MINISTRY OF TECHNOLOGY

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FIRE OFFICES' COMMITTEE

JOINT FIRE RESEARCH ORGANIZATION

FIRE RESEARCH NOTE

NO. 596

CONTROL OF FIRES IN LARGE SPACES WITH INERT GAS AND FOAM PRODUCED BY A TURBO-JET ENGINE. PART 4 PERFORMANCE TESTS WITH INERT GAS IN THE MODELS LABORATORY, FIRE RESEARCH STATION.

by

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F. R. Note No. 596

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SUMMARY

Tests were made of the extinction of fires with the J.F.R.O. inert gas and foam generator in the Models Laboratory, a 250000 ft^3 barn-like building. Inert gas containing 7 per cent oxygen and delivered at 45000 ft^3 per min. at 100° - $120^\circ C$ extinguished oil fires and reduced wood fires to smouldering in 8-10 min. High level ventilation of up to 200 ft^2 did not impair extinction; small distributed leaks allowed air to enter and descend to floor level, where fires could continue to burn; large openings at floor level increased the amount of air that entered the building. The atmosphere within the building became transparent after 2-3 min of gas injection, except in places where air entered the building.

Firemen wearing breathing apparatus and service clothing could work for about 15 min in the atmosphere produced by the inert gas in the building, if the temperature of the atmosphere was not more than about $60^\circ C$. Gas at such a temperature can be supplied by a prototype appliance at present under construction, which incorporates devices to reduce the temperature of the inert gases produced. The appliance will produce gases of a wide range of compositions at temperatures of 40° - $70^\circ C$

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INTRODUCTION

A previous report gave details of the design of an inert gas generator based on a turbo-jet engine and of the gas and foam it can produce.(1) An account is given herein of tests carried out in the Models Laboratory at the Fire Research Station on the extinction and control of fires with inert gas produced by this J.F.R.O. inert gas and foam generator. These tests were part of a programme in which gas and foam from the generator were used against fires in premises of different types. Tests in a set of disused basements in East London, and in a four storey tower at the Fire Research Station are reported elsewhere.(2, 3)

EXPERIMENTAL

Models Laboratory. The Models Laboratory, Fig 1, Plate 1, is a large undivided structure, 130 ft long, 50 ft wide and 40 ft high of about 250000 ft^3 volume. The bottom 10 ft of the walls is of brick, the upper section of the long walls is of double asbestos sheet cladding and the upper section of the short walls is of wired glass in patent glazing bars.

A roof opening of up to 1500 ft^2 area could be obtained by means of a pair of mechanically operated sliding shutters. When the shutters were closed, the gaps around the edge of the sliding sections left a residual opening of 70 ft^2; this was reduced by additional sealing to 30 ft^2 for the last few tests. Floor level ventilation could be provided by doors and shutters at A, B, C, D and E, Fig. 1. Brick arches 10 ft high extended about 10 ft, into the Models Laboratory from the openings B and C. The gas from the generator (Plate 2) was always injected through the large opening A, (Plate 3). Recording room X was used as a control laboratory, and room Y contained the operating gear for the sliding roof; room Z was used in a few tests as an access point for firemen to enter the Models Laboratory from outside.

APPARATUS

Thermocouples and gas sampling points were installed at 5, 20 and 35 ft above the floor and 5 ft from the wall at K, and a mast of 12 thermocouples at 3 ft intervals above the ground was erected near the centre of the Models Laboratory at L. The gas sampling point at J, 20 ft above the floor was used in some tests for continuous monitoring of carbon dioxide or oxygen in the atmosphere. As the proportion of heat lost from the atmosphere through the walls of the Models Laboratory was small, and the temperature of the inert gas was much higher than ambient, on most tests the temperature of the atmosphere was used to monitor its composition, and hence the degree of replacement. In a few of the later tests some of the upper thermocouples on the mast were replaced by wet bulb thermocouples to indicate the moisture content of the atmosphere.

Measurement of the extinguishing properties of the atmosphere

The extinguishing properties of the atmosphere produced by the injection of inert gas and its ability to control combustion were measured by the action of the atmosphere on a number of fires distributed through the building. The fires which were used in the tests were as follows:

(a) Wick lamp fires. In the early tests up to 36 wick lamps were used to give an indication of the way the extinguishing power and hence the distribution of the gas varied throughout the building. These lamps were mounted at 5, 20 and 35 ft above the floor points O, Fig 1. A remote indication system for giving the exact time of extinction of these lamps proved unreliable, but the number of lamps extinguished during and at the end of the tests was observed and indicated the distribution of gas.

(b) Crib and scrap wood fires. The crib fire used in the main programme of tests consisted of 25 pieces of timber 4 in square and 3 ft long, cross laid in layers of 5 pieces with equal 4 in spacing giving a crib 3 ft square by 1 ft 8 in high. The crib was built at a height of 9 ft above the ground on a weighbridge which allowed the loss of weight to be observed. In all tests the fire was placed at a point P, Fig 1 to allow easy observation from the room X. In a number of tests fires of waste wood about 4 ft diameter and 2 ft high were also lit at points Q, Fig 1.

(c) Diesel oil tray fires. 12 tray fires 6 in diameter were mounted at 3 ft increments above the floor on a mast at N, Fig 1. In the group of tests in which firement entered the building, a 7 ft high platform across the Models Laboratory at R_3 supported tray fires of diesel oil, 6 in, 1 ft and 2 ft diameter. Additional 3 ft diameter tray fires were also placed on or near the floor at R_1 and R_2.

(d) Hay Bale fire. This fire was of a bale of hay mounted on a stand 6 ft above the ground at point S, Fig 1. The bale was about 4 ft long and 18 in square. A smouldering fire was established in the bale and immediately prior to the injection of gas in a test a thermocouple was inserted into the smouldering zone, to record the effect of the inert gas on the temperature.

(e) Fibreboard surface. A panel of fibreboard, 8 ft high by 4 ft by 1 in thick was erected 12 ft above the ground at M, Fig 1.

Plate 4 shows a number of these fires burning prior to a test in which firemen entered the building.

EXPERIMENTAL PROGRAMME

The filling of a building with gas of the type used was an unprecedented process and the effect of the gas on such items as electrical services and other apparatus in the building was to some extent an unknown quantity. The velocity and the available pressure in the gas stream from the jet engine appliance were so high that pressures might have built up in the building which could have damaged the windows and asbestos sheet cladding.

Therefore a first group of experiments was carried out in which the total amount of ventilation in the building at first large, was progressively reduced. The main object of these tests was to ascertain whether the gases produced at the maximum output of the appliance and injected directly into the building could damage the contents or structure. These experiments were however combined with observations on the ability of the gas to extinguish or control fires, thus giving information on the effect of openings in the building on the efficiency of the process.

In the second group of experiments the gas was injected at the full rate and with all the openings in the building closed except for the opening at the periphery of the sliding roof and the leaks between the sheets of asbestos cladding. In this group of experiments comprehensive measurements were made of the temperature distribution through the height of the building as a function of time, the visibility in the building and the effect of the gas on the extinction and control of fires of different types.

A third group of experiments was carried out, under similar conditions to the second group but in which laboratory personnel and firemen entered the building for relatively prolonged periods to determine the extent to which useful work could be carried out in the atmosphere produced.

In all tests reported the gas was injected from an open ended duct 30 in diameter, with its axis about 3 ft above the ground at a point near the centre line of the opening A, Fig 1 (Plate 2). Except where stated otherwise the inert gas was injected at about 45000 ft^3/min and had the average composition by volume, oxygen 7 per cent, carbon dioxide 3 per cent, nitrogen 46 per cent and water vapour 44 per cent. The temperature of the gas injected was about 110°C.

RESULTS

Group 1. Exploratory Tests, with varying ventilation in the building.

Test No. 1. In this test doors B, C, D and E were fully opened. The doors A through which the gas was injected were opened to a width of 3 ft and there was an opening in the roof of 785 ft^2. A continuous measure of the carbon dioxide content of the atmosphere was made at the point J on Fig 1 at a height of 20 ft. Temperature was measured also at point K at heights of 5, 20 and 35 ft. During injection of inert gas the bulk of the building became filled with a misty atmosphere except for a part near the openings B, C, D and E, equal to about 10 per cent of the volume of the building, which remained clear. The temperatures reached by the thermocouples were substantially constant after about 5 min, and corresponded to an increase above ambient of 4°, 29° and 34°C, indicating oxygen contents of about 20.3, 18.3 and 17.7 per cent at the heights of 5, 20 and 35 ft respectively. The measured concentration of carbon dioxide at 20 ft was 0.68 per cent. Ambient temperature at the beginning of the test was 15°C. Thus on the basis of the readings of the upper thermocouples there was a dilution of the injected gas with about 3 parts of air, while on the basis of the carbon dioxide content there was a dilution with about $3\frac{1}{2}$ parts of air. The test did not affect the structure of the Models Laboratory or the electrical wiring and equipment.

Test No. 2. Conditions were similar to those of Test No. 1 except that entrances B and C were closed. As well as the temperature and carbon dioxide measurements, two masts of wick lamps were lit and scrapwood fires were lit at positions P and Q_2. The temperatures recorded at K, Fig 1 were substantially constant after 6 min.; however due to a recorder fault the early part of this record was lost. The steady temperatures at 5, 20 and 35 ft were 42°, 65° and 72°C, indicating oxygen contents of about 17.9, 13.4 and 12.3 per cent respectively. The carbon dioxide concentration at 20 ft reached a steady value of 0.9 per cent in 6 to 7 min. These measurements indicate that the injected gas was diluted with about 1 part of air in the upper part of the building and with about 3 parts of air near the lowest, 5 ft thermocouple. Visibility after the first 2 or 3 min of gas injection was good except near ground level, where there was a layer of mist. All wick lamps were extinguished within 6 min of injection. The scrap wood fire at Q_2, Fig 1 continued burning with little change throughout the test, but the flames from the fire at P which was above ground level started reducing in size after 2 or 3 min injection, the wood becoming less involved and after 8 min injection flames were supported from an area of 6-9 in dia. only. The laboratory was entered from time to time after 6 min injection. The atmosphere at head height, 5 ft approximately, felt above blood heat, but was tolerable. When injection of the inert gas stopped the fire at P increased in size and was fully involved in about 5 min. The structure of the Models Laboratory and the electrical equipment were again unaffected by this test, but water condensed on and dripped from main roof beams.

Test No. 3. For this test all openings to the building, except for a 200 ft^2 opening in the roof and doors D and E, were shut. 3 masts of lamps were lit and a wood fire was lit 9 ft above the ground at P. The crib fire was allowed to burn for 5 min when the flames had reached a height of 4 to 6 ft before injecting inert gas. The temperature and carbon dioxide content of the atmosphere are given in Fig 2. They had reached fairly steady values in 6 min and 9 min of injection respectively. The temperatures indicate oxygen concentrations of about 14.3, 12.5 and 11.9 per cent respectively at 5, 20 and 35 ft above floor level. The dilution of the inert gas with air was less than in the previous tests, the highest dilution being 1 part air to 1 part gas from temperature measurement and 2 parts air to 1 part gas from carbon dioxide measurement. Mist was formed in the building as the inert gas was introduced, but the atmosphere cleared after 3 min injection; visibility was very good after 5 min, when the whole length of the building was visible. All the wick lamps were extinguished by 3 min 40 sec. The crib fire continued burning, but the flames reduced in size and luminosity as the test proceeded. From 9 min after injection to the end of the test, the flames were very small, about 6 in high, and almost non-luminous and were at the centre of the crib only. When gas injection was stopped, the crib fire recovered and became fully involved again in 5 min.

In the foregoing three tests, temperatures were measured at the point K, Fig 1 5 ft away from the wall of the Models Laboratory. It was observed that during injection of the inert gas, mist formed at the walls of the Models Laboratory, and dropped down to floor level, where it either spread out or dispersed. In test 4 and subsequently, the mast of 12 thermocouples in the centre of the Models Laboratory was also used, to record temperatures at a position unaffected by the mist formed at the walls. The infra-red gas analyser became difficult to keep stable during the foregoing tests, and in test 4 and subsequently, gas samples were collected for analysis in an Orsat apparatus. Apart from condensation of water on, and drips from the main roof beams, the Models Laboratory was unaffected by the test.

Test No. 4. For this test the roof of the Models Laboratory was closed, leaving only the gap of 70 ft^2 around the edge of the sliding sections. Doors D and E were kept open until 21 min after injection, when they were both shut. 36 wick lamps were distributed throughout the Laboratory at heights of 5, 20 and 35 ft. There was also a crib fire on a weighbridge 9 ft above the ground and a hay bale on a platform 6 ft above the floor at P and S, Fig 1. A loose hay fire was built 2 ft above the floor at Q_2. The inert gas was injected for about 24 min. The atmosphere in the Models Laboratory became misty a few seconds after injecting the gas, but started clearing 2 min after injection, except in the path of the air entering from doors D and E. The speed of entry of air through these doors increased during the first minutes of injection and reached a steady value of about 10 ft/sec after 5 min injection. Some mist remained close to the floor, but after 5 min injection the full length of the Models Laboratory was visible above the 10 ft level, and looking from the door of the recorder room X the atmosphere at head level was translucent, with a visibility of at least 10 ft. The doors D and E were shut after $21\frac{1}{2}$ min injection. Then visibility at ground level increased very rapidly and the mist extending from the doors D and E disappeared.

