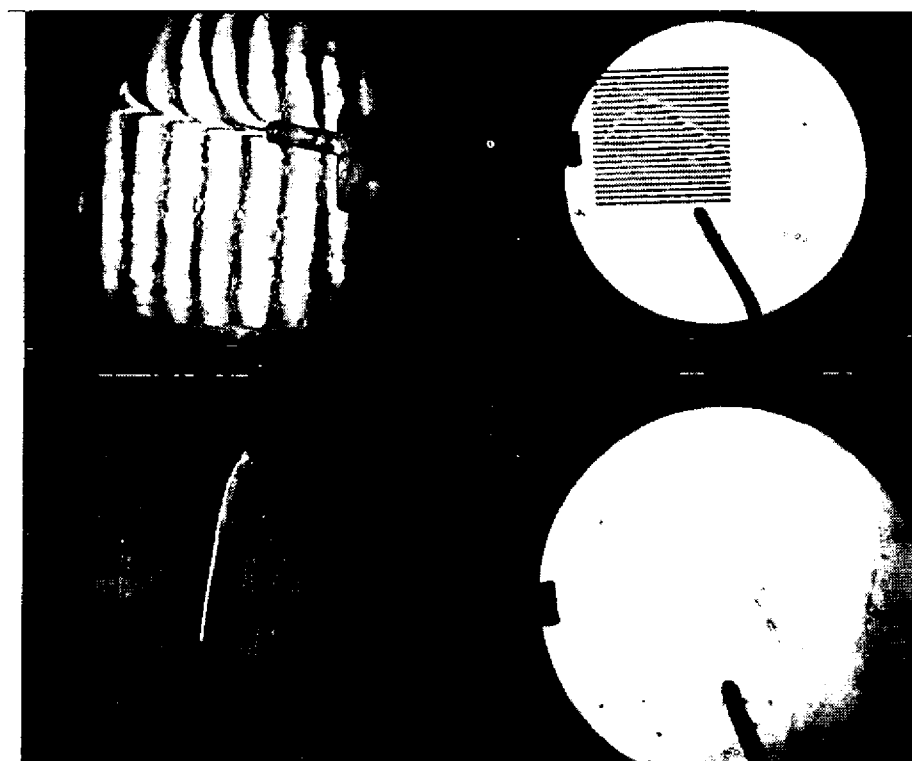


a) Weinberg Method (Flame)

b) Moire Fringe Deflection (Radial)

c) Laser Shadow (Flame)

d) Moire Fringe Deflection (Linear)



