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No 941

THE EFFECT OF ROOF CONSTRUCTION AND CONTENTS ON FIRES IN SINGLE STOREY BUILDINGS

by

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SUMMARY

This note describes 9 fires in single storey buildings visited by the Fire Survey Group of the Fire Research Station. The construction of each building and the way this affected the fire is described. The fuels present and estimates of the burning rates they produce are given in Tables which include data from experimental fires for comparison. The study confirms previous work done on roof venting and shows that venting may restrict fire spread except where rapid burning materials are present.

KEY WORDS: Building, single storey, burning rate, fire load, roof, fire, behaviour, ventilation.

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

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1. INTRODUCTION

1.1. Purpose of the note

This note is one of a series dealing with the work of the Fire Survey Group. The first note[1] set out the broad principles of fire surveying and gave an analysis of some house fires. Another note in preparation examines surveys of some industrial fires. Both notes deal mainly with the direct application of the work to building problems whereas the present note compares data obtained from 9 fires in buildings with the results of some experimental research programmes[2,3] with particular reference to one aspect of fire behaviour and design, viz. the roof venting of fires in single storey buildings.

The comparison has two purposes

a. to confirm that the parameters of the experimental fires were representative of fires in buildings;

b. to provide information on the circumstances in which predictions of fire behaviour on an experimental or theoretical basis can be made.

1.2. Background to roof venting

Roofs may vent fortuitously when the roof cladding is of low fire resistance and structural collapse is minimised when the frame supporting the roof has a high fire resistance compared to that of the cladding, and, as a result of earlier research a roof venting system can be specifically designed to prevent the smoke logging of a single storey building. However it occurs roof venting usually removes smoke and heat giving fire brigades a better chance of tackling the fire. Venting can also restrict fire spread by long flames trapped beneath the roof of a large single storey building. Such flames had been present in three of the incidents surveyed.

1.3. Choice of fires used for the comparison

The roof venting of fires is mainly applicable to single storey buildings
and from 24 such buildings surveyed 8 were selected as the quantity of fuel
burnt and the effective duration of the fire were either known or could be
assessed. One fire in a multi-storey building has been included. The fire
occurred in a section which had been added to the top of a 3 storey block and
was similar in construction to many single storey buildings. As fire was
confined to this section it has been included in this note. One building was
fitted with several old sprinkler systems which would now be classed as
sub-standard for the present use of the building. It has been included as
6 the contents produced a fire which overwhelmed the sprinklers and then spread
to involve a large area.

1.4. Description of the buildings included in the comparison

The buildings were as follows

5 storage buildings
1 factory
2 workshops
1 hospital research unit

The buildings varied in size from 170 to over 10,000 square metres and contained fire loads ranging from less than one up to 1,000 kilograms of fuel per square metre of the floor.

2. METHOD OF PRESENTING THE DATA

The information is presented in the following sequence.

Table 1 lists the general details of the 9 buildings.

Tables 2a and 2b give the fire environment, fire ventilation, and estimates of the fire duration and rates of burning for both fires in buildings and some experimental fires using wood cribs as the fuel. Also included are the results of an ad hoc test which enabled burning data for cardboard cartons to be estimated.

Table 3 gives details of the extent of the fire, the depth of the layer of hot gases, the problems the fire brigade encountered in fighting the fire and the damage sustained.

