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CONTROL OF FIRES IN LARGE SPACES WITH INERT GAS AND FOAM PRODUCED BY A TURBO-JET ENGINE

PART II SMALL SCALE EXPERIMENTS ON THE REPLACEMENT OF ATMOSPHERE

by

G. W. V. STARK and G. H. J. ELKINS

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Fire Research Station.
Boreham Wood.
Herts.
('phone ELStree 1341)

F.R. Note No.588.

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Summary

Small scale tests were made to study the replacement of the atmosphere in a compartment by an inert gas.

The condition necessary for the replacement of the atmosphere in a compartment with another atmosphere of different density by stratified flow is the introduction of the replacing atmosphere over a large area at a low velocity. This can be done by introducing the replacing atmosphere through a filter bag. A lighter replacing atmosphere must be introduced at high level, and the compartment must be vented at low level for efficient replacement. A modified Richardson number greater than 2 is necessary to attain a high degree of stratified flow.

For many practical situations the introduction of the replacing atmosphere by turbulent mixing flow appears more satisfactory than by plug flow.

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Introduction

A study of the problems of the control of smoky fires in large buildings led to the suggestion of the use of an inert gas generator based on a turbo-jet engine(1). It was proposed to carry out tests in the Models Laboratory at the J.F.R.O., a building of 250,000 ft^3 capacity. The present note describes some experiments, using a $^1/10$ scale model of the building, designed to obtain information which would indicate the best way of introducing the inert gas into the building.

Design of Experiments

The inert gas generator(2) can supply 45,000 ft^3/min of a gas containing 7 per cent (vol) of oxygen and 44 per cent water vapour at 100° - 120°C, with a density about two-thirds of that of air at room temperature. The existing atmosphere in a building would be replaced by the inert gas in the shortest time if the inert gas exhibited stratified flow.* Stratified flow is defined as the flow of gas that allows it to form a discrete layer, the growth of which displaces the existing atmosphere. The experiments were therefore designed to determine the condition under which stratified flow could be obtained.

The nature of the replacement of the atmosphere in a compartment can be correlated by the Richardson number, a dimensionless group relating buoyancy and turbulent stresses, defined by

$$Ri = \frac{\frac{g}{\rho}\frac{d\rho}{dy}}{\left(\frac{du}{dy}\right)^2} \qquad (1)$$

The conditions responsible for producing stratified flow or mixing flow occur at the point of entry of the injected gas into the compartment. Therefore a modified Richardson number

$$N_1 = \frac{gL}{V^2} \quad \frac{\rho_o - \rho_1}{\rho_1} \qquad (2)$$

was used, where g = gravitational constant

L = characteristic length (dia. of input duct)

ρ_o = density of initial atmosphere

ρ_1 = density of injected atmosphere

V = entrance velocity of injected atmosphere into the compartment measured in consistent units.

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*Stratified flow has sometimes been referred to as plug flow. However, it is proposed to restrict the term "plug flow" to describe the replacement of the atmosphere in a long compartment, such as a corridor, in which the replacing gas travels as a plug along the compartment, with sharp separation between the existing and replacing atmospheres.

By plotting a term, in dimensionless form, for the state of the atmosphere, against N_1, the boundary between the conditions of injection for stratified flow and those for mixing flow could be defined.

The replacement of the atmosphere in a compartment by fully turbulent mixing with an injected gas can be calculated and the concentration of injected atmosphere at time t is given by

$$C = 1 - e^{-\frac{rt}{V}} \qquad (3)$$

where C = proportion of injected atmosphere in compartment

r = rate of injection

t = time of injection

V = volume of compartment.

The extent of departure from turbulent mixing may therefore be assessed by comparing the observed composition of the atmosphere with that calculated from the above equation.

Experimental

Apparatus

A one-tenth scale chamber was made in the shape of the 250,000 ft^3 Models Laboratory in which the bulk of the full scale programme of tests were to be carried out. The dimensions are given in Fig.1. It was constructed from hardboard on 1 in. studding, lined internally with $\frac{1}{2}$ in. foamed polystyrene weighing 2 lb/ft^3, the inner surface being lined with polished aluminium foil. Openings were made, corresponding with doorways in the models laboratory at both "ground" and "roof" level. Openings not in use were closed by plugs of the same construction as the model chamber.

The replacement of air in the model chamber, hereinafter called the initial atmosphere, by air containing one per cent carbon dioxide and raised 25°C above ambient, hereinafter called the injected atmosphere, was monitored at the sampling positions, shown in Fig.1. The change in temperature, or carbon dioxide content, of the atmosphere in the chamber could be used for this purpose. Comparative tests, one of which is illustrated in Fig.2, showed that thermal losses were too great for temperature to indicate composition but that carbon dioxide content was satisfactory.

The apparatus for supplying the injected atmosphere Fig.3 was so arranged that the atmosphere could be injected at either the top or the bottom of the model chamber (positions A and B, Fig.2) and the degree and the position of venting could be varied by uncovering appropriate openings in the model chamber.

The entrance velocity of the injected atmosphere could be varied by three means:

(a) by varying the rate of flow of injected atmosphere;
(b) by supplying the gas through 1 in, 2 in. or 3 in. diameter ducting, the last size being one tenth of the diameter to be used in the full scale tests;
(c) by fitting filter bags, of the same diameter as the duct, 1 ft, 3 ft or 5 ft long through which the injected atmosphere entered the model chamber.

Results

Preliminary tests

Tests were first made with smoke bearing atmospheres and smoke trails to discover the method of introduction of the injected atmosphere that would give the least disturbance to the initial atmosphere and produce stratified flow, i.e. flow which would produce a sharp separation between a smoke bearing and a clear atmosphere. Tests for stratified flow were made with either smoke bearing initial atmosphere and clear injected atmosphere or vice versa. The injected atmosphere was introduced, at rates of flow of 34 ft^3/min or more, from an open ended 3 in. duct or from open mesh or closely woven filter bags 3 in. diameter and 5 ft long attached to the duct; and either at the top or bottom of the model chamber.