a) Mach-Zehnder Interferometer

b) Grid Deflection

c) Dark Field Schlieren

d) Shadow Method

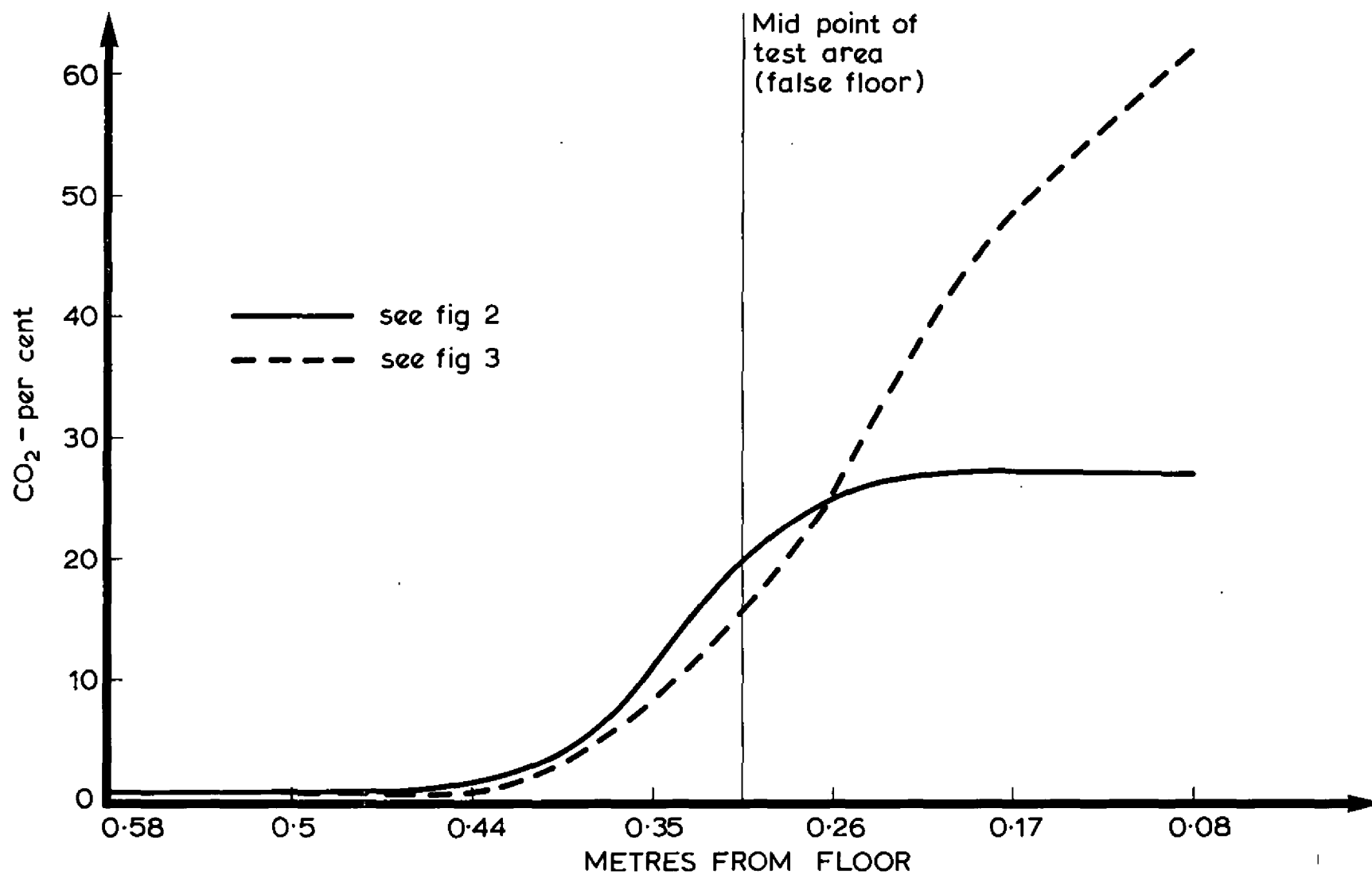