The effect of the gas on the fires is shown in Fig 3; curve A shows the weight of the crib, curve B shows the rate of weight loss of the crib, and curve C the temperature of the hay bale against the time of injection of the inert gas. Curve B shows that there was a pronounced reduction in the rate of loss of weight between 3 and 5 minutes after injection of the gas, after which the loss of weight continued to decrease much more slowly. The rate of loss of weight at the end of the test was 1/6 th of the rate at the beginning of the test. The temperature records from the mast of 12 thermocouples and from the three thermocouples 5 ft from the wall of the Models Laboratory are shown in Figs 4 and 5. The temperature of the inert gas injected into the building is included in Fig 4. The temperature of the inert gas increased when first injected, and was then adjusted at the generator to give a steady temperature after 8 min injection. The atmosphere in the building 12 ft or more above the floor had a very small temperature gradient. Closing doors D and E at $21\frac{1}{2}$ min produced a substantial increase in the temperatures 3 ft to 9 ft above the floor, but a much smaller increase at higher levels. The temperature of the hay bale reduced slightly during the main part of the test, but showed a substantial reduction after the external doors were closed. Smoke from the fires at P and S, Fig 1, reduced quickly on injection of gas, and only traces were visible after 5 min injection. The hay bale

produced a column of smoke at first dense but which became very thin after 10 min injection of gas. The loose hay fire produced dense smoke for the first 6 min of injection, but the density reduced rapidly until 8 min after injection, after which only a thin column of smoke was visible. No smoke was visible from any of the fires shortly after doors D and E were closed. When injection of inert gas was stopped, all fires recovered quickly, the hay fires smouldering strongly and the crib fire increasing to full burning in less than 5 min.

Samples of the atmosphere in the Models Laboratory were collected at point K, Fig 1 from 35, 20 and 5 ft above the floor at 5, 10 and 15 min after injection of inert gas respectively. The composition of the samples is given in Table 1; the atmosphere was assumed to be saturated for the analysis, because mist was observed near the walls at the sampling point. The temperatures at the sampling points, Fig 5, were then used to determine the water vapour content of the samples.

TABLE 1

Composition of Atmosphere in Models Laboratory, Test 4

Gas sample	1	2	3
Height, ft.	35	20	5
Time after injection, min	5	10	15
Temperature, °C	61	65.5	44.5
Oxygen, per cent	14.7	15.2	16.0
Carbon dioxide, per cent	0.8	N.D.	0.4
Nitrogen, per cent	63.9	N.D.	74.3
Water vapour, per cent	20.6	25.2	9.3

N.D. = Not determined

Condensation of water on main roof beams was again the only effect of the test on the Models Laboratory.

Group 2. Tests with Minimum Ventilation

For this group of tests all openings to the Models Laboratory were closed. The ventilation therefore consisted of the peripheral gap around the sliding roof, and the leakage through the wall cladding. For the majority of the tests, the peripheral gap was 70 ft^2, but a few tests were made after the sliding roof had been partially sealed when the peripheral gap was 30 ft^2.

Tests with 70 ft^2 Roof Opening

The experimental apparatus which varied slightly from test to test included;

A mast supporting 12 diesel oil tray fires, 6 in dia. at increments of 3 ft above the floor, at N, Fig 1.

A wood crib fire as in Group 1 tests at P, Fig. 1.

A hay bale fire as in Group 1 tests at S, Fig 1.

A compressed air cylinder with remote indication of pressure and temperature at J, Fig 1.

A mast of 12 thermocouples in the centre of the Models Laboratory; three alternate couples in the top 6 were fitted as wet bulb thermocouples in some tests. Wall thermocouples and gas sampling points at K, Fig 1.

One test is reported in detail, the others gave similar results.

Test No. 8. The observations during this test were similar to those of test 4, Group 1. On injection of the gas into the Models Laboratory the atmosphere quickly became misty. Mist formed close to the point of entry of the inert gas and passed upwards and then along the Laboratory during the first minute. After 2-3 min the atmosphere cleared. In the first 3 min of injection flames from a scrap wood fire on the floor at Q_2, Fig 1,

were reduced, but then increased in size as the test proceeded. The flames were fairly large after 15 min of injection. The top 3 diesel oil fires on the mast were all extinguished within 4 min 15 sec, but the top fire was the last to go out. The next 4 fires were extinguished before 5 min 30 sec and all but the bottom fire were extinguished by 7 min 15 sec. The bottom fire was still burning at the end of the test. The crib fire at P was reduced to glowing combustion and a faint reddish flame about 6 in high in 9 min, and remained this until the end of the test. This behaviour was not typical and in all other tests in this group the crib fire was reduced to smouldering combustion only. The variation of rate of burning with time is shown in Fig 6. Temperatures measured during the test from the wall and mast thermocouples are shown in Figs 7 and 8 respectively. Fig 7 includes also the temperature of the injected gas stream. The rise in temperature and pressure of a compressed air bottle placed 2 ft from the wall of the Models Laboratory and 3 ft above the floor are shown in Fig 9.

Gas samples were collected at point J from time to time during the test and single samples of gas were collected 15 min after injection from the sampling points at K, Fig 1. The moisture content of the samples was taken as the saturation moisture content at the temperature of the sample for the same reasons as for Group 1 tests. The variation of composition with time is shown in Fig 10, and the composition of the three 15 min samples is given in Table 2 below.

TABLE 2

Composition of atmosphere in Models Laboratory, Test 8

Gas sample	1	2	3
Height, ft.	35	20	5
Time after injection min	15	15	15
Oxygen, per cent	14.7	14.0	14.9
Carbon dioxide, per cent	1.2	0.7	1.4
Nitrogen, per cent	64.5	55.5	66.6
Water vapour, per cent	19.6	28.8	17.1

The composition of the atmosphere, Fig 10, became substantially constant after 8 min injection, and all fires were under control or extinguished by this time. The wall temperature, which was higher at 20 ft than at 35 ft above the floor, and the composition of the atmosphere at these sampling points, indicated a greater dilution with air at 35 ft than at 20 ft. This effect was noted for all tests in this group.

The moisture content at 27 and 21 ft above the floor in the middle of the laboratory, calculated from the wet and dry bulb thermocouples is given in Fig 11. The moisture content of the atmosphere calculated from the measured temperature of the atmosphere in the building with reference to the temperatures of the injected inert gas and the initial temperature of the atmosphere in the laboratory is included for comparison.

Tests with 30 ft^2 roof opening

A few tests were made after additional sealing had been fitted to the sliding roof of the Models Laboratory, which reduced the minimum opening due to leaks around the edge of the roof to 30 ft^2.

The fires used in these tests were 3 ft tray fires of diesel oil at 8, 10 and 16 ft above the floor, a standard wood fire 12 ft above the floor, and a 6 ft tray fire of paraffin primed with petrol on the floor. The last fire was used to fill the Models Laboratory with smoke and the quantity of fuel used was sufficient to burn only until the inert gas was injected. The other fires were lit a sufficient time beforehand to ensure that they were fully developed when the inert gas was introduced. The gas when first introduced was highly inerting, containing about 7 per cent oxygen; it was delivered at 45000 ft^3/min at 100° - 110°C for about 15 min. Then the composition of the gas was changed, by stopping the reheat, to a gas containing 16 per cent oxygen at about 60° - 70°C; this gas was delivered at about 25000 ft^3 min. During this last stage the Models Laboratory was entered to observe the state of the fires.

In these tests the Models Laboratory became smoke-logged about 5 min after lighting the paraffin tray fire on the floor, except for 3 - 5 ft at floor level where the smoke was thin. However, on injecting the inert gas the whole of the building became smoke-logged in a few seconds. Observers outside the building saw smoke seeping from the joints between the asbestos cladding and along the edge of the roof at the start of the test, the smoke being replaced by steam opposite the point of injection shortly after the start of injection of the inert gas. As the tests proceeded the steam replaced more and more of the smoke until only steam was seen emerging after about 10 min injection. Visibility inside the Models Laboratory improved after this time and at 12 to 14 min after injection, the atmosphere within the building was such that windows could be seen 80 ft from the Recorder room door, and obstacles and structures in the building could be identified. When the gas was changed at 15 min all fires appeared to be out. The atmosphere quickly became misty, but the mist largely cleared after about 5 min injection of the cooler gas. All the diesel oil fires were then seen to be out. In two out of three tests the wood crib fire slowly recovered, during the injection of the 16 per cent oxygen gas; the carbonised wood at first glowed and this was followed by the production of small flames, which then increased in size until they were about 3 ft long. In the third test the carbonised wood showed no flames during the 15 min injection of the cool 16 per cent oxygen gas, but when injection was stopped and the building was ventilated by opening doors and the sliding roof, the glowing combustion increased to full flaming combustion in about 5 min.

The temperatures recorded at 3, 6, 12, 24 and 36 ft from the mast of 12 thermocouples for one of these tests is given in Fig 12. A large temperature gradient was produced by the hot light combustion gases during the preburn period. The injection of the hot highly inert gas resulted in the mixing of the atmosphere in the building, and after about 13 min injection equilibrium was again established with a much reduced gradient of temperature, the minimum temperature at 3 ft above the floor then being from 76 - 78°C. The injection of less inert gas, produced by turning off the reheat at the turbo-jet engine reduced the temperature gradient further, the minimum temperature at 3 ft falling to about 70°C in 2 min. The temperature close to the ground reduced further as the time of injection of the less inert gas increased. After about 10 min injection of the less inert gas the temperature at the 5 - 6 ft level was about 60°C, and although the atmosphere in the Models Laboratory felt very warm, personnel found that they could walk through the building in normal clothing and without breathing apparatus. The degree of comfort was higher when full fire service uniform and great-coat was worn.

Group 3. Tests of the performance of work in inert gas atmospheres

A series of tests were made to assess the capacity for work in the atmosphere created in the Models Laboratory by the injection of hot inert gas at 100°C or more, with a roof opening of 70 ft^2. By arrangement with the Chief Officer of the Hertfordshire Fire Brigade Officers and B.A. teams from the Brigade took part in these tests.

Exploratory Test. Inert gas at 100°C containing 7 per cent oxygen was injected into the Models Laboratory, to examine the feasibility of firemen, wearing normal service clothing and breathing apparatus, entering and working in the atmosphere created. Brigade officers wearing compressed air breathing sets with normal uniform clothing entered the building through the door H, Fig 1, a few minutes after the injection of the inert gas at 45000 ft^3 min, and stayed in the atmosphere for 17 to 20 min. The temperatures registered by the thermocouples are given in Fig 13; the thermocouples in the middle of the Models Laboratory failed after the first 5 min of test.

Comments of the officers on their experience are summarised below:

I. The time spent in the atmosphere was approaching the limit of endurance. (Temperature at head level about 60°C).

II. Exposed skin was affected by the heat. The covering of the skin by the wearing of full face mask breathing apparatus and ear-muffs or scarves, gloves and leggings made the atmosphere bearable.

III. The air from the compressed air breathing sets became hotter as time in the atmosphere increased, and added to the discomfort.

The structure of the Models Laboratory, and the electrical and other equipment in it, were examined after each test. Apart from the dripping of condensed water from the main roof beams, and a light condensation of water on the walls, no other harmful effect was observed. All electrical equipment and wiring continued to function correctly, although the wiring system and switchgear were not specially protected against moisture and condensation.

Tests of entry and performance of tasks by firemen. Some tasks were devised to assess the performance of firemen at an incident in which hot inert gas is used. A series of fires were placed in the Models Laboratory at different levels. Five diesel oil fires two of 6 in dia. two of 1 ft dia. and one of 2 ft dia. were placed 3 ft apart on a platform 7 ft high in the middle of the building. A wick lamp and an evacuated gas sampling bottle were placed alongside each fire. One 3 ft dia. tray fire of diesel oil was placed on the floor and another 2 ft above the floor. Crib fires of 4 in square timber were placed 10 ft and 3 ft above the floor; a scrap wood fire was placed on the floor and a fire of an 8 ft high, 4 ft wide and 1 in thick panel of fibre board was placed 12 ft above the floor. Five sacks of gravel weighing 12 stone each were placed at different locations in the building to simulate unconscious people to be rescued. The general layout of the fires in the Models Laboratory is shown in Plate 3.

The breathing apparatus teams from the Hertfordshire Fire Brigade were asked to perform the following tasks:

1. To enter the laboratory and to operate the cocks of the gas sampling bottle so as to collect samples of the atmosphere, when the associated tray fire went out.

2. To enter the laboratory 10 min after injection of the inert gas and to extinguish (a) the floor level fires and (b) the wood crib fires and (c) the fibre board panel fire.

3. To enter the laboratory and find and remove the 12 stone sacks, representing the rescue of persons.

Two tests were performed; the temperature record of the first test, is given in Fig 14 and the times of extinction of the fire are indicated in the Figure. The temperature record of the second test is given in Fig 15; in this test the gas samples at regular intervals were taken by Fire Research Station personnel. The composition of the gas was determined in the latter test only, because the tray fires, except the 2 ft diameter fire, had gone out when firemen entered during the first test, and doubt existed as to the validity of the samples.

The firemen completed the set tasks in from 5 to 12 min after entry. The high level wood and fibre board fires were extinguished by breaking them down and applying water from hand lines. The 3 ft dia. diesel oil fires were extinguished with portable foam extinguishers. The five oil fires at the 7 ft level were observed and went out as follows: the wick lamps went out 4 to 5 min after gas injection, the 6 and 12 in dia. fires went out 6 to 7 min after gas injection and the 2 ft fire went out 14 min after gas injection. The composition of the gas from the second of the two tests is given in Table 3.

TABLE 3

Composition of atmosphere 7 ft above floor in Models Laboratory

Gas Sample	1	2	3	4
Time, min	5	10	15	20
Temp. °C	65	65	64	53
Oxygen, per cent volume	12.5	13.1	13.5	15.0
Carbon dioxide, per cent volume	2.1	2.3	1.3	1.9
Nitrogen, per cent volume	61.4	59.6	62.2	69.1
Water vapour, per cent volume	24.0	25.0	23.0	14.0

Note: Carbon monoxide was detected in small quantity. The marked change in composition of the final sample was due to the introduction of air into the Models Laboratory through door H, Fig 1 which was of necessity open for the entry of firemen and the removal of the 12 stone sacks.

The removal of the 12 stone sacks was accomplished quickly for 4 of the sacks, but the fifth sack was placed where it could not readily be seen. The firemen, on being informed of the presence of the fifth sack but not its location, re-entered and removed it in a further minute or so. The total time taken for the task was about 6 or 7 minutes.

