FIRES IN REAL SCENARIOS

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1. SUMMARY

Studies have been carried out to determine the effect of sprinklers on fires typical of a number of occupancies including simulated office furniture, supermarkets, carpet displays, libraries, video stores and liquor stores.

After surveys of actual fire loads, the experiments were conducted in a specially designed sprinklered fire-calorimeter with a collecting hood 6 m x 6 m leading to a vertical duct 1 m in diameter. Details of the rig are given elsewhere **[1]**. Only well ventilated fires were studied. Rate of heat release and production of various toxic chemicals were monitored during the tests. Both sprinklered and unsprinklered fires were used. The results were used to establish the unsprinklered burning behaviour and the fire-control effects of sprinklers.

Before sprinkler operation, the rate of fire growth could be modelled as t^2-fires as given in NFPA 92B (1991 Edition) **[2]**.

It was found that operation of sprinklers controlled but did not extinguish the fires. This was expected as parts of the fire load were shielded from the spray. Also there were significant increases in the concentration of carbon monoxide when the sprinklers operated. Sprinklers had little effect on the concentrations of other toxic products measured.

The results from the tests were extrapolated to large single storey buildings for the same occupancy classes and the results used to compare the required and the available escape times for different occupancies, particularly whether the use of sprinklers would improve the chances of escape from those premises.

It was found that in most of the cases studied, adequate escape times will be available without any special measures. For very rapid fire growths, however, special measures, such as availability of trained staff may be needed. Standard response sprinklers will have little impact.

2. BACKGROUND AND INTRODUCTION

Growth of a fire depends on the type and quantity of fuel, the source of ignition and the availability of oxygen. Hence the growth of a fire will be different in different types of premises. Also, the burning properties will depend on the materials and their quantity as well as their arrangements. For example, a roll of carpet in a horizontal position will behave differently in a fire compared to when it is standing vertically. Thus, fires in realistic scenarios are needed to determine the likely fire growth in those occupancies.

Sprinklers and/or vents are often used to control a fire and to keep the escape routes clear of smoke. However, it is probable that a water spray acting on the burning materials will change their burning characteristics. This may result in a change in the composition and concentration of the fire products and the situation in the fire compartment and the adjacent areas may worsen. This was also studied.

In some fire scenarios, the compartment may be smoke-logged quickly and the time needed for safe evacuation may not be achieved. In those cases, a sprinkler system may provide additional time for escape (by controlling the fire), which may be vital. In this study, the fires have been matched to theoretical fire growth curves to estimate the effect of sprinklers in improving life safety.

For smoke control and some other fire safety engineering purposes, it is necessary to specify a design fire size, or a fire growth curve. At present, although a number of fire growth curves can be found in the published literature **[2]** it is not always clear how appropriate they are to a particular type of occupancy. As a result, there is a risk that inappropriate fire curves may be used for design of smoke control systems. Similar problems exist with steady state design fires, for example a 5000 kW, 9 m^2 fire is often used in various categories of buildings in the UK, although this fire is only really recommended for retail areas fitted with standard response sprinklers.

Thus the main objectives of the work were :

- to derive appropriate design fires for fire safety engineering
- to determine control of fire due to sprinklers
- to determine whether sprinkler or other measures would improve chances of escape
- whether operation of sprinkler changes the production of toxins from fires significantly.