FIG. 7 CONCENTRATION OF CO₂ WITH SAMPLING POSITION

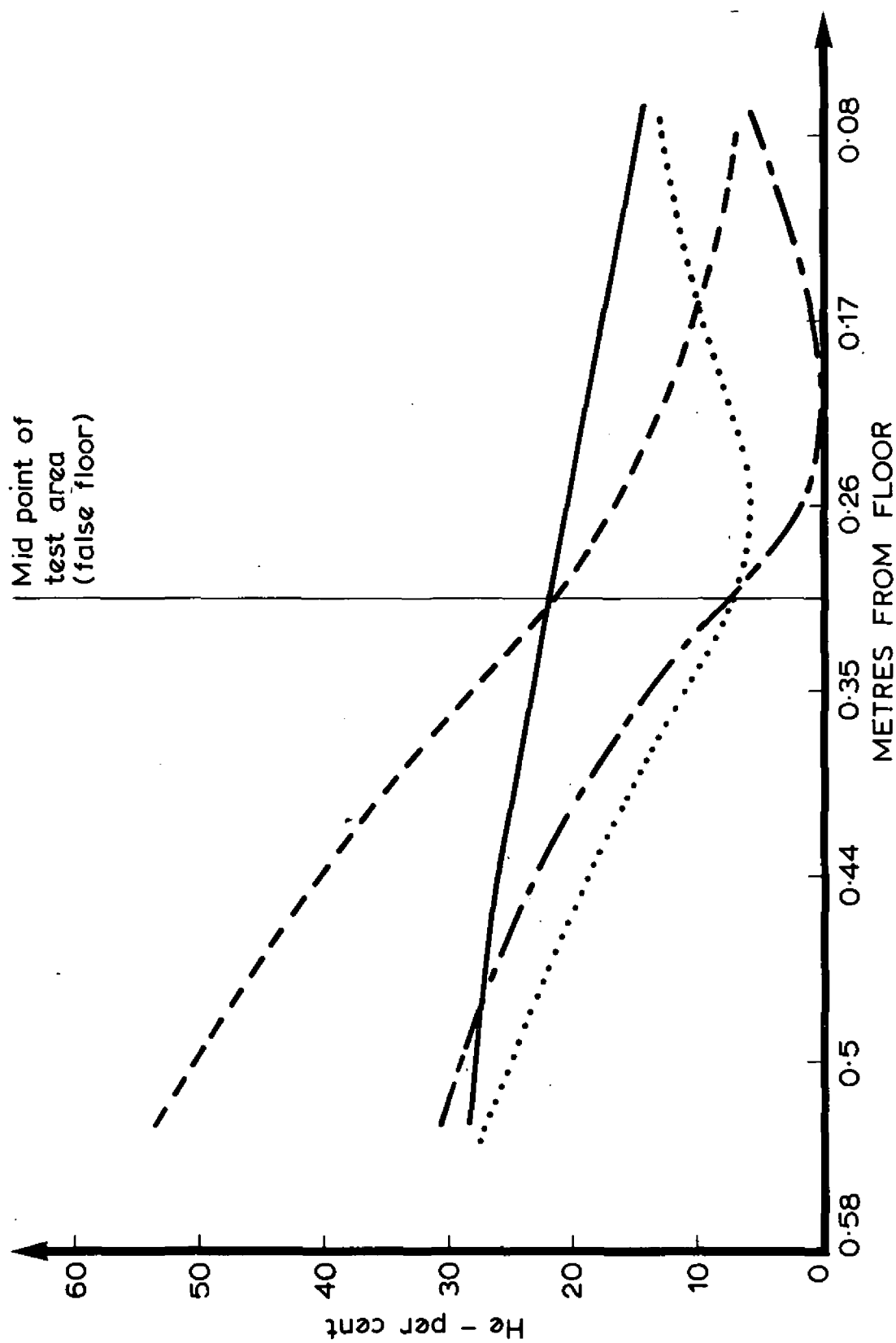
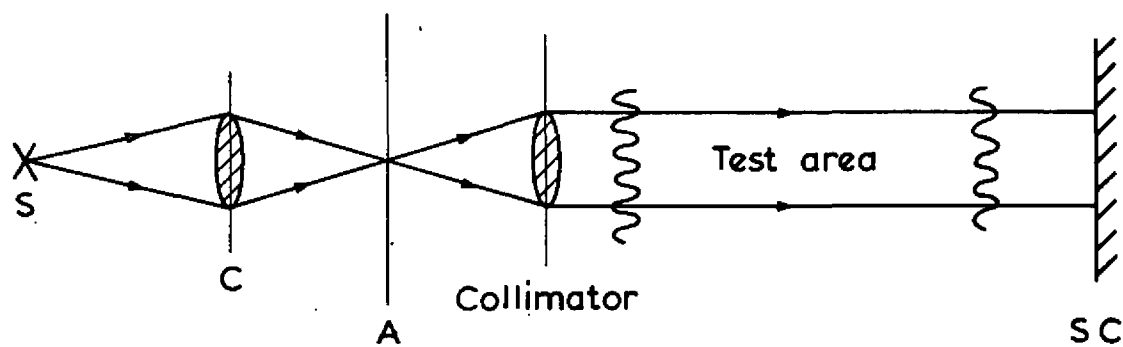