The extinction of the fires above the floor required some of the firemen to ascend ladders. The firemen experienced increasing discomfort as they ascended. The sensations of the firemen at different levels in the Models Laboratory are given below:

1. No appreciable discomfort was felt at floor level when the atmosphere was entered for a short time only. The temperature felt warmer close to the walls of the building than in the main body of the building, but in the second test there were some areas where the temperature was too hot to remain. Relief was obtained by moving away from these areas. (Temperatures at 5 - 6 ft level, first test 60 - 65°C, Fig 14, second test 70 - 75°C, Fig 15.)

2. Temperatures at normal hand level were tolerable during the first test. During the second test gloves were found to afford greater comfort. (Temperatures at 3 - 4 ft level, first test 50 - 55°C, second test 60 - 65°C).

3. Hands extended above the head felt very hot in the first test, but the condition could be borne for 2 - 3 min. (Temperature at 8 - 9 ft level 68 - 73°C). During the second test hands could be kept in this position for a few seconds only unless they were protected with gloves. (Temperature at 8 - 9 ft 78 - 82°C).

4. On ascending ladders to a head height 10 - 12 ft above the floor the temperature on exposed skin during the first test was just tolerable. (Temperature at 10 - 12 ft 78 - 83°C). During the second test, exposed skin at this height felt scalded and the condition could be tolerated for a second or so only (Temperature at 10 - 12 ft 85 - 93°C).

5. On ascending ladders to 15 ft above the floor exposed skin was scalded in a few seconds during the first test. (Temperature at 15 ft above floor 80 - 85°C). During the second test the scalding sensation was intense and could be borne for very short periods of time only (Temperature at 15 ft 92 - 97°C).

The firemen experienced no major difficulties in finding their way about in the Models Laboratory. Although the atmosphere in the building was somewhat misty, they were able to see objects 30 to 40 ft away. (Plate 5). They found that their comfort in the hot atmosphere was greatly increased, even when working above floor level, by applying water spray from their hand lines on to their bodies and exposed skin. By so doing, the atmosphere 8 - 9 ft above the floor was tolerable for at least 4 min, the duration of their exposure at this height.

DISCUSSION

The tests reported here have indicated the conditions under which the injection of inert gas from the J.F.R.O. inert gas and foam generator can control and extinguish fires in the Models Laboratory and similarly dimensioned buildings.

When there is a high degree of ventilation at high and low levels, and inert gas containing 7 per cent oxygen is injected at 45000 ft^3/min, the losses of inert gas are too high for the oxygen content of the atmosphere to be reduced to the level, about 14 per cent, needed for the extinction of flames. Roof or high level ventilation of 200 ft^2 can be tolerated with this condition of injection, and all fires except those close to the ground should be extinguished or reduced to smouldering, provided that the floor level ventilation is not great; test 3 in the exploratory series suggests that a 70 ft^2 opening to the 6 ft 6 in level does not have much effect on the extinction of a fire 9 ft above the floor. However, subsequent tests indicated that a further reduction in low level ventilation resulted in a more inert atmosphere being produced. Thus to achieve the maximum efficiency in the usage of inert gas, it is desirable to operate with restricted high level ventilation and as little ventilation near the floor as possible, bearing in mind that in a building of the capacity and height of the Models Laboratory, the presence of roof leaks or high level ventilation of up to 200 ft^2 should still allow extinction of fires to take place.

The conditions of injection of inert gas in these tests would be expected to give turbulent mixing of the injected gas and the atmosphere existing in the Models Laboratory, since the modified Richardson Number, N_1 is 0.002 (see appendix). The temperature distribution in the Models Laboratory for the tests showed a gradient from the floor level upwards, with the rate of increase of temperature decreasing as the distance from the floor increased. The temperature range of the gradient also reduced as the ventilation areas were reduced. The gradient was due to the entry of air at low velocity, (Values of $N_1 \ll 1$) through the openings and the distributed gaps between the cladding of the Models Laboratory. This aspect of the replacement of atmospheres in buildings is discussed more fully elsewhere(4).

A reduction in overall ventilation substantially raised the temperatures in the lower parts of the Models Laboratory. Thus, although firemen were able to enter the Models Laboratory and work in reasonable comfort while on the floor in the tests with the 70 ft^2 roof opening and the distributed wall leakage, they would not have been able to do this if the roof ventilation were reduced or if the distributed leaks in the walls were not present to produce stratification of the atmosphere. It is therefore desirable to introduce inert gas at a lower initial temperature than the 100° - 120°C used in the present tests.

The normal issue of fire service uniforms gave sufficient body protection to permit firemen to work for about 15 min in humid atmospheres at about 60°C, with short spells at higher temperatures. However exposed skin at the face, neck and hands required protection; the face mask of the compressed air breathing apparatus, scarves and gloves appeared to give adequate protection. The extra comfort that firemen obtained by spraying themselves with water could have an appreciable effect on the time firemen could spend in hot atmospheres.

The firemen commented on the discomfort felt on breathing the heated air from their compressed air breathing sets. The normal use of compressed air would cancel any increase in pressure produced by the rising temperature of the cylinder, the increase in temperature however could produce discomfort, the final temperature of the cylinder being well above body temperature. It is considered unlikely that the alternative oxygen breathing apparatus at present in use in the Fire Brigades would give greater comfort. The carbon dioxide absorption bag used with oxygen sets presents a large surface and would heat gases rapidly, and the cooling device often used with such apparatus loses efficiency at high temperatures. However, liquid air or oxygen breathing apparatus should prove more suitable for use in hot atmospheres than the above two types of breathing apparatus, because oxygen or air could be supplied at low temperatures.

The tests have shown that little damage to buildings should result from the introduction of the hot, humidified gas, this damage being restricted to water condensation on massive pillars, beams etc. Electrical supply systems in the Models Laboratory at the normal voltage (440 v), in standard conduit and trunking and using standard switch gear did not appear to be affected. The wider application however to buildings in which there are high voltage electrical systems might lead to a break-down of electrical insulation.

Deviations were observed between direct measurements, and calculated values, of carbon dioxide in the atmospheres, the directly measured value being the lower. As there were no marked deviations for the other gases in the atmospheres, it is likely that carbon dioxide was lost either in the sampling line or in the building. The relative humidity measured by the wet and dry bulb thermocouples was consistently lower than the calculated value; this deviation was probably due to the inefficiency of the wet bulb system.

CONCLUSIONS

Inert gas produced by a turbo-jet engine can rapidly extinguish flames and reduce solid fuel fires to smouldering. Using the J.F.R.O. experimental gas generator in a barn-like building of 250000 ft^3 volume, these effects would be produced in 8 - 10 min when inert gas containing 7 per cent oxygen is introduced at 45000 ft^3/min. The presence of distributed leaks, such as leaks at the joints of light cladding, can result in the continued burning of fires on the ground in such a building. The efficiency of extinction and control of fires is greatest when ventilation is at the top only of such a building; with injection of inert gas at the above rate, 200 ft^2 of high level ventilation can be tolerated without serious reduction in the efficiency of extinction and control of fires.

The entry of firemen into the atmosphere produced by the injection of the inert gas would be facilitated by a reduction in temperature of the atmosphere to 60°C or less. A prototype appliance at present being constructed incorporating devices for the production of inert gas at such temperatures, should allow firemen to enter premises into which the gas is injected to mop up residual smouldering gases.

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 foam."

(2) D. J. RASBASH, G.W.V. STARK, G.H.J. ELKINS and B. LANGFORD. F.R. Note No. 527. "Control of Fires in Large Spaces with Inert Gas and Foam Produced by a Turbo-jet Engine. Part 6. Trials in collaboration with the London Fire Brigade at disused basement premises."

(3) G.W.V. STARK and J. F. CARD. F.R. Note No. 550. "Control of Fires in Large Spaces with Inert Gas and Foam Produced by a Turbo-jet Engine. Part 9. The distribution of gas and control of fires in a multi-storey building."

(4) D. J. RASBASH, G.W.V. STARK, G.H.J. ELKINS. "A Model Study of the Filling of Compartments with Inert Gas." 2nd International Fire Protection Seminar, Vereinigung zur Forderung des Deutschen Brandschutzes, held at Karlsruhe, 30th September, 1964 - 2nd October, 1964.

APPENDIX

Factors describing the mode of distribution of gas injected into a compartment

The mode of distribution of gas injected into a compartment may be ascertained from the value of a modified Richardson's Number, N_1, given by

$$N_1 = \frac{gL}{V^2} \frac{\rho_o - \rho_1}{\rho_1}$$

where
- g = gravitational constant
- L = characteristic length (diameter of entry duct)
- V = entrance velocity of injected gas into compartment
- ρ_1 = density of injected gas
- ρ_o = density of initial atmosphere in consistent units

If N_1 is larger than 2, the mode of distribution of gas is by stratified flow, i.e., the flow of gas that allows it to form a discrete layer, the growth of which displaces the initial atmosphere.

If N_1 is substantially less than 1, the mode of distribution is by turbulent mixing; i.e. the injected gas is intimately mixed with the initial atmosphere, and the concentration C of injected gas at time t after the start of injection at a rate r is given by

$$C = 1 - e^{-\frac{rt}{Q}}$$

where Q is the volume of the compartment.