In the tests with smoke bearing initial atmospheres, no clearly demarked stratification between injected and initial atmospheres was observed for any condition of injection. In the tests with smoke-bearing injected atmosphere, mixing of the injected and initial atmosphere took place when the injected atmosphere was introduced through an open ended duct, or through the open mesh filter bag, at either the top or bottom of the model chamber. When the injected atmosphere was introduced through a closely woven filter bag, mixing took place when the injected gas was introduced at the bottom of the model chamber. However, clearly defined layers were obtained when the injected gas was introduced at the top of the model chamber for a wide range of rates of flow of injected atmosphere. Losses of injected atmosphere were high when the vents at the top of the model chamber were open, but when the vents at the bottom were open, the model chamber filled with a distinctly separated injected atmosphere layer, to a plane somewhat below the level of the top of the vents. The layer of atmosphere between this plane and the floor of the model chamber remained fairly clear, and the smoke-laden atmosphere escaped from the upper part of the vents.

The closely woven terylene fabric had a permeability given by

$$Q = 42.2\ H^{0.695} \qquad (4)$$

where Q = flow of air through fabric ($ft^3\ ft^{-2} min^{-1}$)

and H = head developed across cloth (in W.G.)

The change in concentration of injected atmosphere in the model chamber with time for a coarse filter fabric having about 110 holes/in^2 of about 1/16 in. and for the above closely woven terylene fabric are given in Fig.4. The theoretical curve for fully turbulent mixing and the curve for ideal stratified flow are given also in the figure.

The movement of the atmosphere within the model chamber was examined by observing the behaviour of smoke plumes. Tests were made with clear injected atmosphere introduced at the top of the model chamber through the closely woven filter bag, and with vents opening at the bottom of the model chamber only. They showed that there was a general tendency for the atmosphere to circulate for all the conditions tested ($N_1 = 0.3$ to 6.0). The direction of circulation of the smoke plumes sometimes reversed shortly after the introduction of the injected atmosphere. Also the smoke plumes at times mixed with the clear initial atmosphere to form discrete layers of dilute smoke and at times circulation took place in the model chamber in discrete layers of depths up to one foot.

Conditions for stratified flow

The above tests with smoke plumes showed a deviation from perfect stratification in stratified flow. The change in composition of the gas at the sampling points in the model chamber during injection can indicate such departure. A result of a typical test expected to give stratified flow is shown in Fig.5, in which the expected change in composition for perfect stratified flow is also given.

An estimate of this deviation may be obtained by calculating a stratification factor

$$P = \sqrt{\frac{(\Delta t\ 25\text{–}50)_A \times (\Delta t\ 25\text{–}50)_B}{t_A \times t_B}} \qquad (5)$$

where $(\Delta t_{25-50})_A$ and $(\Delta t_{25-50})_B$ are the times taken for the amount of initial atmosphere replaced to increase from 25 to 50 per cent at the sampling points A, B respectively, and where t_A and t_B are the times from injection for the injected gas to reach the sampling points A and B respectively. The result for sampling point C has been omitted from the calculation of P, as the smoke tests indicated that the venting of the chamber influenced the composition of the atmosphere at this level. If diffusion is neglected then $P = 0$ for perfect stratified flow and $P = 1.8$ for perfect turbulent mixing. P has been plotted against N_1 for all tests with injection of gas through a filter bag at the top of the model chamber in Fig.6. The range of experimental conditions is given in Table 1.

Table 1

Test Conditions

Gas injected at top of chamber through a filter bag

Filter Bag		Range of Gas Entrance Velocities (ft/sec)	Range of N_1
Dia. (in)	Length (ft)		
1	1	1.46 - 2.50	0.034 - 0.101
1	3	0.49 - 1.38	0.13 - 0.949
1	5	0.29 - 0.83	0.34 - 2.62
2	1	1.08 - 3.40	0.038 - 0.39
2	3	0.36 - 2.42	0.075 - 3.48
2	5	0.22 - 1.51	0.22 - 9.45
3	1	0.71 - 2.27	0.13 - 1.31
3	3	0.24 - 1.93	0.175 -11.5
3	5	0.14 - 1.31	0.39 -30.9

Although there is a scatter in the points for individual tests, a mean curve can be drawn. There is a pronounced change of slope at about $N_1 = 1$. P lies between 0.2 and 0.4 for values of N_1 greater than unity while for values of N_1 less than unity, the value of P increased as N_1 decreased. Extrapolation to $N_1 = 10^{-2}$ gave a value of P approximating to that for perfect turbulent mixing. The results are illustrated by the plots of composition of the atmosphere in Figs 5 and 7. In Fig.5 the change of composition with time is given for a test in which N_1 was substantially greater than unity and, in Fig.7 the change of composition with time is given for a test in which N_1 was substantially less than unity. Curves for perfect stratified flow and turbulent flow are included in each of the figures.

Conditions for turbulent mixing. The test reported above (Fig.7) indicates that a high degree of turbulent mixing is obtained, when injecting gas through a filter bag, provided N_1 is substantially less than unity. Low values of N_1 are obtained by injecting from an open ended duct, and the change in composition in such a test is given in Fig.8 together with the curves for perfect stratified flow and turbulent flow. The injection of the replacing atmosphere at the bottom of the chamber, even at values of N_1 greater than unity, gave replacement approximating to turbulent mixing; this is illustrated in Fig.9 for conditions of introduction of the injected-atmosphere, (at $N_1 = 5.75$ and through a filter bag) that would have given replacement by stratified flow, had injection taken place at the top of the model chamber.

Discussion

The tests reported herein have shown that for stratified flow to be the predominant method of filling a compartment, N_1 as defined in equation 2 should have a value greater than unity, and a minimum value of 2 is indicated by Fig.6 as being reasonable. However, stratified flow is unlikely to be attained unless the buoyant gas is introduced near the top of the compartment. Probably the important criterion here is that the distance between the inlet and the ceiling should not be very much greater than the diameter of the inlet. This condition would not often be found in fire incidents at which an inert gas generator might be used, except possibly in basements, ship's holds, or in buildings where permanent ducting was installed and could be used for the introduction of inert gas. Introduction of the gas through an open ended duct or at low levels would replace the atmosphere primarily by turbulent mixing. In addition the rising plumes of hot gases from fires would further modify the mixing pattern(3). It would therefore seem that, unless special considerations or circumstances operated, inert gas for extinction of fires should be injected so as to produce turbulent mixing. This is also the simplest method of injection.