3. FIRES

3.1 Fire growth

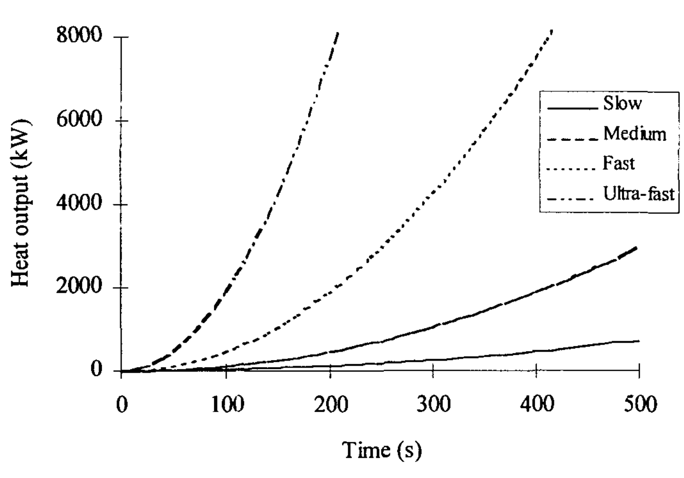

Figure 1 : t^2 fire

To cover the range of different fire growth rates, it was decided to match t^2 fire growth rates to the observed fire growths, with and without sprinkler operation. The t^2 growths are given by $q = \alpha t^2$, where q is the heat output, t is time and α is a constant which determines the rapidity of fire development. Details of the t^2 fires are given elsewhere **[2]**. Figure 1 gives various t^2 fire growths.

Fires in solid materials may have an incubation period during which the fire remains very small. NFPA 92B **[2]** recommends that the incubation period is ignored and the fire be graded on the rising part of its growth curve. However, in some cases, especially where an automatic smoke detection system is installed, alarm will often be given during this incubation period which will allow evacuation procedures to be initiated.

3.2 Convective heat flux

Actual heat outputs from fires can vary by orders of magnitude depending on types and arrangements of the fuel. As data for heat release rates for real fires are simply not available in many cases, a fire size of 3 m x 3 m (often referred to as a 10 m^2 fire) with a convective heat output of 5000 kW is usually used in the UK for smoke ventilation design in shops, which implies a convective heat output of about 500 kWm^{-2}. In the present study, prior to sprinkler operation, no assumption about the convective heat flux has been made. Where available, the heat flux has been calculated from the mass flow rate and the temperature of the hot gases in the chimney [3]. Otherwise, values calculated from the measured heat release rates and estimated fire sizes (from visual observations and photographs) have been used. It was found that before sprinkler operation, the convective heat flux was 65 - 75 percent of the rate of heat release. After sprinkler operation however, this ratio was reduced to 30 - 50 percent. The reduction is due to the cooling effect of the sprinklers on the fire gases. This may be further studied so that 'real' sprinkler cooling can be incorporated in the current computer models.

3.3 Floor area and ceiling height

The floor areas chosen for computer modelling was somewhat arbitrary although an attempt was made to use realistic scenarios. The areas were chosen such that the operation of standard response sprinklers would coincide with one of the manual sprinkler operation times in the experiments. For open plan offices, a floor area of 400 m^2 has been used. For other occupancies the areas varied between 1000 m^2 and 2500 m^2.

Ceiling heights of 3.5 m and 4 m have been considered here. Higher ceiling heights will afford longer escape times.

4. COMPUTER MODEL

The model used a simple computer program, 'FILTIMSP' [4], developed in the Fire Research Station. It calculates the smoke filling times and layer temperatures for various fire scenarios.

The fire must be directly below the final smoke layer with an undisturbed plume. The plume is modelled by the formula

$$M = 0.188\ Py^{1.5},$$

based on work by Hinkley [5]. M is the mass flow (kgs^{-1}), P is the fire perimeter (m) and y is the height of rise (m) of the plume. There is a choice of fire growth models. The fire may be of constant heat output, a 'square law' growing fire or an exponentially growing fire. Square law fires with user-specifiable parameters have been used in this report. A further option is for a fully specifiable fire development based on experimental measurements.

The total area of natural vents or a total fan extract capacity, as well as the total inlet area below the smoke layer have to be specified. The extracts are assumed to be mounted at the highest part of the ceiling. This option of the program, ie smoke exhaust ventilation, was not included in the study.

Sprinklers may also be specified. The temperature of the hot layer at which the sprinkler would operate has to be specified.

The program calculates the mass of hot gases entering the layer in 1 s intervals. The depth and the temperature of the layer is also calculated every second, taking account of any smoke ventilation. If sprinklers are specified, it is assumed that the layer temperature does not increase after sprinkler operation due to spray-cooling of the gas layer. Also the maximum fire size may be limited to a specific value.

The program tests for onset of flashover at a layer temperature of 550 ^{0}C. It can also test for any specific hazard conditions (clear layer height and/or temperature of the hot gas layer).