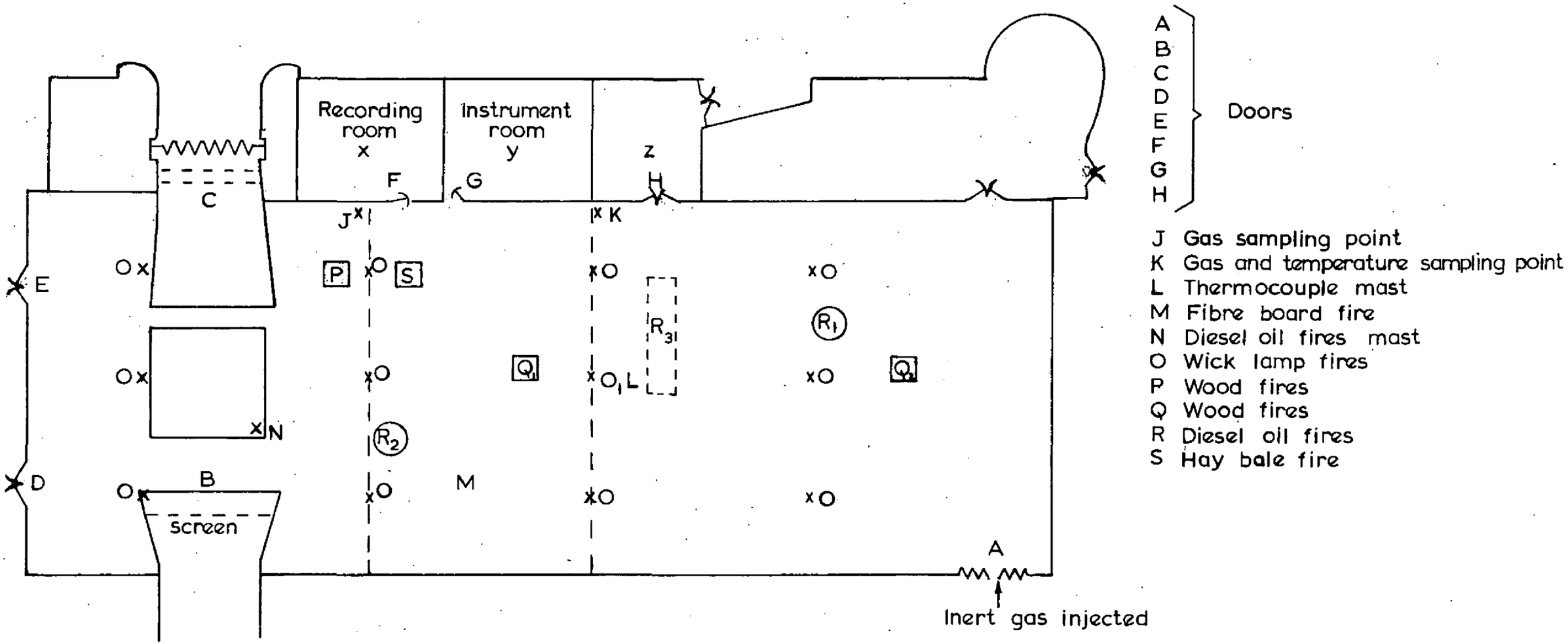


FIG.1. PLAN OF MODELS LABORATORY – FIRE RESEARCH STATION

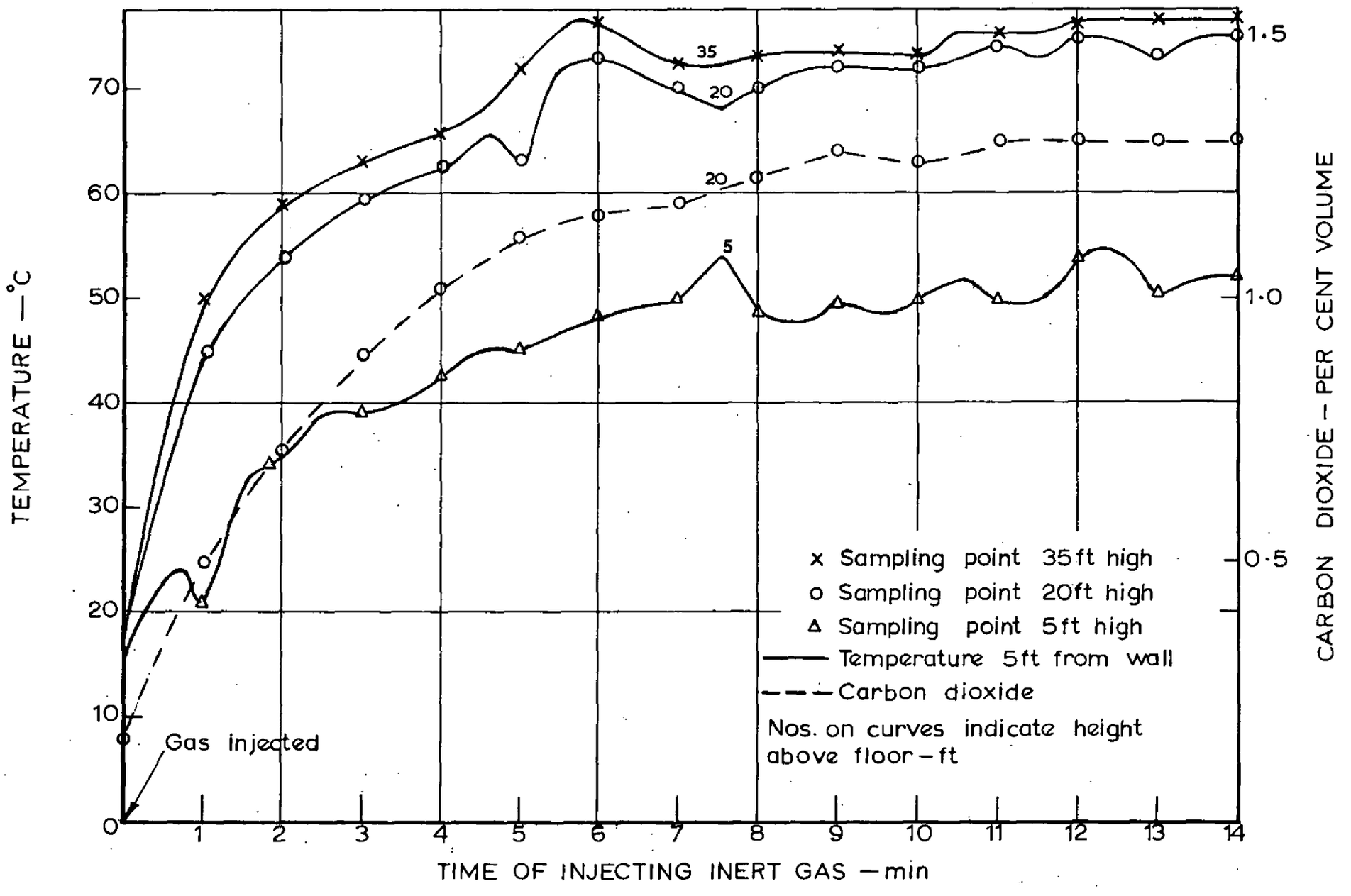
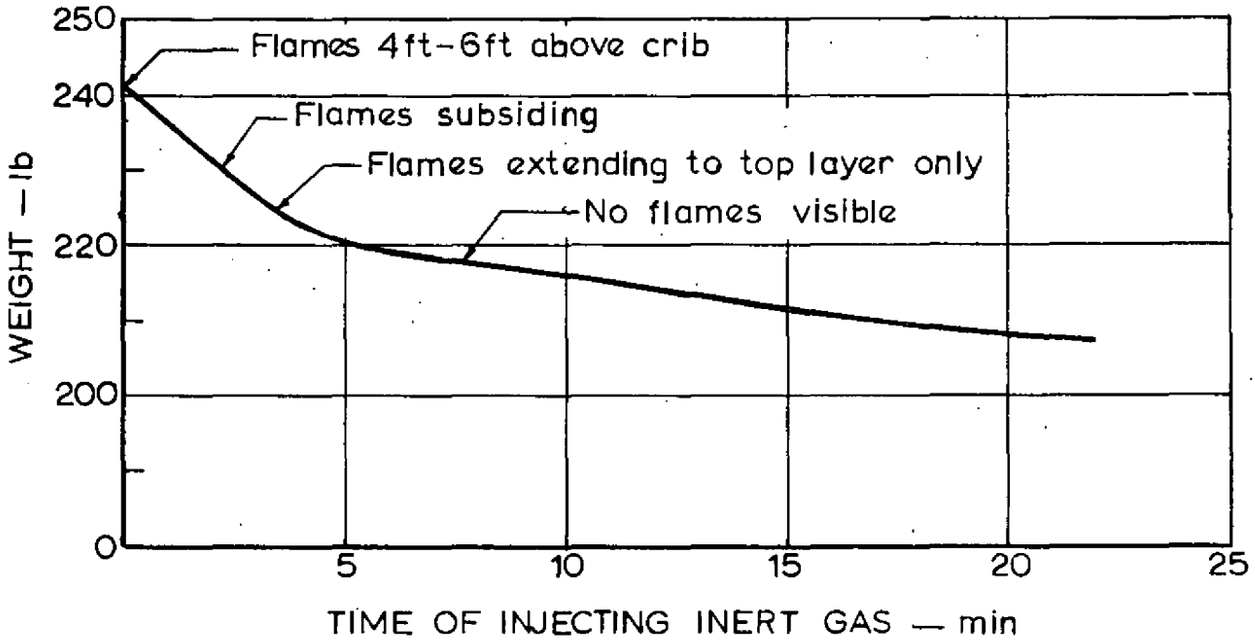
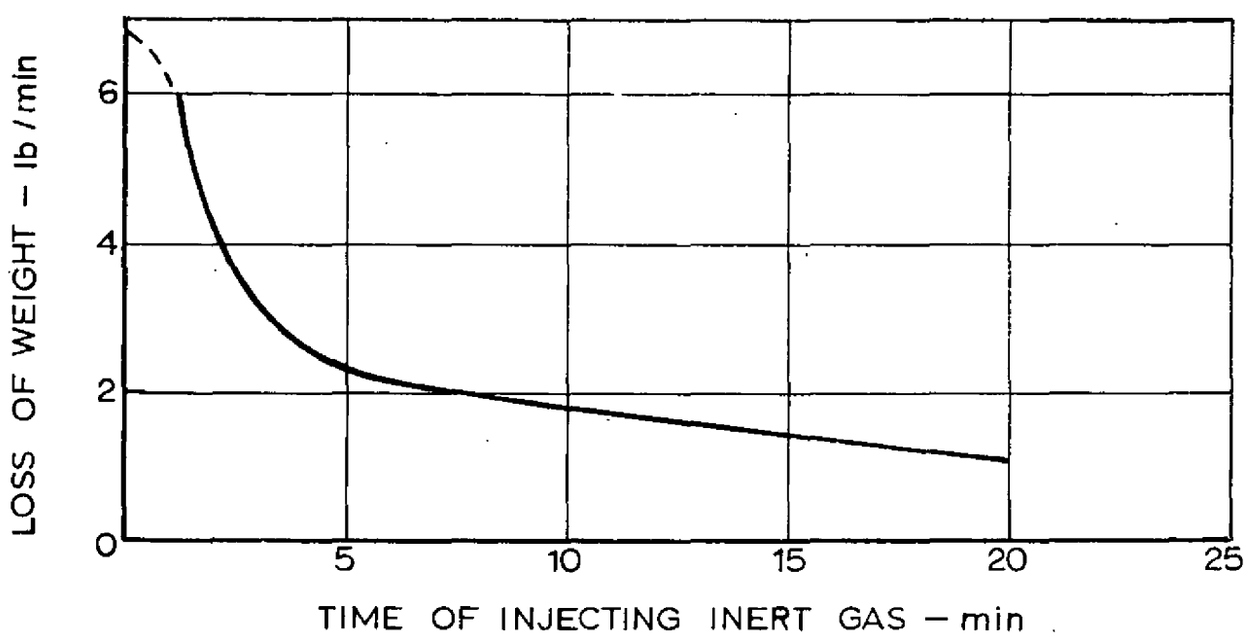


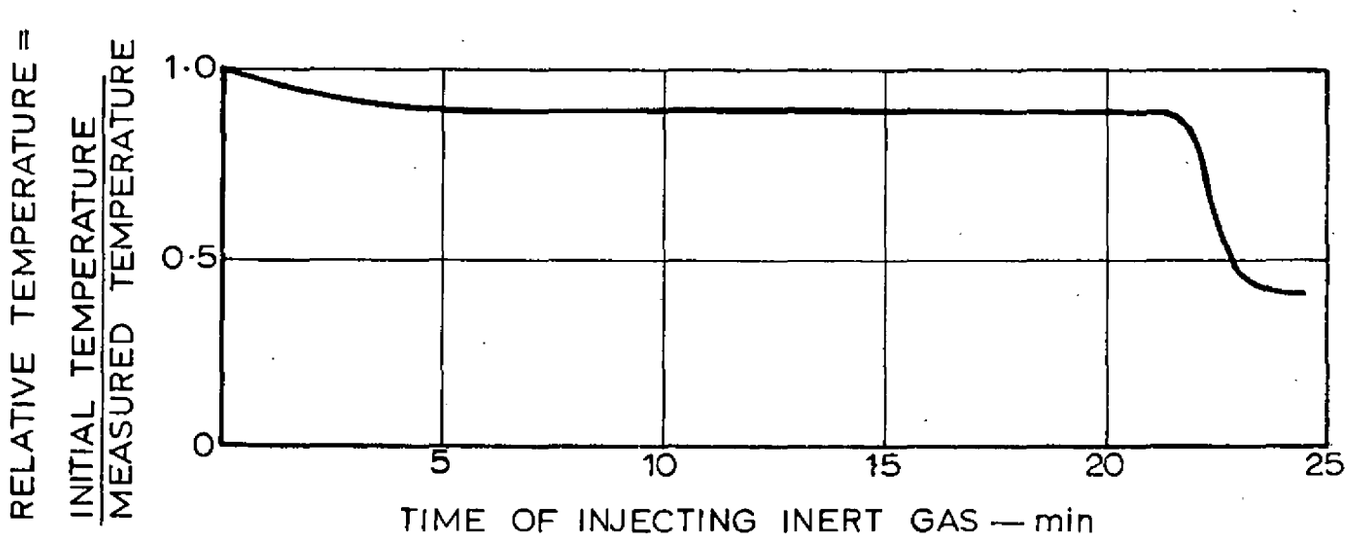
FIG.2. EFFECT OF INJECTION OF FULL REHEAT GAS ON TEMPERATURE AND CARBON DIOXIDE CONCENTRATION — TEST No.3.