There may be circumstances under which inert gas would be injected into a building at floor level through a bag, which would increase the value of N_1 over that for an open ended duct; this could happen for example if extra cooling of a hot gas stream were obtained by spraying water on to such a bag(4). The results of the model test indicate that in a tall building such injection would result in turbulent mixing. It is most likely that the turbulent mixing took place when the injected buoyant gas entrained air as it rose from the floor of the model chamber. A calculation of the entrainment of air from a line source buoyant plume(5) indicated that the gas reaching the top of the model chamber from the floor, a distance of at least 16 diameters, would arrive at ten times the flow rate and at one tenth the concentration at the line of injection. Therefore a high degree of turbulent mixing would be established shortly after injection.

Conclusions

The work reported in this note was undertaken to assist in the assessment of the potential use in fire-fighting of an inert gas generator, based on a jet engine, producing 45,000 ft^3/min of gas at about 100°C, containing 7 per cent oxygen. The model chamber used was $^1/10$ scale of the Models

Laboratory in which some full scale tests were to be made.

The results indicate that replacement by stratified flow requires the admittance of gas at a high level from a large area such as a filter bag. Turbulent replacement requires admittance of gas at a low level or from a small area at a high level. For the purpose of extinguishing fires it is in general advantageous for replacement to be by turbulent mixing; a possible exception to this is for fires at high level only and with moderate amounts of ventilation at the top of the building. On the other hand for the purpose of clearing smoke from a building it is generally advantageous that replacement should be by stratified flow.

Adopting a value of 2 for N_1, the modified Richardson number, the 45,000 ft^3/min of gas from the projected experimental inert gas generator, at a density of 0.047 lb/ft^3, would need to be admitted through a filter bag at least 20 ft long and 2.5 ft diameter to produce stratified flow.

References

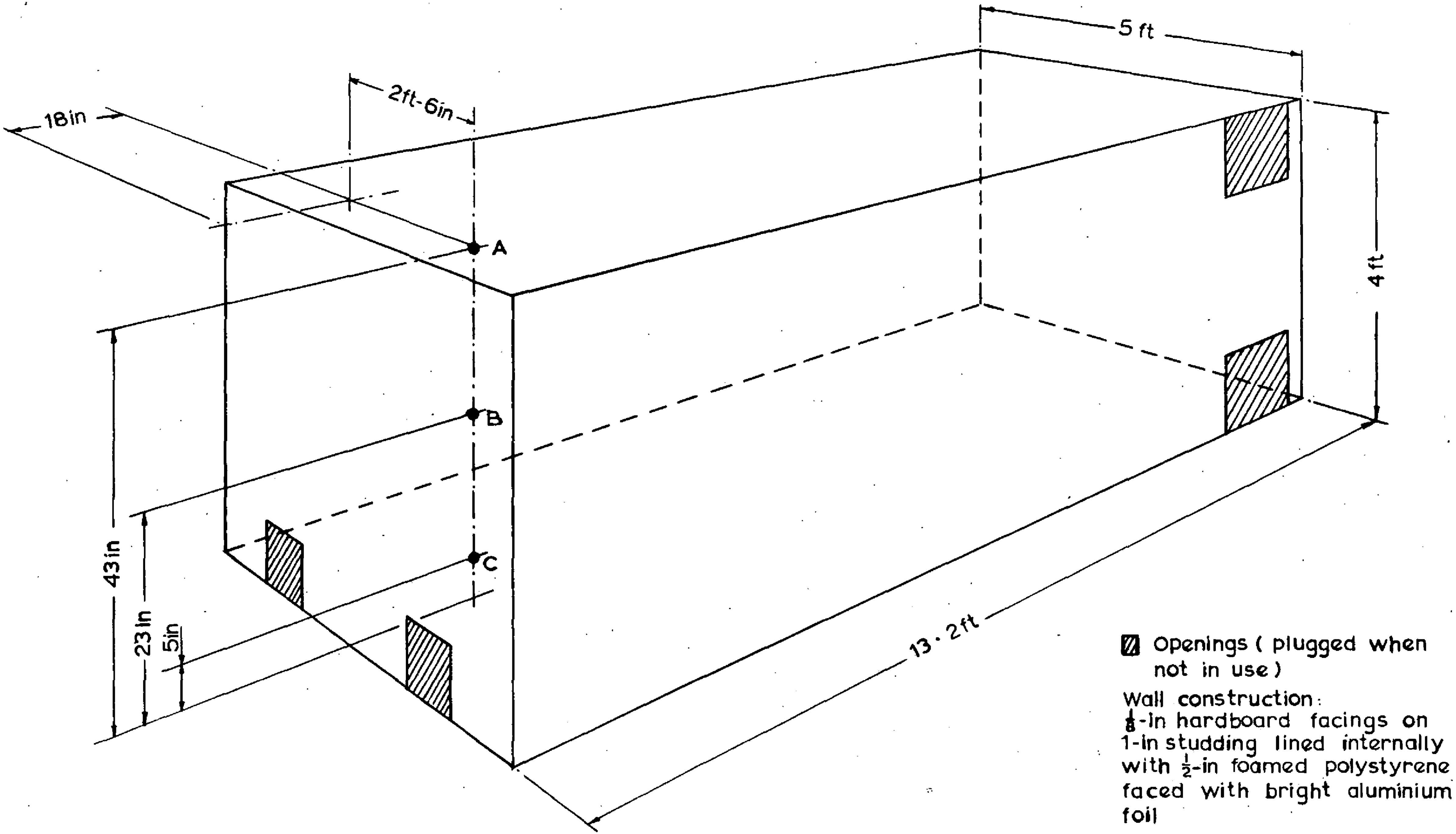
(1) D. J. RASBASH. F.R. Note No.507, "Control of fires in large spaces with inert gas and foam produced by a Turbo-jet Engine. Part 1. Introduction and Properties of Inert Gas and Foam2.

(2) G. W. STARK. F.R. Note No.512, "Control of fires in large spaces with inert gas and foam produced by a Turbo-jet Engine. Part 3. The design and operation of an inert gas generator".

(3) D. J. RASBASH, G. W. V. STARK and G. H. J. ELKINS. "A model study of the filling of compartments with inert gas". Paper delivered at Second International Fire Protection Seminar, organised by Vereinigung zur Förderung des Deutschen Brandschutzes, Karlsruhe, 1964.

(4) D. J. RASBASH. Unpublished work on the design of prototype inert gas generators.

(5) G. K. BATCHELOR. "Heat convection and buoyancy effects in fluids". Quart. J. Res. Meteor. Soc. 1954, 80, 339-358.