5. ESCAPE TIME

5.1 Available escape time

This is defined as the time to the onset of hazard (when escape will be difficult) from the detection of fire. It is assumed that detection will be rapid. Specifying the onset of hazard is somewhat subjective. In this report it is assumed that the onset of hazard will occur when the height of the cooler clear layer is less than 2.5 m (ie the room is becoming smoke-logged) and/or the temperature of the hot gas layer is more than 200 ^{0}C, when the radiation from the hot layer can cause severe pain and discomfort.

Available escape time has been calculated from the actual fire growth and control data using 'FILTIMSP'. The layer depths and the hot layer temperatures have been plotted against time; other hazard criteria (ie other than the ones mentioned above) may be considered if necessary.

5.2 Required escape time

The required time comprises two components,

a) response time, ie time needed to realise the danger and hence the need to escape and
b) evacuation time, ie time needed to reach a location of safety from the danger zone.

5.2.1 Response time

Response time, ie the time needed for people to realise the danger and to start to evacuate does vary over wide ranges. This time also has two parts, fire detection and reaction.

There may be delays in fire detection, although with automatic smoke detection, the delay should be short (40 s as recorded in experiments in the Cardington fire-calorimeter).

Proulx and Sime **[6]** have shown that using only a fire bell as an alarm, the reaction time in an underground station could be as long as nine minutes. Presence of trained staff to assist in evacuation would considerably improve the situation. With effective public address and/or organised staff involvement, the reaction time can be reduced to 60 - 90 s **[6]**.

An 'average to slow' maximum response of 300 s has been adopted in this study. It has also been assumed that with proper fire training (quick response), the maximum response time will be reduced to 90 s.

It is realistic to assume that the response time will decrease for small rooms. An equation of the form $T_R = \beta \log(A)$, where T_R is the response time, A is the floor area and β some constant, has been used. The choice is arbitrary but it has the merit that the response time decreases as the area of the room decreases. For 'average' response time, $\beta = 75$ and for quick response, $\beta = 22.5$, so that the maximum response times mentioned above are achieved for a floor area of 10000 m^2.

5.2.2 Evacuation time

Evacuation time, ie time needed to move to a region of safety from the hazard area can be estimated considering maximum travel distances and 'walking pace'. However, in the UK, the Approved Document B [7] does not equate evacuation time with travel distance; instead number and width of doors are specified such that evacuation time will be 150 s or less. As with response times, evacuation times should be less for smaller premises; hence an evacuation time based on travel distance, with a maximum of 150 s has been considered in this report. Assuming a slow walking pace of 0.3 ms^{-1}, the evacuation time in seconds would be 3.3 times the travel distance in metres, which would be proportional to the characteristic dimension (length) of the space. It will also depend on the location of the exit doors. It is acknowledged that in offices, for example, the walking pace considered here may be deemed to be too slow. Occupied spaces are assumed herein to be square and, taking the width of the premise as the approximate effective maximum travel distance, the evacuation time becomes by $T_E = 10\sqrt{A} / 3$, where A is the floor area and T_E is the evacuation time with a maximum of 150 s. The total times needed for escape calculated in this way are plotted against time in Figure 2.

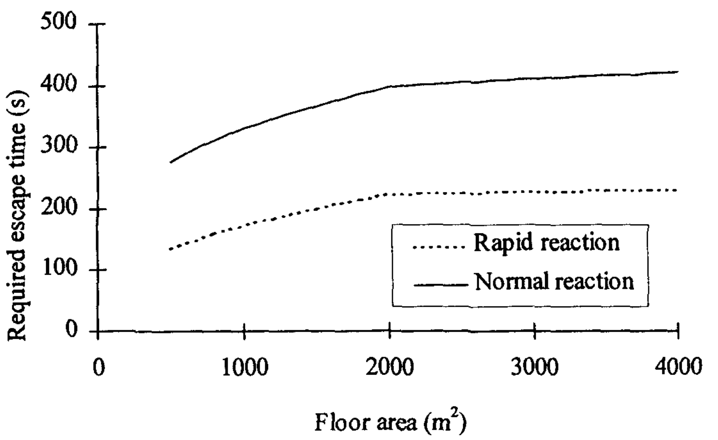

Figure 2: Required escape times vs floor areas

5.3 RESULTS

Brief descriptions of fire growth rates for various occupancies are given below. Details of the experimental techniques have been given elsewhere [1]. Required and available escape times are given in Table 1. Plate 1 shows the experimental rig.