A – LOSS IN WEIGHT OF WOOD CRIB

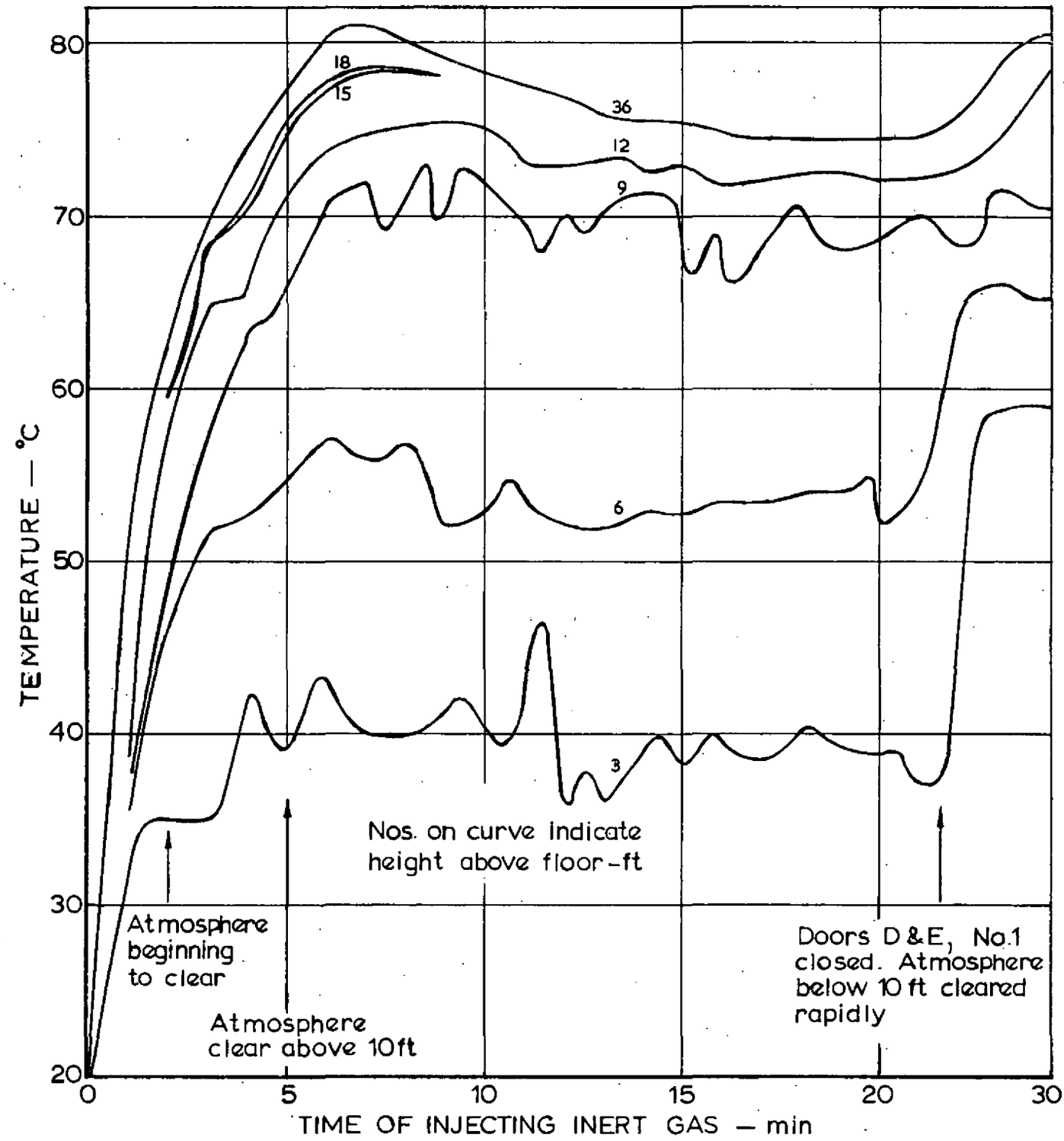


B – RATE OF BURNING OF WOOD CRIB

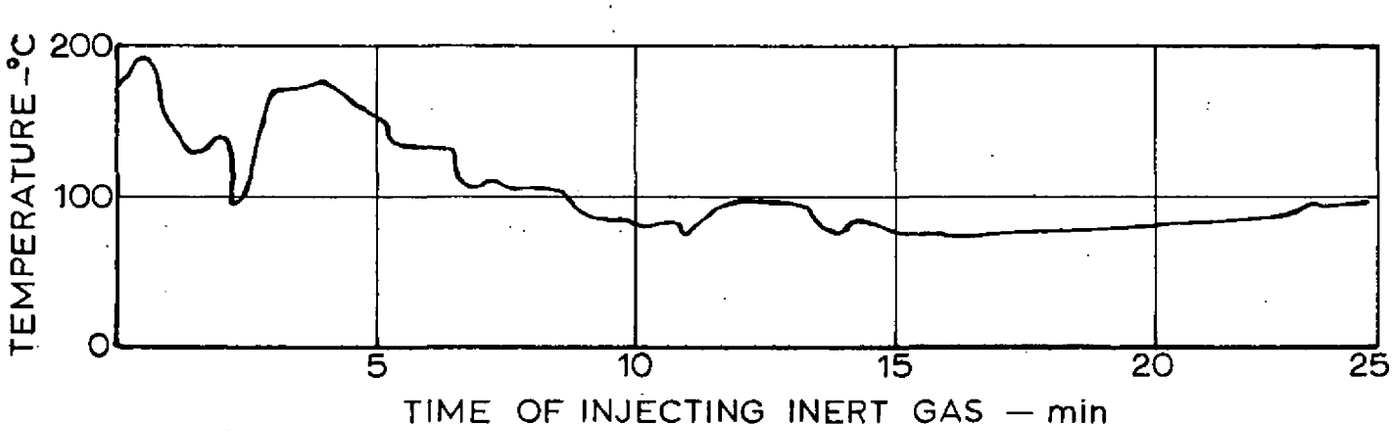


C – RELATIVE TEMPERATURE OF HAY BALE

FIG.3. THE EFFECT OF INERT GAS ON FIRES – TEST 4
70 ft^2 ROOF VENTILATION – APPROXIMATELY 70 ft^2
WALL VENTILATION



(A) TEMPERATURE FROM MAST THERMOCOUPLES IN CENTRE OF LABORATORY



(B) TEMPERATURE OF INJECTED INERT GAS

FIG.4. TEMPERATURE MEASUREMENTS
TEST 4 — 70 ft^2 ROOF VENTILATION
APPROXIMATELY 70 ft^2 FLOOR LEVEL

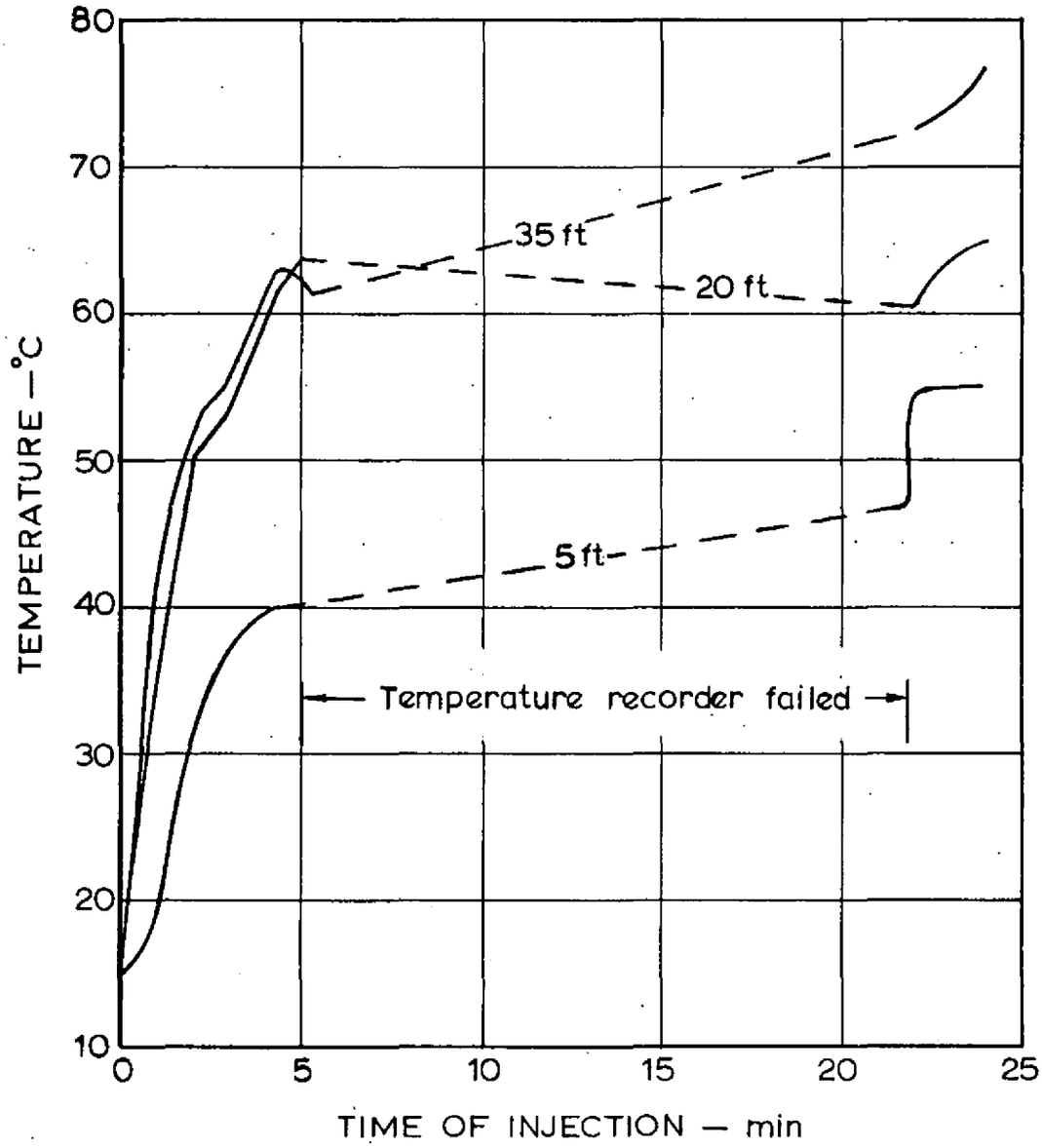


FIG. 5. TEMPERATURE AT WALL OF MODELS LABORATORY TEST 4 — 70 ft^2 ROOF VENTILATION — 70 ft^2 FLOOR LEVEL VENTILATION