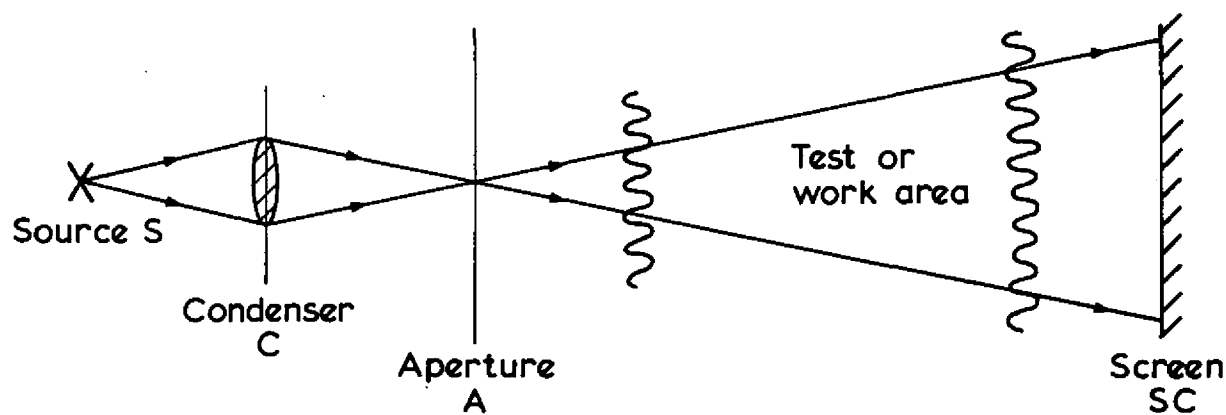
FIG. 8 CONCENTRATION OF H_2 WITH SAMPLING POSITION

APPENDIX 1

Brief summary of optical methods

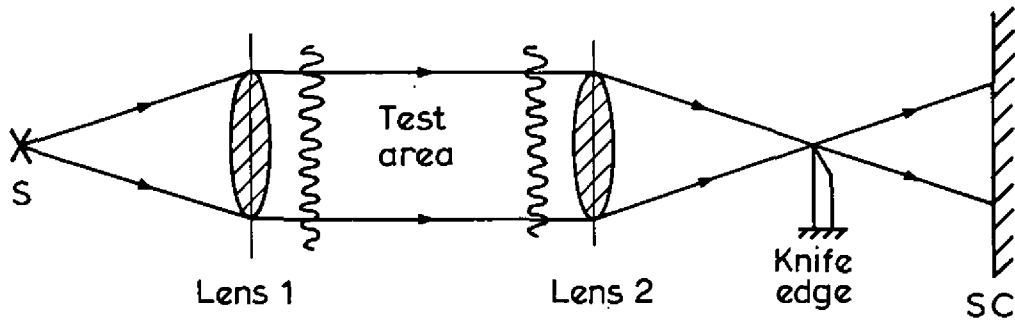


i) DIVERGENT BEAM

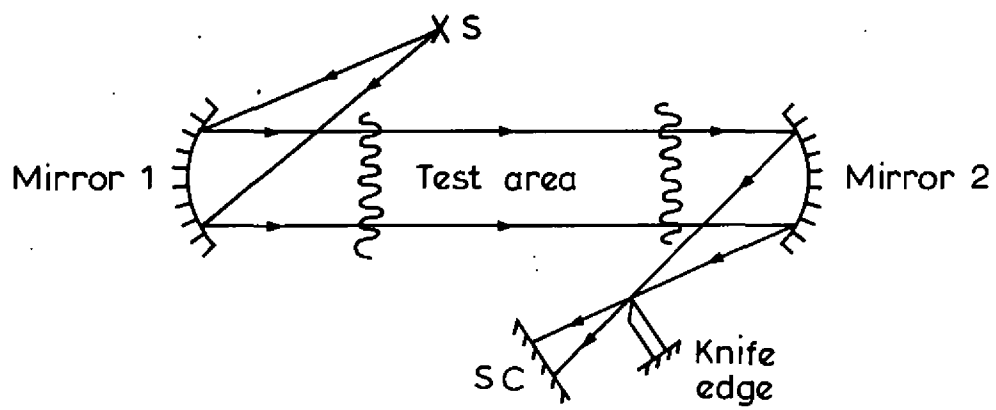


ii) PARALLEL BEAM

1. SHADOW METHODS