5.3.1 Fires in office furniture

A survey of fire loads in a limited number of cellular offices of 'traditional' appearance has been carried out by Webb et al [8]. The survey considered the papers, plastic trays, visual display units (vdus) and computers etc in the office as initial fire loads (but not the desk tops which would only be involved at a later stage of the fire). The results showed that the exposed fire load varied between 2.7 and 36.7 kgm^{-2} of floor area in these offices.

The actual arrangement was similar to one of the offices surveyed in **[8]**. The actual fire loads were 25 kgm^{-2}, which were severe but not extreme.

Office furniture fires follow a medium t^2 curve ($\alpha = 0.0117$) after an incubation period of 100 s. It is assumed that the office is open plan and the fire does not spread to adjacent 'workstations'. Maximum fire size for an unsprinklered fire reached about 1000 kW (although flashover and full involvement of the compartment can be expected with a lower ceiling).

Direct measurement of convective heat flow through the chimney gave an average heat flux of 270 kWm^{-2} before sprinkler operation. After sprinkler operation, the heat flux was reduced to 190 kWm^{-2}. For a 400 m^2 office with a 3 m high ceiling, sprinklers will operate 430 s after ignition. Operation of the sprinklers will quickly control the fire without necessarily extinguishing it, for example any fire beneath the 'desk' will be shielded from spray and hence will continue to burn.

In the event of a fire, sufficient escape times will always be available, even without a sprinkler system. This is largely confirmed by the UK fire statistics.

5.3.2 Fires in a supermarket

Two different scenarios were considered. Fires in packets of crisps in a 4 m length of gondola produced a rapidly developing fire, reaching 6200 kW in 390 s. The actual characteristics for one of the fires were :

Incubation period 120 s.
Fast t^2 fire growth ($\alpha = 0.047$) between 120 s and 300 s.
Ultra fast t^2 fire growth ($\alpha = 0.188$) between 300 s and 360 s.
More rapid than ultra fast t^2 fire growth ($\alpha = 0.22$) between 360 s and 390 s.
Sprinklers turned on at 390 s.

Convective heat fluxes were 220 kWm^{-2} and 150 kWm^{-2} for pre- and post-sprinkler operation respectively. Areas to be modelled were chosen to get an estimated standard response sprinkler operation at 390 s after ignition.

The experimental rig had a 4 m high ceiling with a suspended ceiling at 3.32 m. This gave a floor area of 1700 m^2 with a 4 m high ceiling as one of the scenarios. The other scenario was a 2500 m^2 shop with a 3.32 m high ceiling (3.32 m is the standard ceiling height used by the supermarket chain which was the commercial customer for these tests).

Operation of sprinklers quickly controlled the fires at the top shelf but the packets of crisps at lower shelves continued to burn and the reduction in fire severity was slow. The fire size remained at 600 kW - 800 kw for about 400 s after operation of the sprinklers.

For a 1700 m^2 shop with a 4 m high ceiling, adequate escape times will be available for escape without sprinklers and without any staff training.

For the 2500 m^2 shop with a 3.32 m high ceiling, the onset of hazard was 382 s. With normal reaction, the required escape time will be 405 s; with trained staff, ie quick reaction time, the required escape time will be 226 s. Thus staff assistance will be needed to achieve safe evacuation. Sprinklers will only operate after the onset of hazard, so they will not help in escape.

In two experiments metal dividers were used every 1.2 m in the shelves to reduce horizontal fire spread. The fire growth was slower. After a 90 s incubation period, the fire matched a t^2 curve with $\alpha = 0.025$, about midway between medium and fast fire growth. The unsprinklered fire has also been modelled for a 1700 m^2 shop with a 4 m high ceiling. The convective heat flux before predicted sprinkler operation was 210 kWm^{-2} (convective heat output was 2200 kW). Manual sprinklers were turned on at 510 s. Standard response sprinklers were unlikely to operate in that time in a 1700 m^2 shop, unless a sprinkler was over the fire. Hence the post-sprinkler scenario has not been modelled.