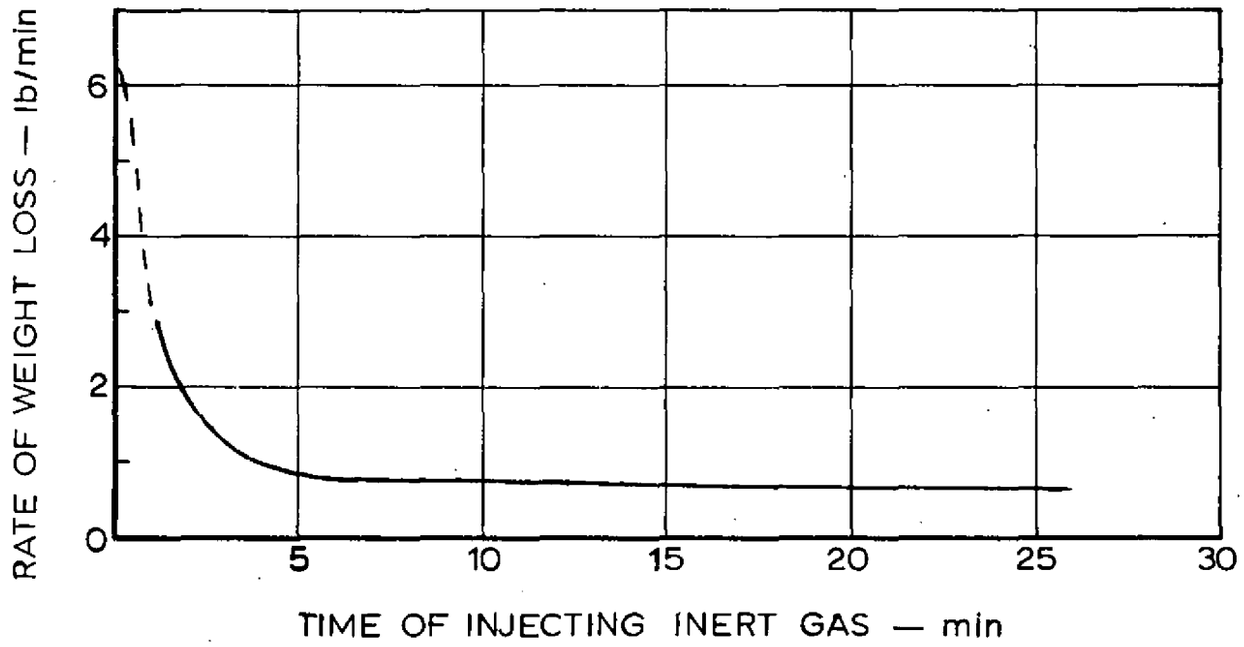


FIG.6. RATE OF LOSS OF WEIGHT OF CRIB FIRE – TEST 8

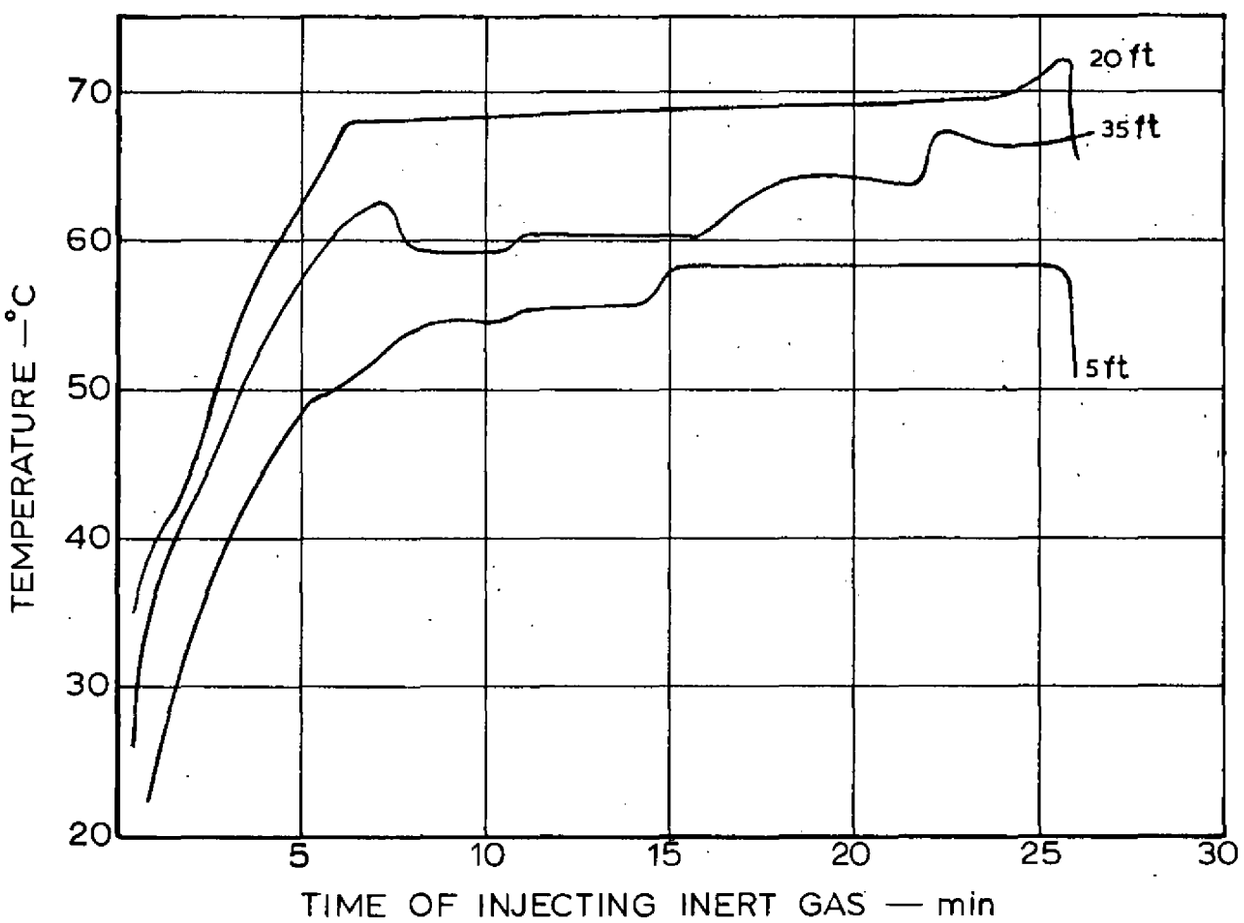


FIG.7A. TEMPERATURE AT WALL OF MODELS LABORATORY TEST 8

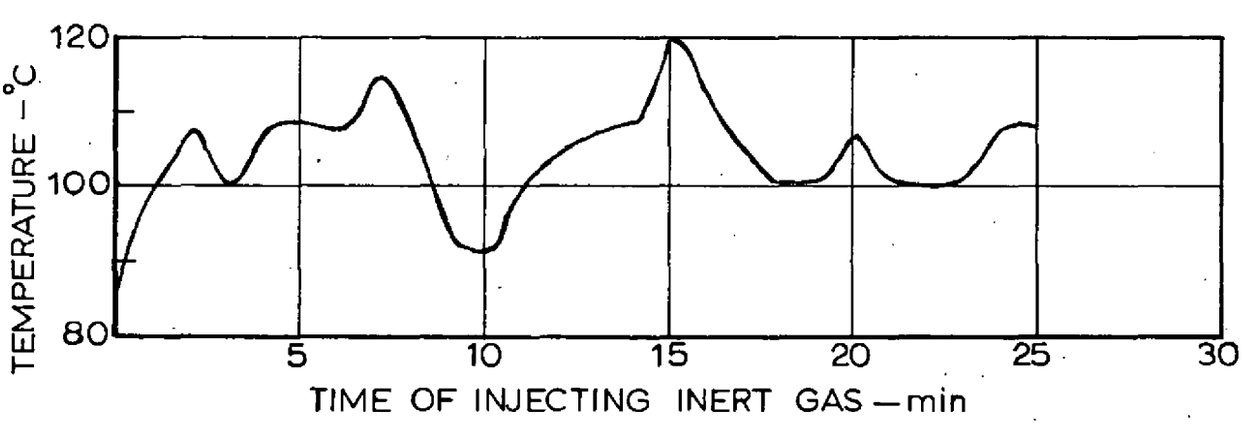


FIG.7B. TEMPERATURE OF INJECTED INERT GAS—TEST 8
70ft ROOF VENTILATION—ALL DOORS CLOSED

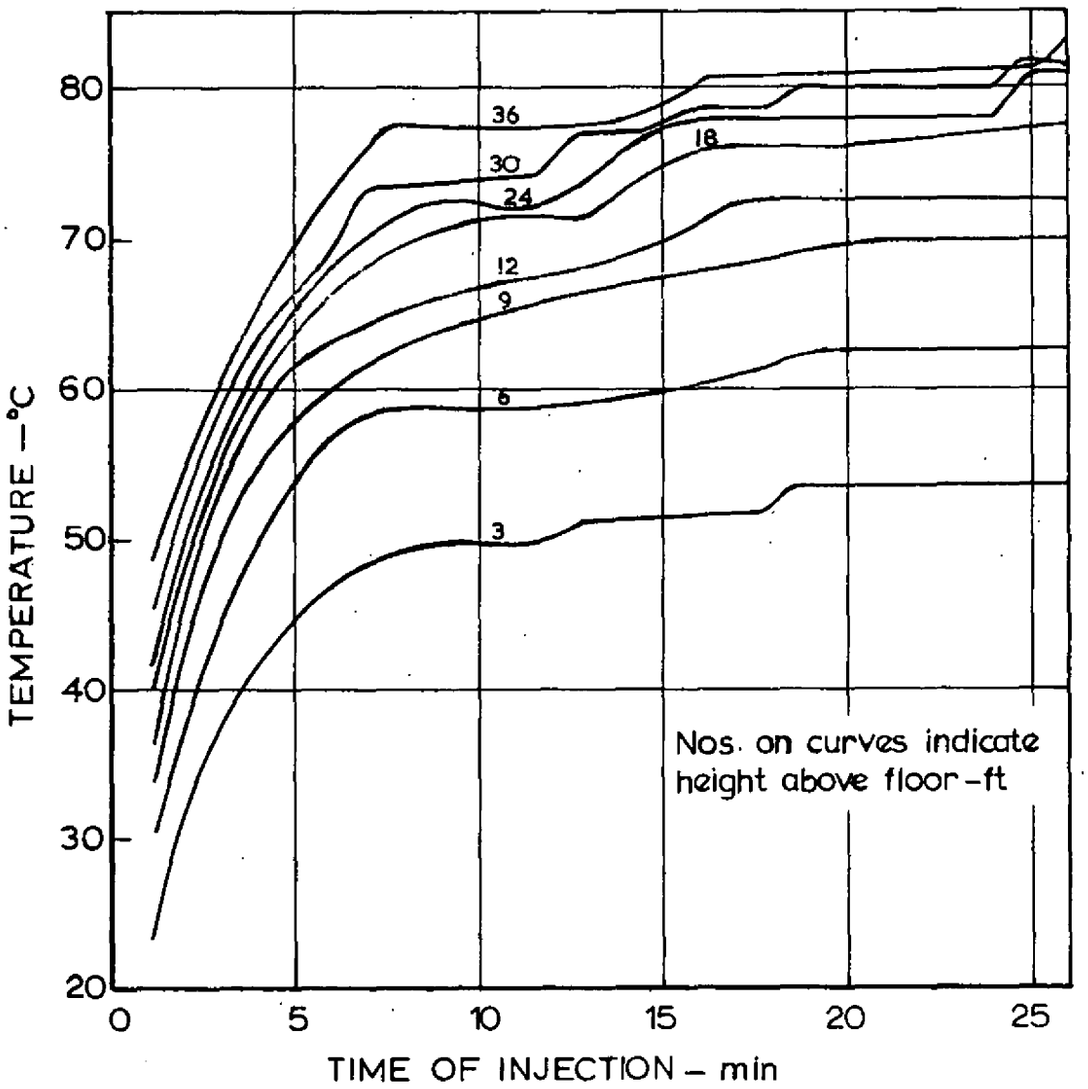


FIG.8. TEMPERATURE IN MIDDLE OF MODELS LABORATORY TEST 8 — 70ft ROOF VENTILATION — ALL DOORS CLOSED

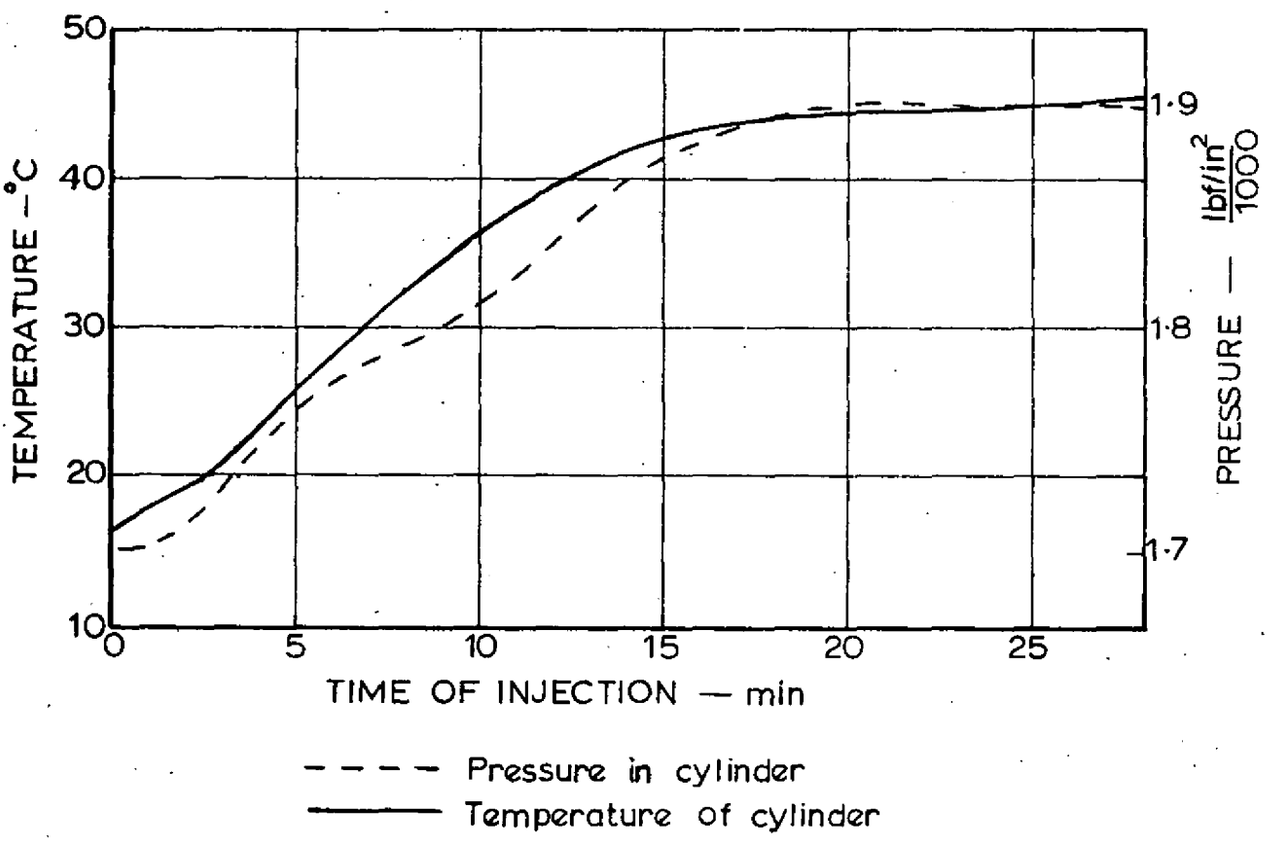


FIG.9. EFFECT OF EXPOSURE TO INERT GAS ON A COMPRESSED AIR CYLINDER

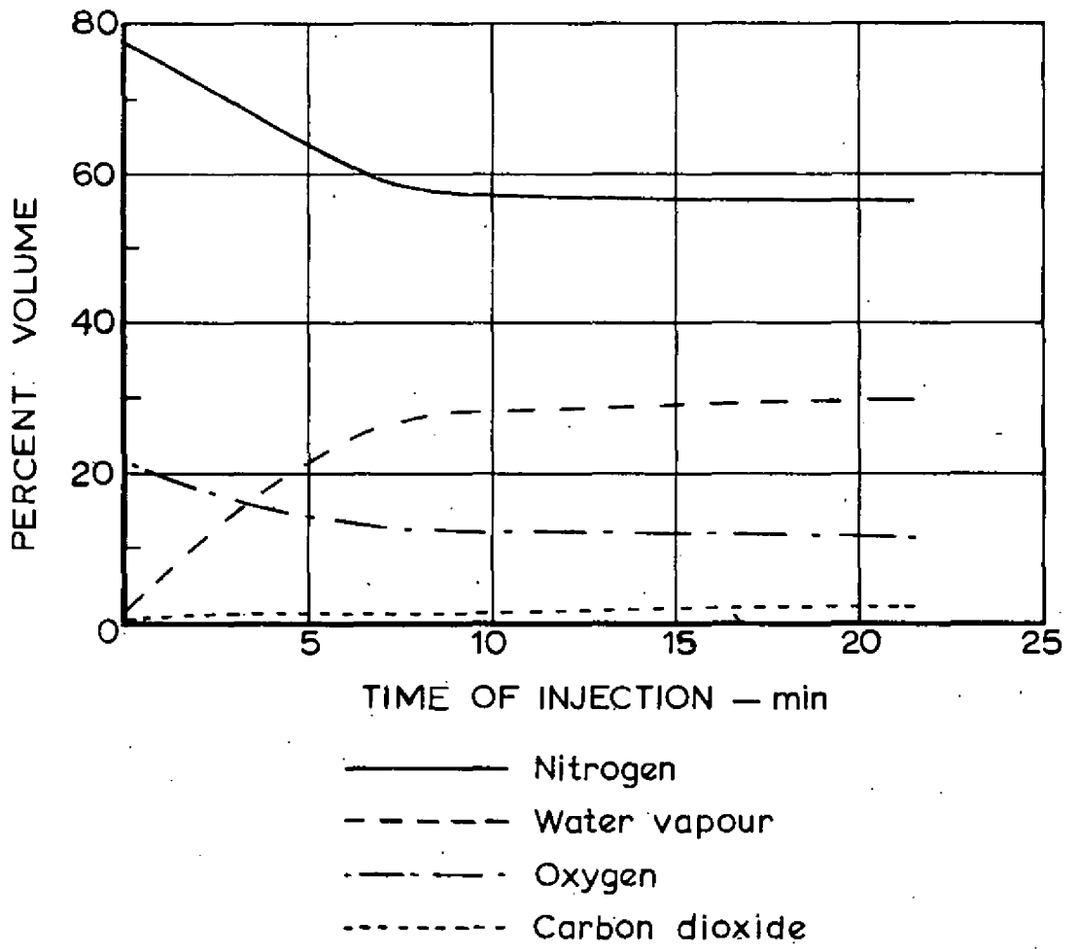


FIG.10. COMPOSITION OF ATMOSPHERE IN MODELS LABORATORY TEST 8, 70ft^2 ROOF VENTILATION, ALL DOORS CLOSED