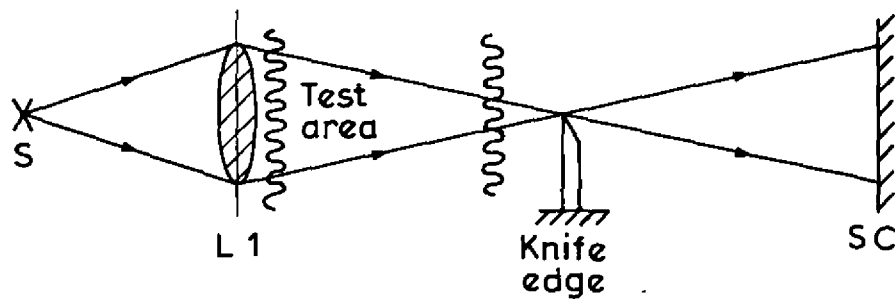


i) TWO LENS SYSTEM

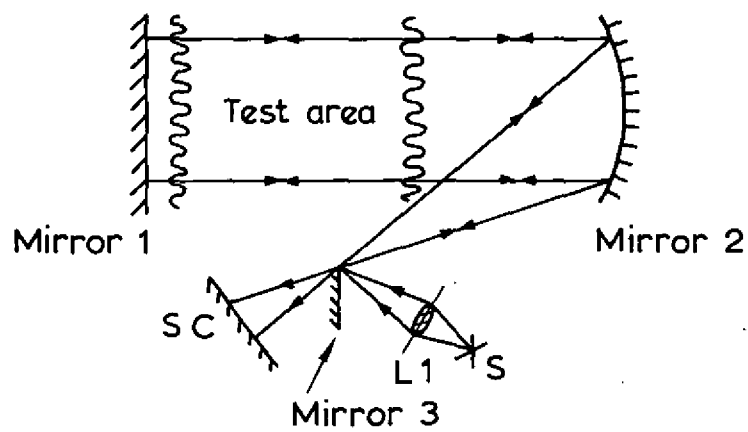


ii) TWO MIRROR SYSTEM

2a SCHLIEREN METHODS

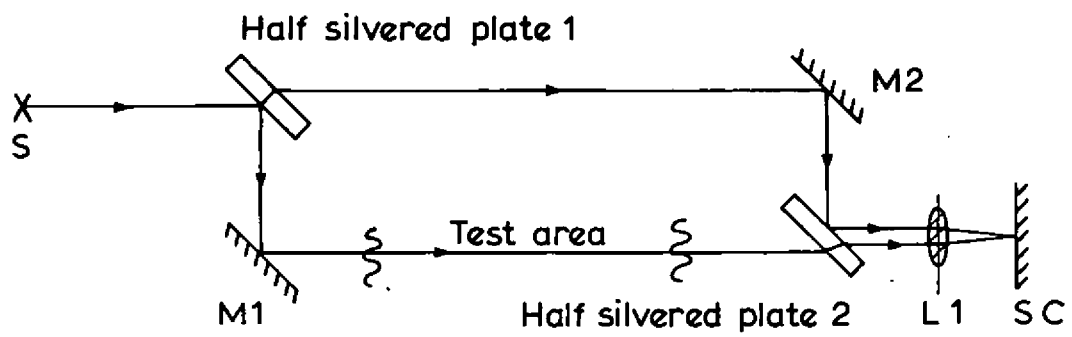


iii) SINGLE LENS WITH NON-PARALLEL LIGHT

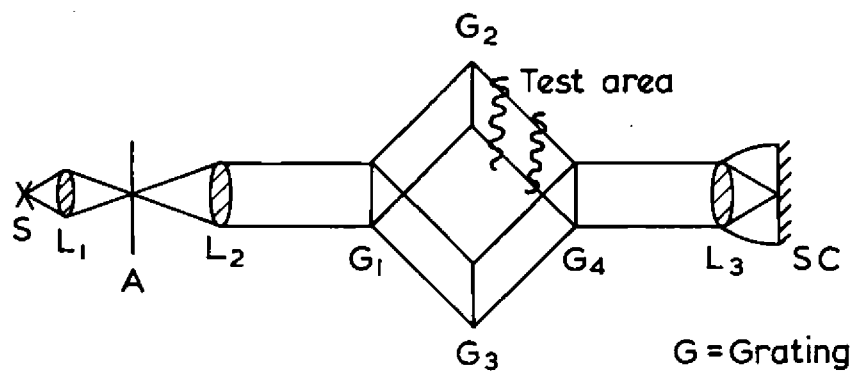


iv) SINGLE MIRROR WITH PARALLEL LIGHT