Fire growth rate in a second scenario, where fire lighters and kitchen rolls were used as fuels, were much slower. The rate was between medium and fast t^2 fire (α=0.02). Although use of sprinkler will increase the available escape time, it was not necessary for safe escape.

5.3.3 Fires in carpet displays

A test fire in a carpet display followed a medium t^2 curve ($\alpha = 0.014$) after an incubation period of 120 s. For modelling, the floor area for the calculation is 1000 m^2, typical of this type of retail. Ceiling height is 4.0 m. Convective heat flux before sprinkler operation is 650 kWm^{-2}.

From smoke filling calculations, the height of the clear layer will be reduced to 2.5 m in 525 s (Table 1). As only 330 s is likely to be needed for escape, there should be no life safety implications. Also, any sprinkler will operate late, in about 540 s.

5.3.4 Fires in libraries

Three tests were carried out. In the first two, the rate of fire growth was halfway between slow and medium (α=0.08) after an incubation period of 70 - 100 s. In the other test, where the ignition was in a different place, the growth was very slow (α=0.002). This demonstrates the variability in fires with irregular solid fuel arrangements. Plate 2 shows an experimental fire.

Considering libraries with floor areas of 400 m^2 and 1000 m^2 (ceiling height 3.5 m), sprinklers will not be activated before the premise is smokelogged, so they will not help in life safety. However, in both cases, presence of trained staff will be required to ensure safe evacuation. For larger libraries, with a floor area of 2000 m^2 (say), adequate escape time will be available without any special measure.

5.3.5 Fires in video stores

In one test, the fire growth rate was a little slower than fast (α=0.032) after an incubation period of 70 s. The growth rate continued till 265 s, when sprinklers were activated. Operation of sprinklers quickly controlled the fire and by 400 s, the fire was almost extinguished. In a subsequent test without sprinklers, although the fire growth was similar for the first 250 s, it slowed down afterwards.

For a 1000 m^2 shop with a 3.5 m high ceiling, the available escape time will be 303 s (including the incubation period). 307 s are required for escape, so sufficient escape time will be available. Sprinklers will not operate before onset of hazard.

5.3.6 Fires in liquor stores

Fire growths were variable although in the early stages the growth rates were between slow and medium (α=0.006). There was an extra variability as bottles containing low-concentration alcoholic drinks such as wines and beers, when broken due to the fire, tended to cause local control of fire. With such a fire growth, sufficient time for escape should be always available.

6. TOXIC PRODUCTS

The main toxic products from these fires were CO and CO_2 although their levels were low. Operation of sprinklers increased the levels of CO in most cases, although the levels were still not large enough to endanger life in short periods. Other chemical species monitored such as HCl, aldehydes including acrolene and cynides were either not present or present only at very small quantities, indicating that life-threatening concentrations of these chemicals are only likely either with vitiated fires or with fires in special materials.

7. CONCLUSIONS

i) A single or a composite t^2 fire growths are appropriate as design fires for the occupancies studied. It is likely that the same is true for most other occupancies - although experiments are needed to determine what growth rate should be used.

ii) Although sprinklers control a fire, they may not extinguish it. In a shop, goods can often be sheltered from the water spray by shelving, so that significant horizontal fire spread may occur even after sprinkler operation.

iii) In shops, goods may be on display on long shelves. This gives a possibility of very rapid fire growth, even after sprinkler operation. This can be remedied by simple measures, such as using dividers in shelves to reduce horizontal fire spread.

iv) For ultra fast fire growths, sufficient escape times may not be available if trained staff to assist in evacuation are not present. For slower fire growth, sufficient times for escape are likely to be available without any special measure. Normal response sprinklers will have little impact.