▨ Openings (plugged when not in use)

Wall construction:
$\frac{1}{8}$-in hardboard facings on 1-in studding lined internally with $\frac{1}{2}$-in foamed polystyrene faced with bright aluminium foil

FIG.1. THE MODEL CHAMBER

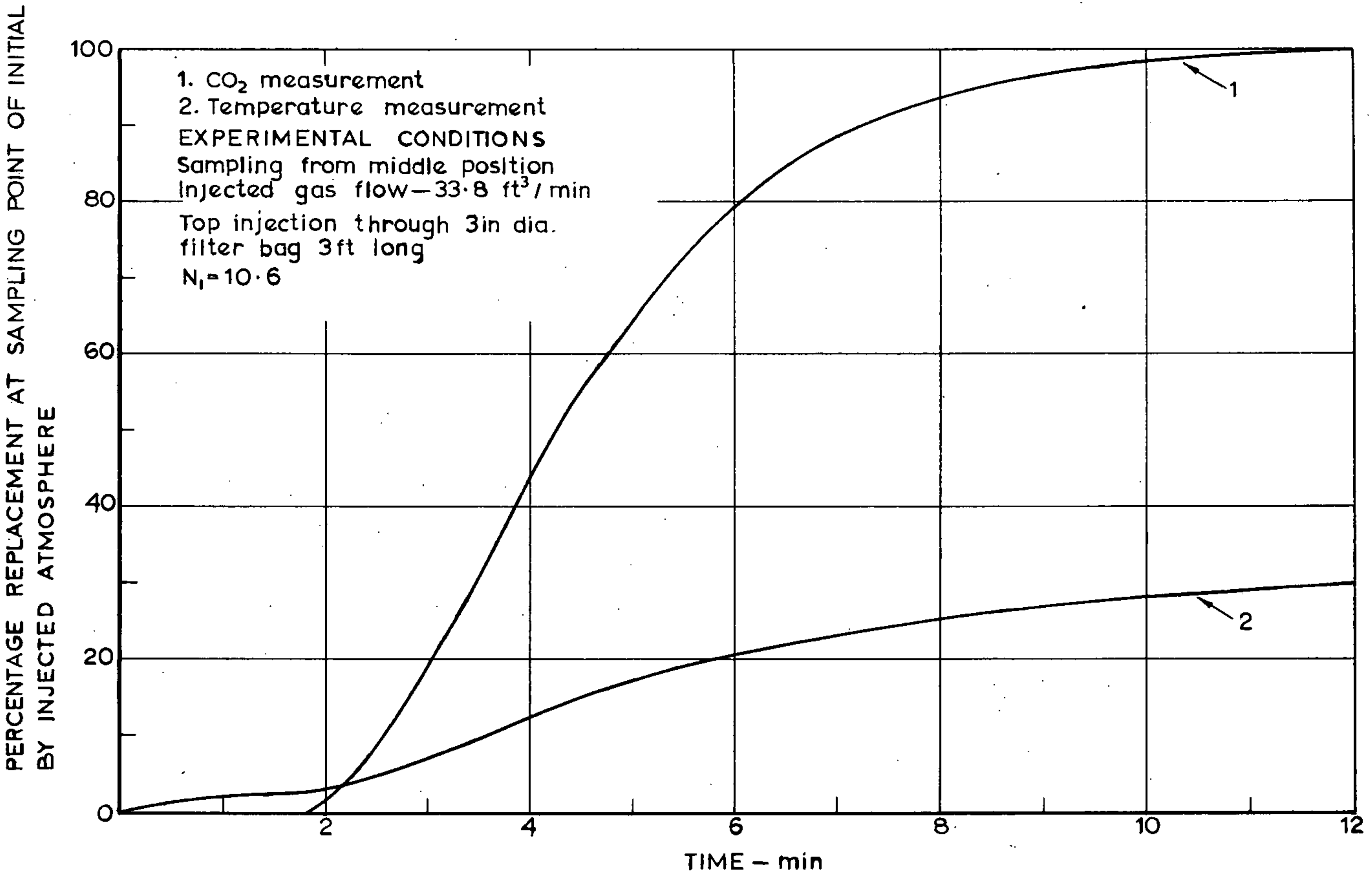


FIG.2. COMPARISON OF METHODS OF MEASURING REPLACEMENT OF ATMOSPHERE IN MODEL CHAMBER

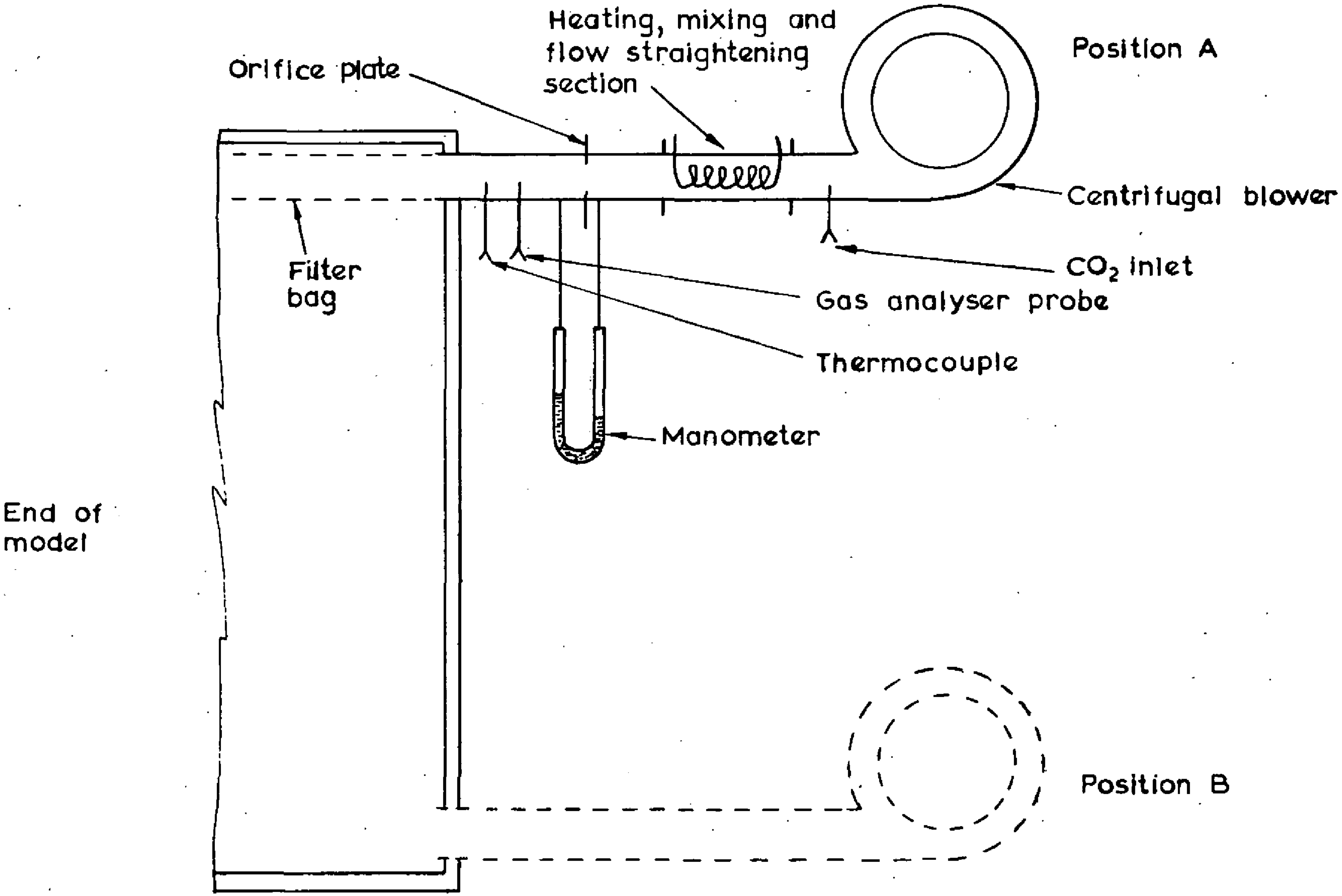


FIG. 3. SYSTEM FOR PROVIDING INJECTED ATMOSPHERE