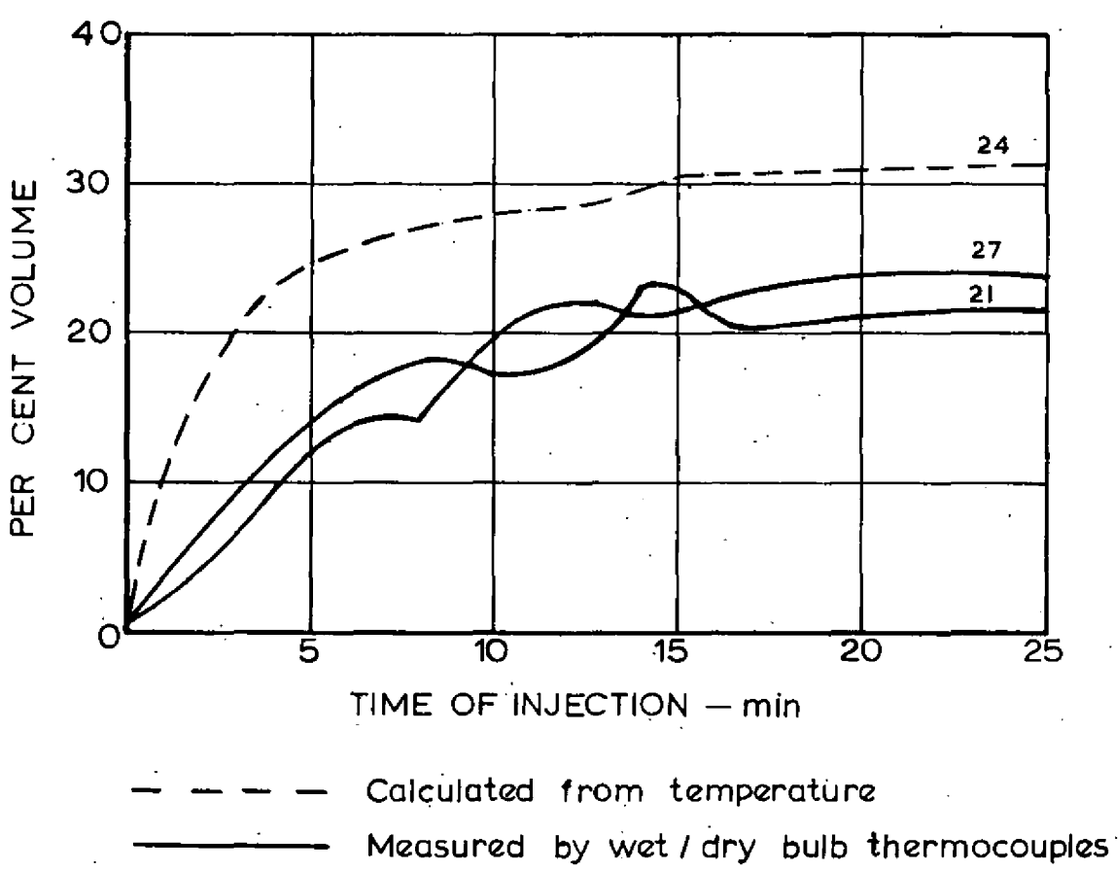


FIG.11. MOISTURE CONTENT OF ATMOSPHERE IN MODELS LABORATORY — TEST 8, -70 ft ROOF VENTILATION ALL DOORS CLOSED

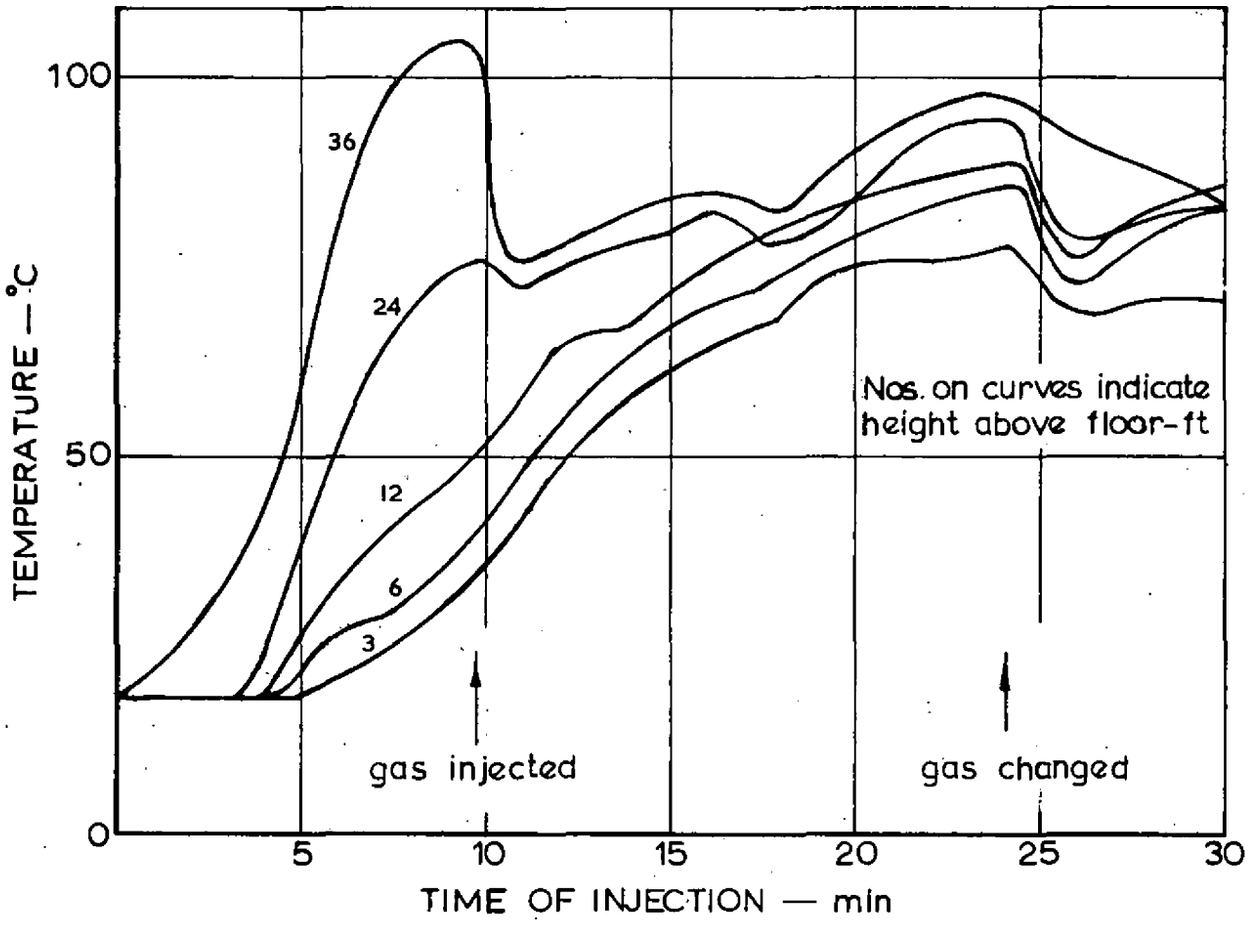


FIG.12. TEMPERATURE IN MODELS LABORATORY TEST 21-30 ft^2 ROOF VENTILATION PREBURN OF DISTRIBUTED OIL AND WOOD FIRES

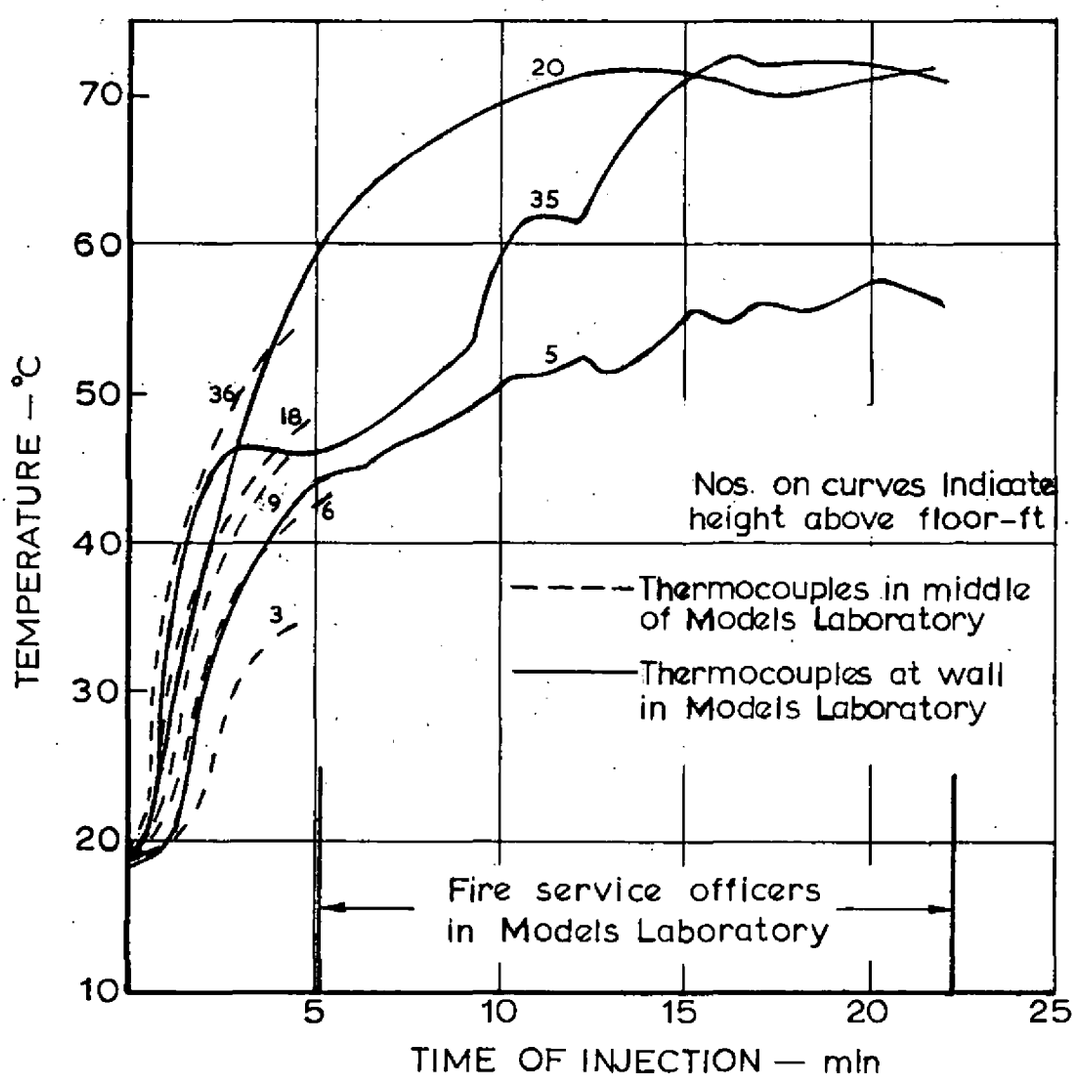


FIG.13. TEMPERATURE IN MODELS LABORATORY TEST 12 — ENTRY OF FIREMEN — 70 ft^2 ROOF VENTILATION

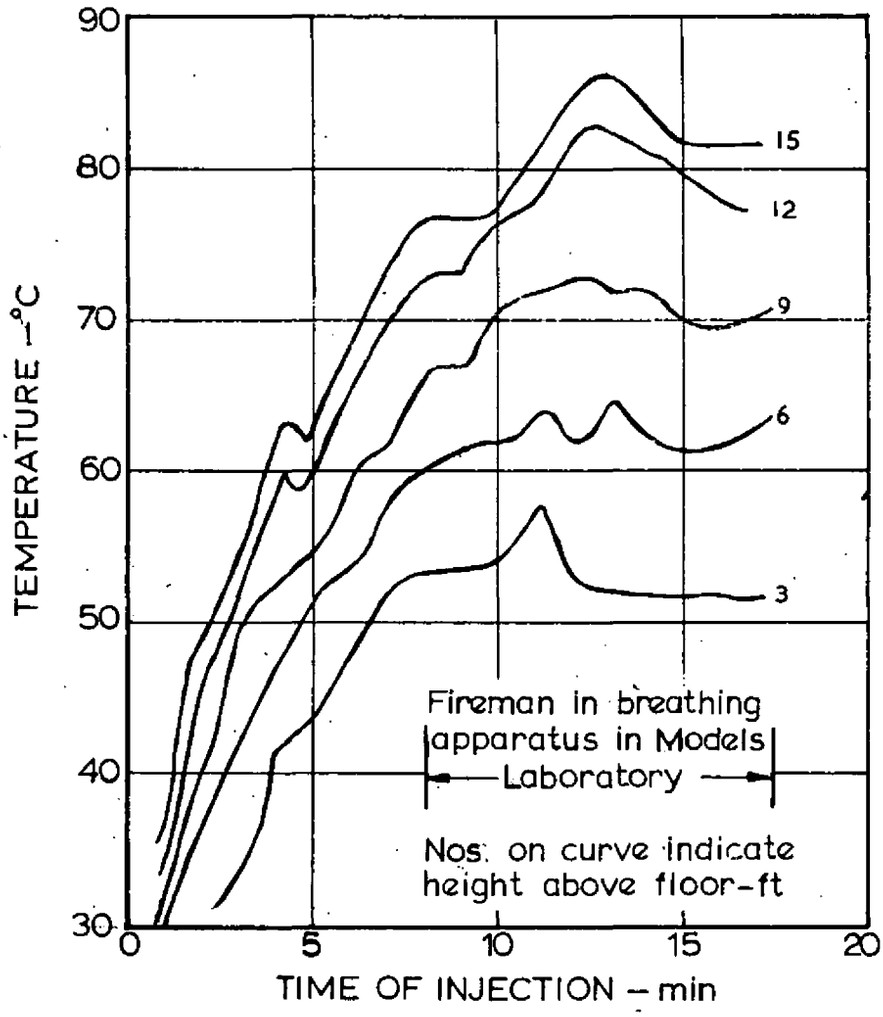


FIG.14. TEMPERATURE IN MODELS LABORATORY – TEST 13
PERFORMANCE OF TASKS BY FIREMEN – 70 ft^2
ROOF VENTILATION – 30 ft^2 GROUND VENTILATION
AT TIMES OF ENTRY OR EXIT OF FIREMEN