[Note: The situation will be worse for premises with low ceilings, eg 3 m.]

v) Levels of toxins produced in freely burning fires are likely to be small.

vi) It is desirable to extend the study to other occupancies to build up a library of design fires.

vii) In the experiments, the heat flux varied from 150 kWm^{-2} to 650 kWm^{-2}. So the use of 500 kWm^{-2} as a constant pessimistic heat flux for sprinklered solid fires may not always be justified. Also, water spray cooling from sprinklers reduced the convective heat flux from a fire. This should be studied further.

8. REFERENCES

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Table 1 : Required and available escape times from the model using real fire data.

Type of fire	Floor area (m^2)	Ceiling height (m)	Sprinklers**	Available escape time (s)	Required escape time (s)	
					Quick reaction†	Normal reaction
Crisps	1700	4.00	Yes	390	210	380
Crisps	2500	3.32	Yes	382	226	405
Crisps*	1700	4.00	No	430	210	389
Office furniture	400	3.00	No	268	NA	NA
	400	3.00	Yes	268	NA	NA
Carpets	1000	4.00	No	525	173	307
Videos	1000	3.50	Yes	303	173	307
Liquor stores	1000	3.50	Yes	413	173	307

* Metal partitions in the shelves reduced horizontal fire spread.
** Sprinklers did not operate before onset of hazard.
† Quick reaction assumes presence of trained staff to assist in evacuation.