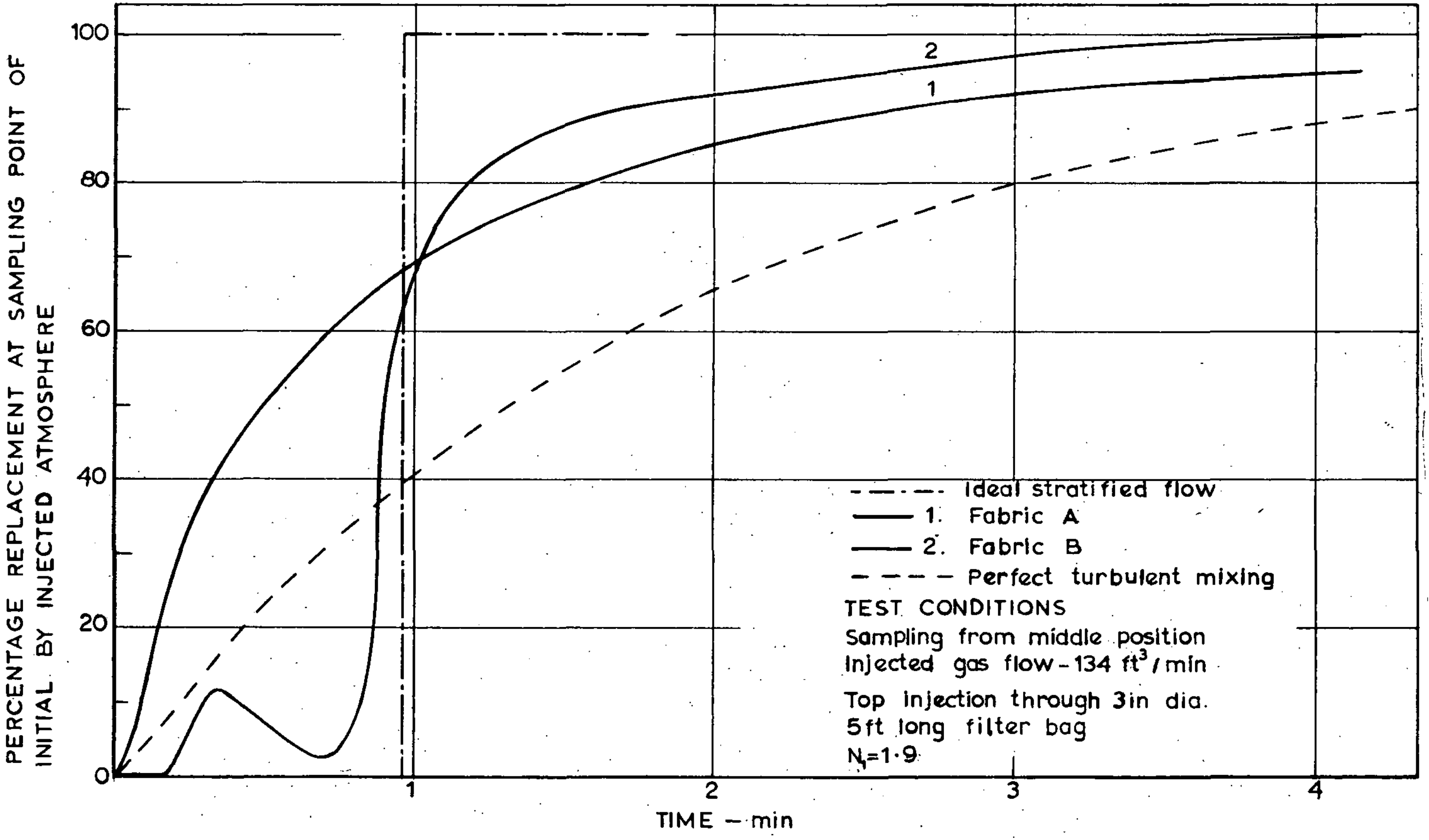


FIG.4. THE EFFECT OF POROSITY OF FILTER BAG ON MODE OF GAS FLOW

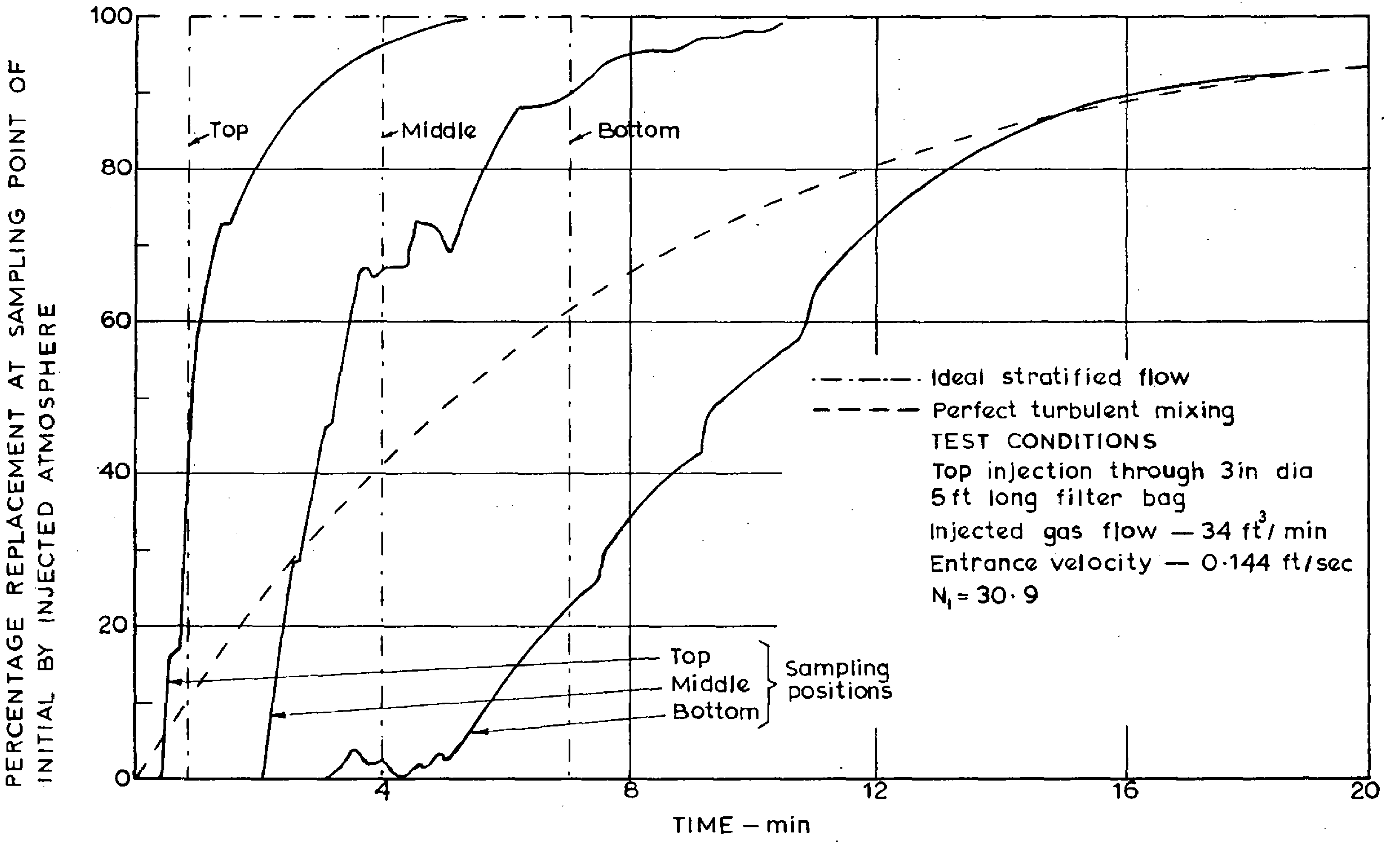


FIG. 5. REPLACEMENT OF ATMOSPHERE AT DIFFERENT HEIGHTS IN MODEL CHAMBER