2b SCHLIEREN METHODS

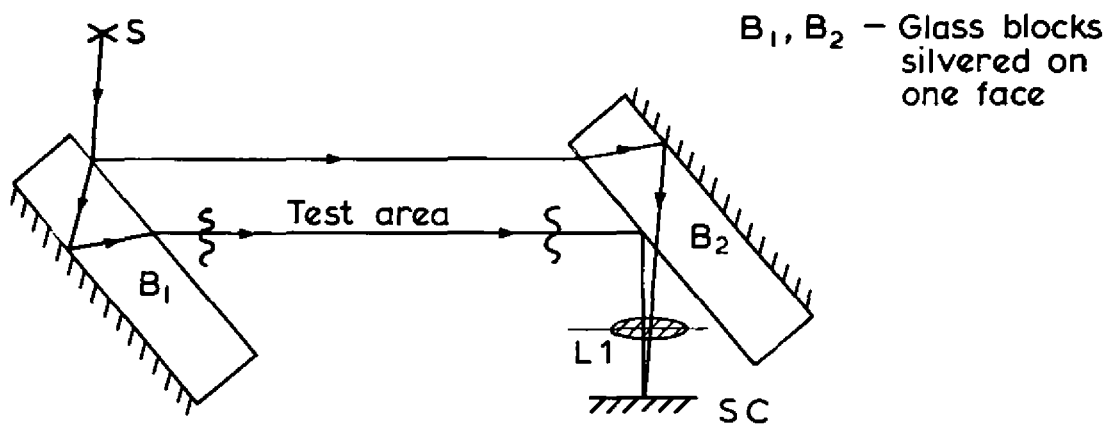


i) MACH - ZEHNDER INTERFEROMETER

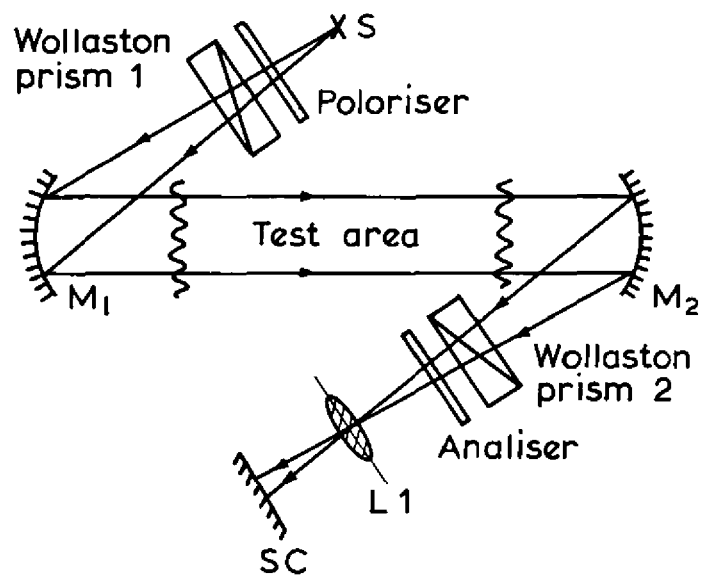


ii) WEINBERG - WOOD INTERFEROMETER

3a INTERFEROMETRY

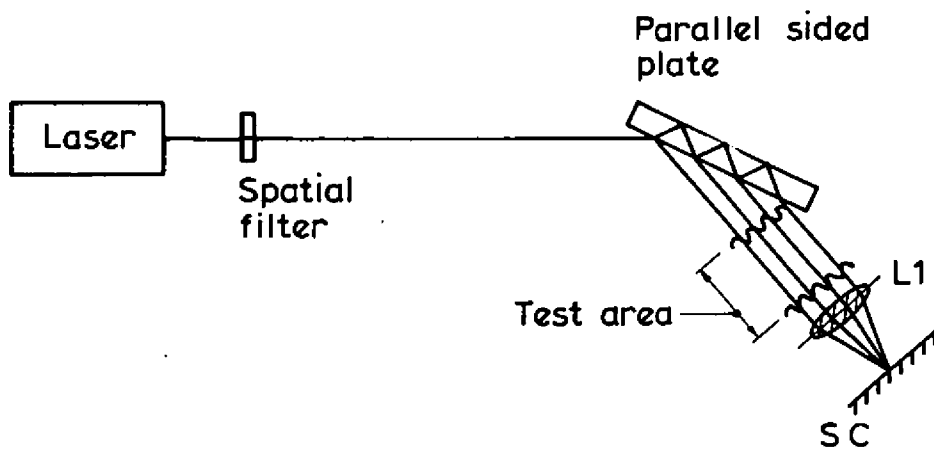


iii) JAMIN INTERFEROMETER