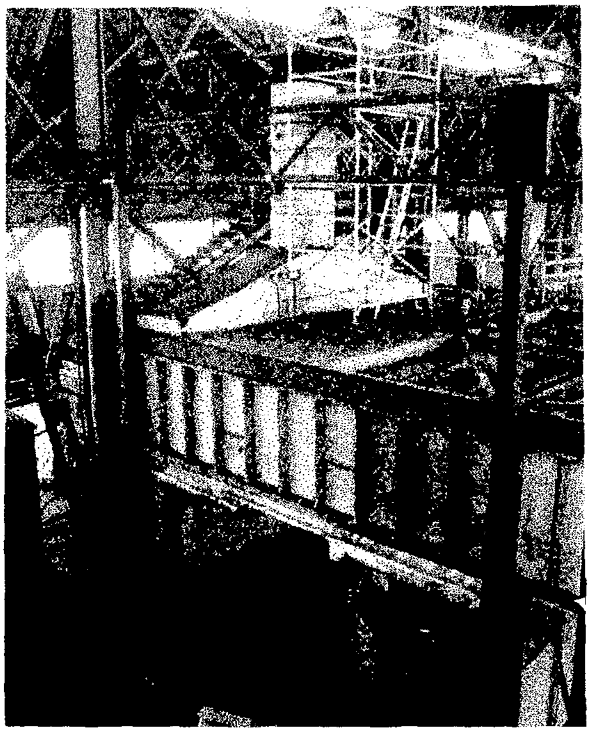

Plate 1: The experimental rig

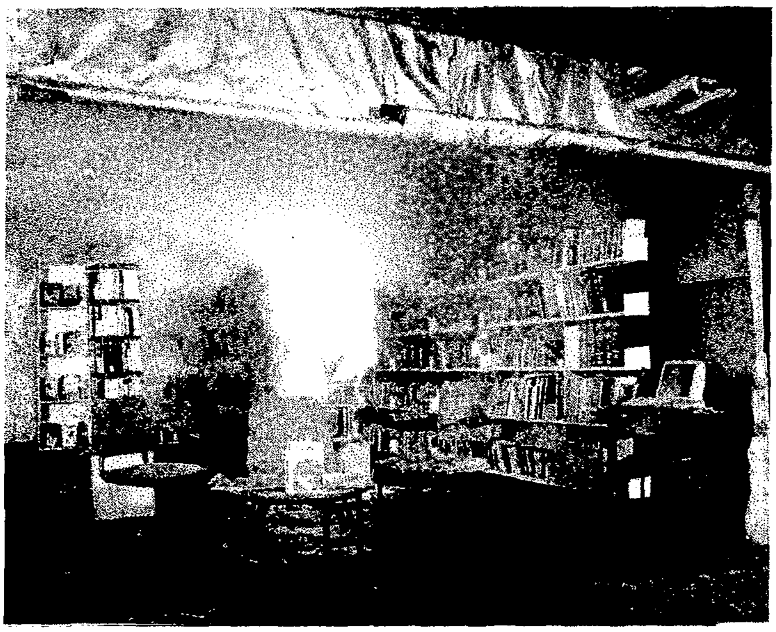

Figure 2: Fire in a simulated library

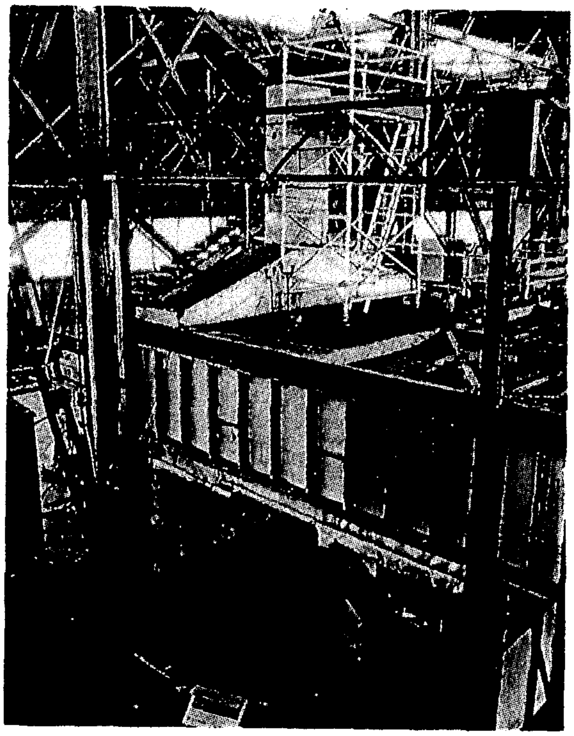

Plate 1 : The sprinklered calorimeter

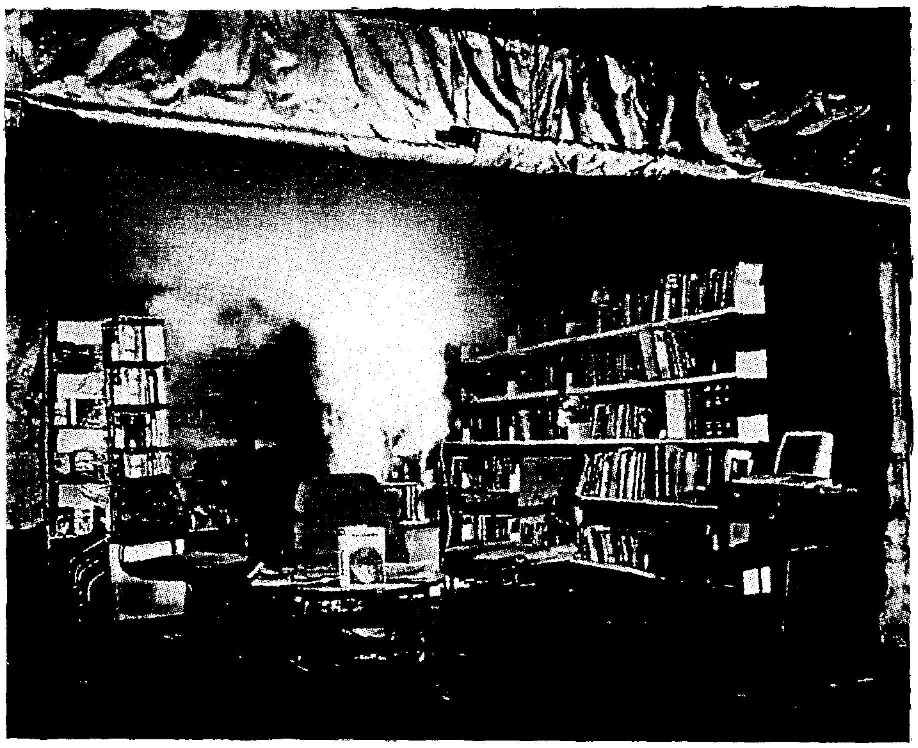

Plate 2 : Fire in a simulated library