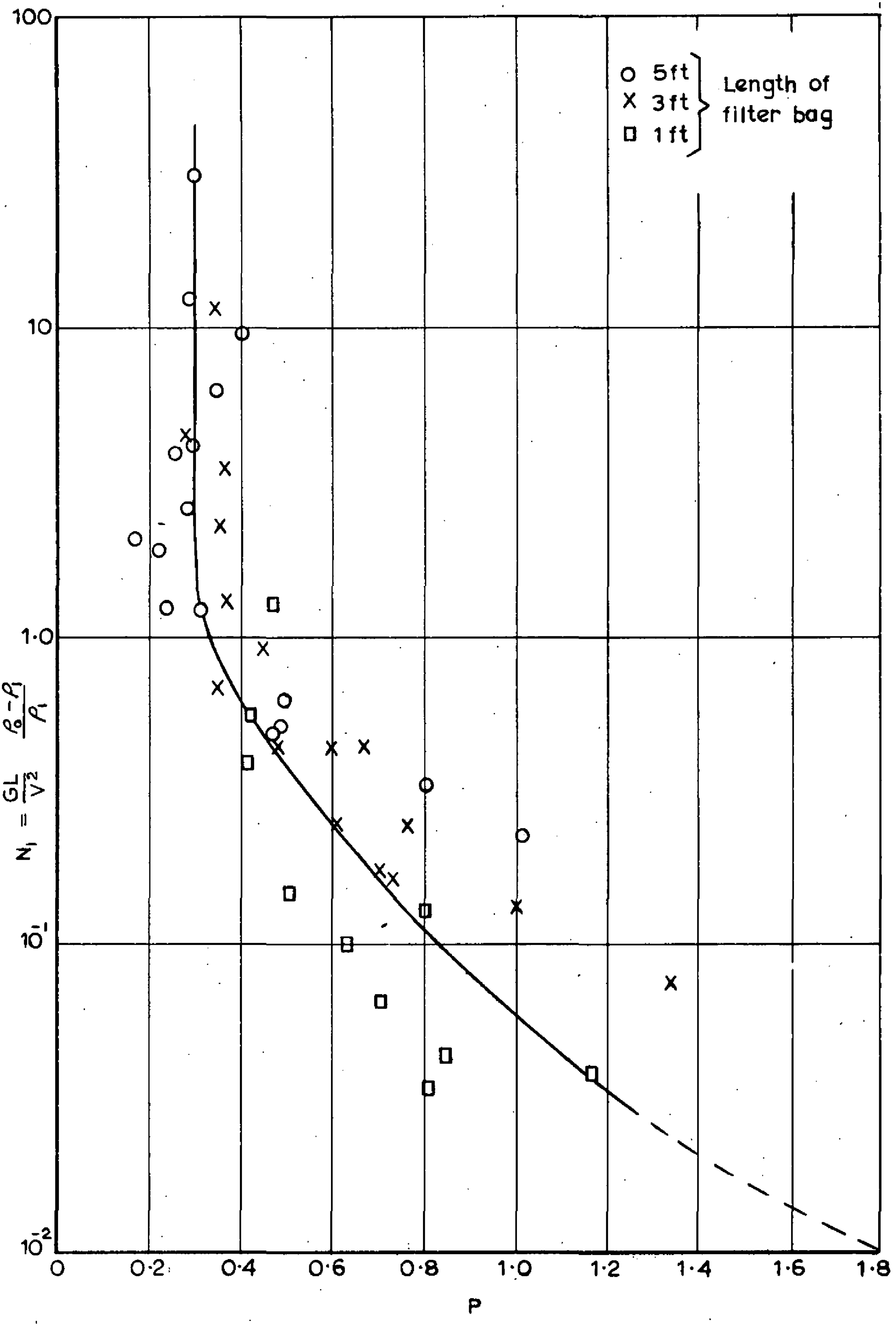


FIG.6. RELATION BETWEEN N_1 AND P–TOP INJECTION OF GAS THROUGH FILTER BAG

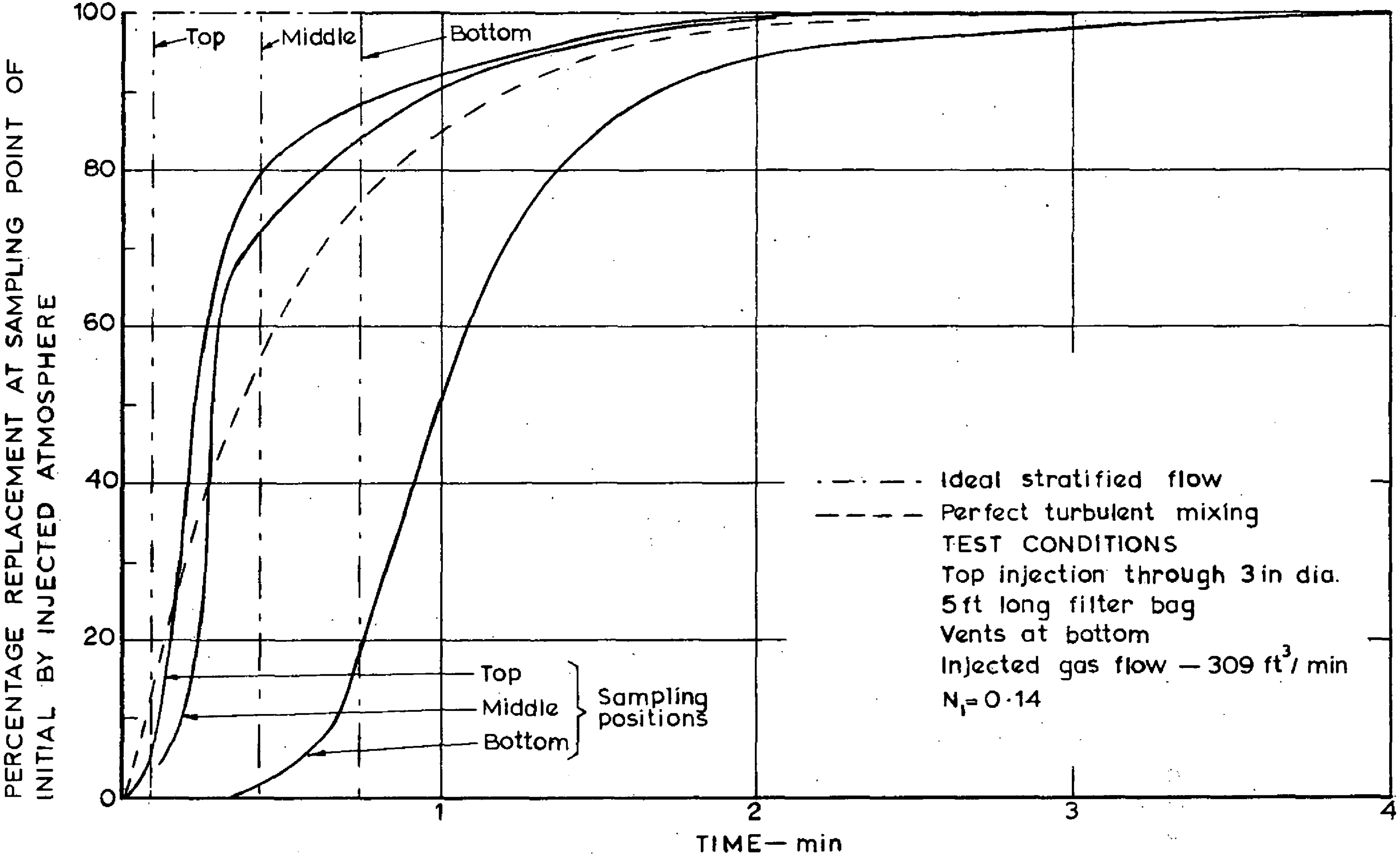


FIG.7. REPLACEMENT OF ATMOSPHERE AT LOW N_1