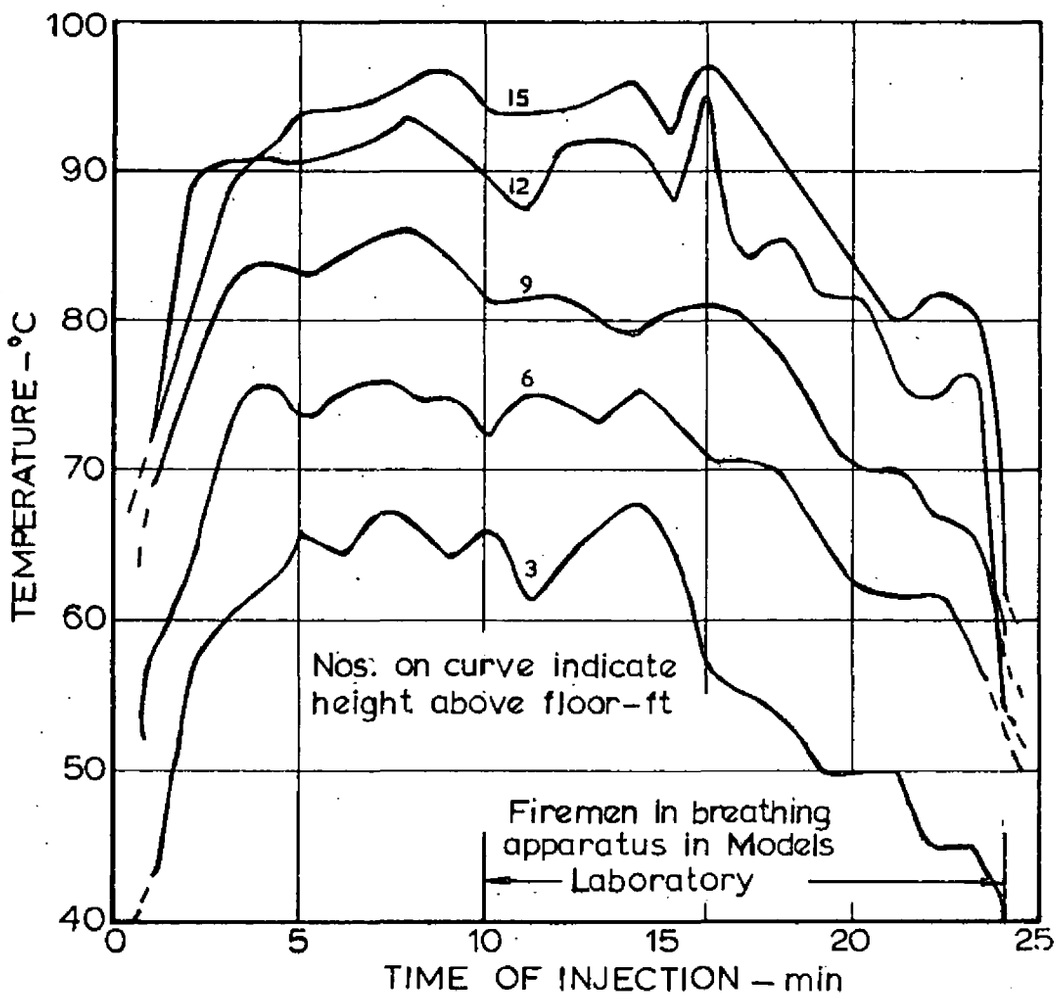
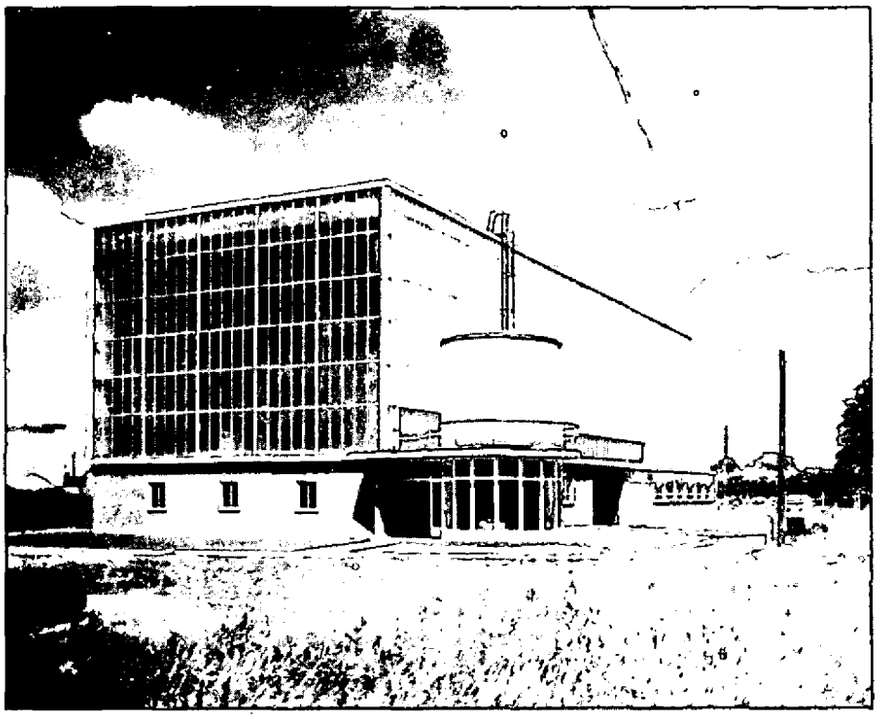
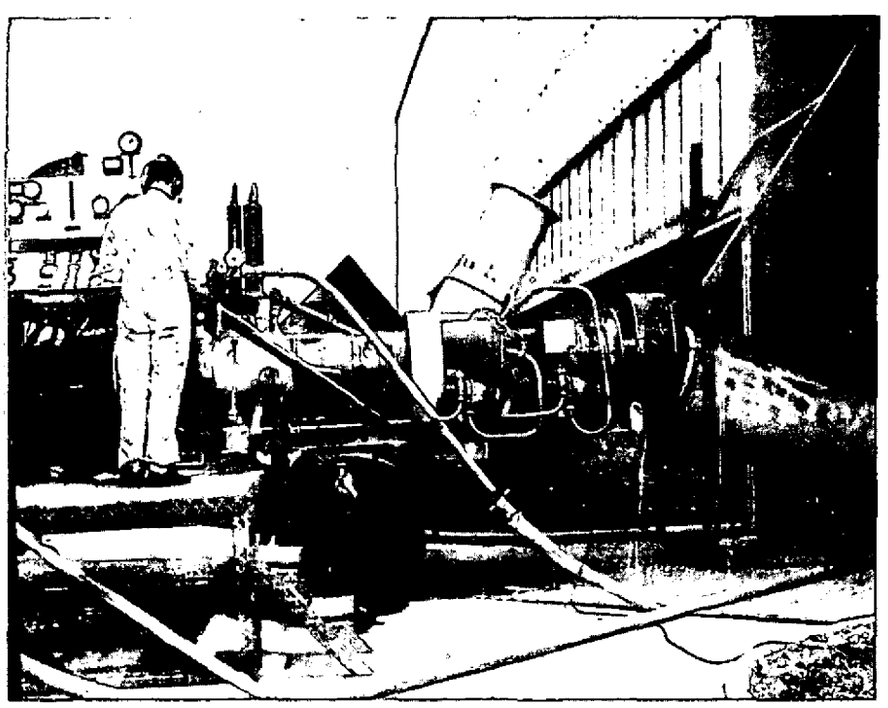


FIG.15. TEMPERATURE IN MODELS LABORATORY – TEST 15
PERFORMANCE OF TASKS BY FIREMEN – 70 ft^2
ROOF VENTILATION – 30 ft^2 GROUND VENTILATION
AT TIMES OF ENTRY OR EXIT OF FIREMEN



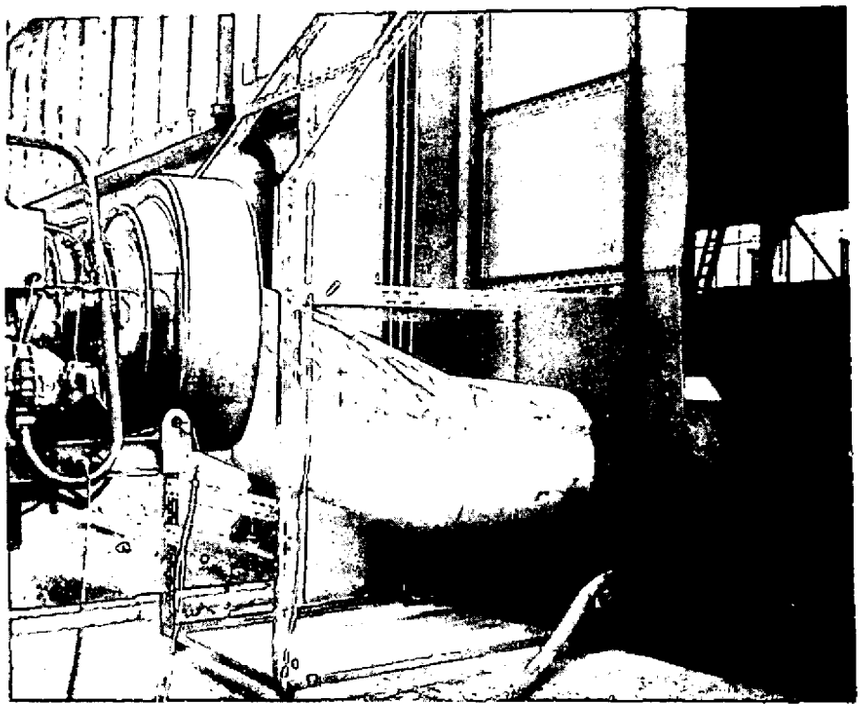
MODELS LABORATORY, FIRE RESEARCH STATION

PLATE 1



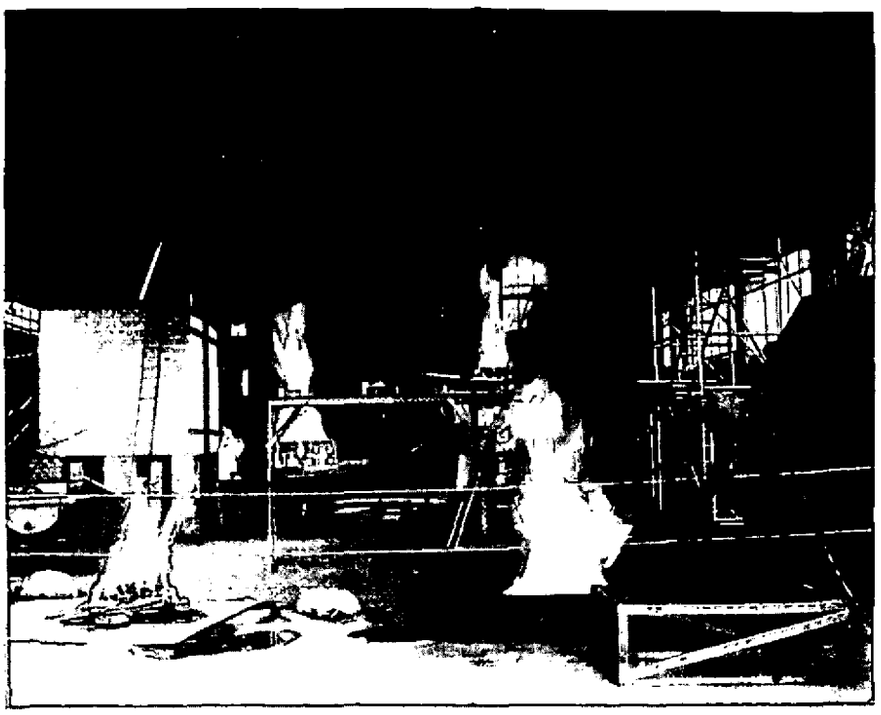
J.F.R.O. INERT GAS AND FOAM GENERATOR
SITED FOR INJECTION OF INERT GAS INTO
MODELS LABORATORY

PLATE 2



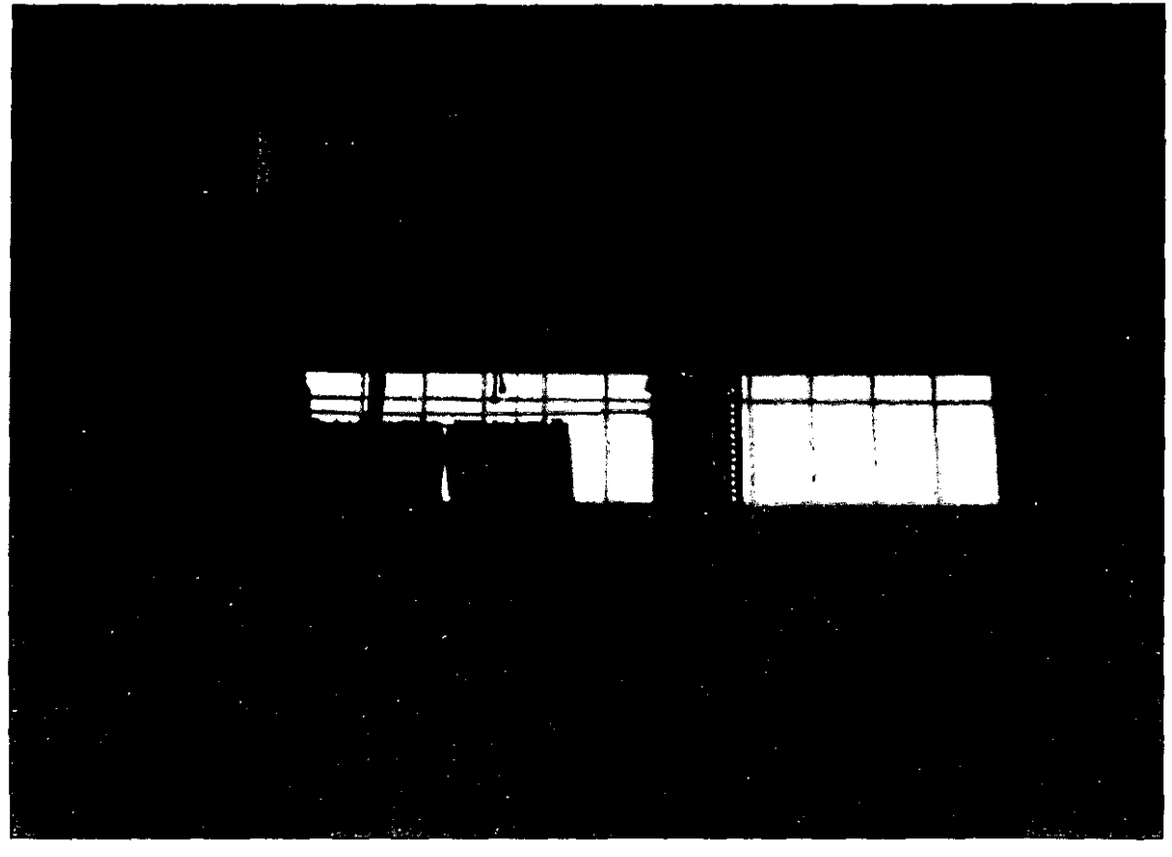
DUCT FOR INTRODUCING INERT GAS
(ONE LEAF OF FOLDING DOOR DRAWNBACK)

PLATE 3



TIMBER AND OIL FIRES IN MODELS LABORATORY

PLATE 4



VISIBILITY IN MODELS LABORATORY TEST IN WHICH FIREMEN ENTERED DISTANCE FROM CAMERA TO WINDOW 45 ft.

PLATE 5