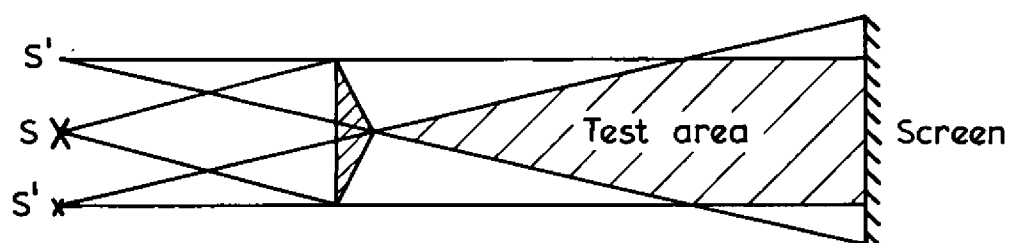


iv) SCHLIEREN INTERFEROMETER

3b INTERFEROMETRY

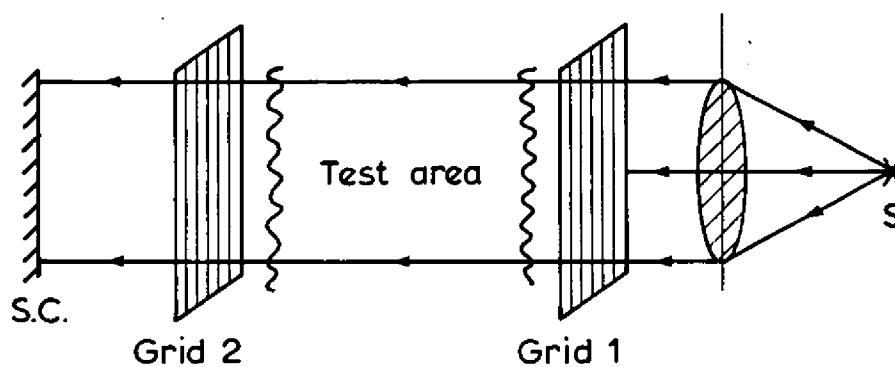


i) WEINBERGS METHOD



ii) FRESNEL FRINGE SOURCE

a) Interference fringe pattern deformation



iii) TWO GRID METHOD

b) Moiré fringe deformation

4 DEFLECTION METHODS