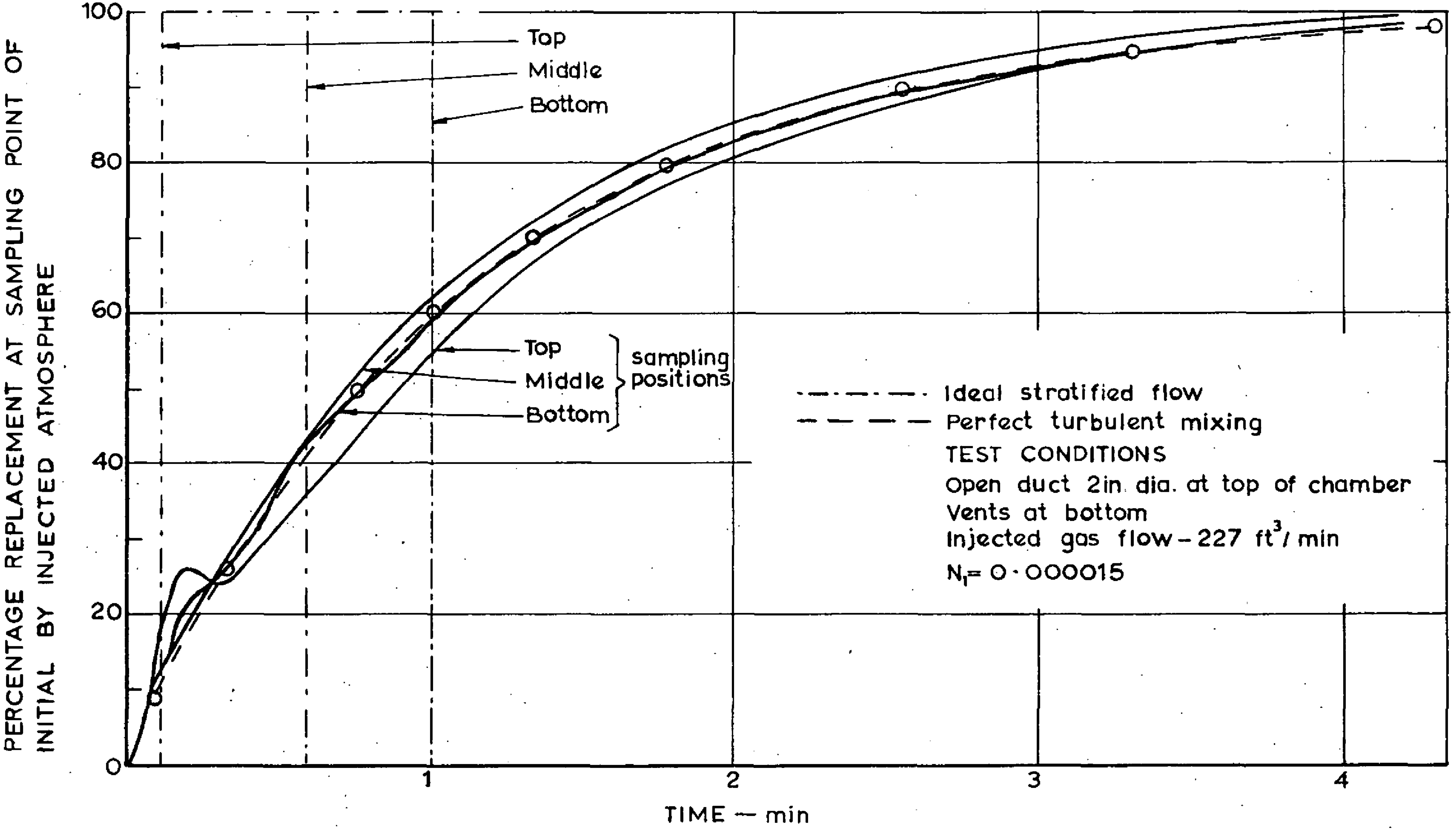


FIG. 8. REPLACEMENT OF ATMOSPHERE BY TURBULENT MIXING AT LOW N_1

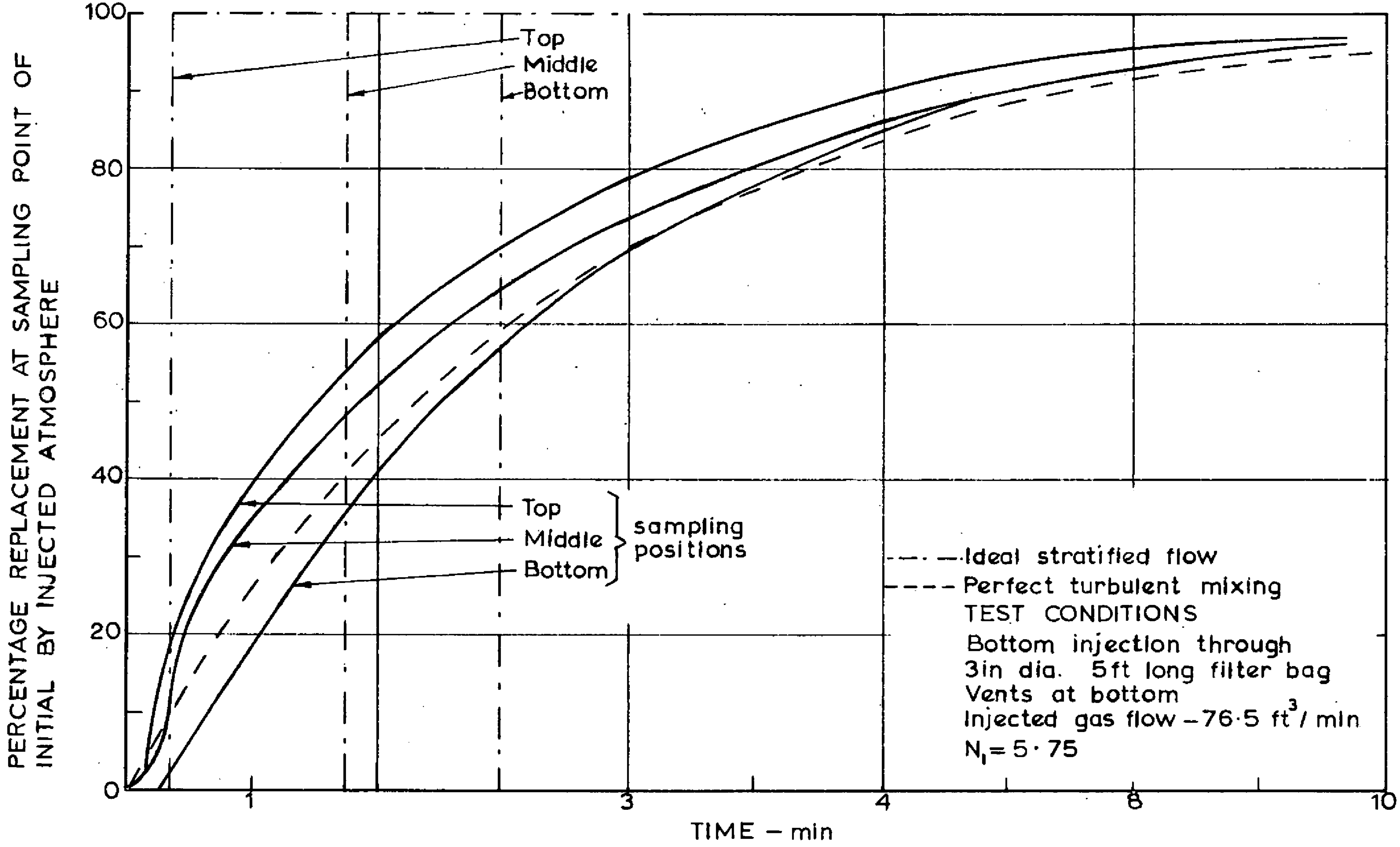


FIG.9. REPLACEMENT OF ATMOSPHERE IN MODEL CHAMBER — BOTTOM INJECTION