TABLE 1. BUILDING DESCRIPTION AND CONTENTS

Incident No.	Building purpose		Constructional details									Dimensions of build[g] or compt[t] m
	Occupancy type	Contents	Date	Constr. type	Walls	Roof	Roof lining	Heights m			Roof glazing	
								Eaves	Apex	Storage		
1. H.53	Furniture store	Stacks of crated furniture	1950	Concrete frame	Brick corr.asb.	Corr.asb.	–	3.3	4.8	3.3	PVC rooflights	9 x 19
2. B.48	Timber store and workshop	Stacked and sawn timber, machinery	Pre.[1]	Timber frame	Timber	Corr.asb.	–	3.3	4.8	1.5	–	9 x 19
3. B.26	Garage repair shop	Vehicles, petrol and cellulose	1965	Timber frame	Brick glass	Corr.iron	–	3.3	4.0	0.8	GRP rooflights	13 x 20
4. S.7	Hospital research unit	a*. Library b*. Research equipment	Pre.[1]	Aluminium frame	Corr.asb.	Corr.asb.	Fibre insulation board	3.3	4.8	3.0	–	10 x 46
5. B.75	Factory	a*. Paint spray booth b*. Metal components	Pre.[1]	Timber frame	Brick	Bitumen on timber	–	3.6	6.6	–[2]	–	18 x 74
6. H.11	Cardboard and timber store	a*. Stacked cardboard b*. Stacked chipboard	1955	Timber frame	Corr.iron	Corr.iron	–	4.2	6.6	a. 1.8 b. 2.4	–	13 x 30
7. B.93	a. Factory b. Store	a*. Electrical goods b*. Cardboard cartons	1955	Steel frame	Concrete Corr.asb.	Corr.asb.	Plaster-board	4.5	7.2	5.0[3]	GRP rooflights	46 x 48
8. S.1	Warehouse	a*. Stacked cardb'd cartons b*. Stacked cardb'd reels	1963	Steel frame	Brick Corr.asb.	Corr.asb.	–	10.0	16.0	7.0	–	50 x 83
9. S.8	Warehouse[4]	Wrapped and packaged Consumer goods	Pre.[1]	Cast iron columns. Steel frame	Brick	Slate	Timber	4.8	6.0	3.6	Wired glass	87 x 120

*See plans of buildings (Section 11)

1 Pre 1939
2 Bitumen covered roof timbers formed the fuel
3 On mezzanine floor
4 Sprinklers installed. These were ineffective as upper racks shielded those beneath

TABLE 2A. FIRE ENVIRONMENT AND VENTILATION

Fire	Incident or test ref. and fuel	Compartment and fire area		Fire ventilation		
		Comp[t] area m^2	Fire area m^2	Area of roof vented m^2	Initial method of venting	Subsequent vent[n]
Fire incidents	1	170	32	28	PVC rooflights failed	Corr.asb failed
	2	170	9	20	Corr.asb failed	-
	3	260	6	6	GRP rooflights failed	-
	4	460	418	362	Roof collapse	Walls perforated
	5	1,360	1,150	1,150	Roof collapse	-
	6a*	90	90	90	Roof collapse	-
	6b*	300	300	300	" "	
	7	2,200	250	645	Roof perforated	-
	8a*	1,300	1,300	1,300	Roof collapse	-
	8b*	2,500	2,500	2,500	" "	
	9	10,200	8,360	8,360	Roof collapse	-
Fire tests[1]	K) D) wood F) cribs L)	28.5 28.5 28.5 28.5	8.65[2] 8.65[2] 8.65[2] 8.65[2]	11.1 m^2 window opening in one wall		
	Cardboard	28.5	8.65[2]	2.6 m^2 window opening in one wall		
Column number		1	2	3	4	5

*Refers to contents in Table 1

1 Reference 3

2 Floor area covered by wood cribs

TABLE 2B. BURNING DATA FOR FIRE INCIDENTS AND FIRE TESTS

Est^{d} fire duration min (s)	FUEL							Incident or test Ref.	Fire
	Est^{d} total wood equivalent of fuel present kg	Est^{d} fuel consumed kg	Fuel cons^{d} %	Est^{d} fire load cons^{d} per unit fire area kg m^{-2}	Est^{d} total rate of burning MW	Est^{d} burning rate per unit area of: Fire kW m^{-2}	Est^{d} burning rate per unit area of: Comp^{t} kW m^{-2}		
30 (1,800)	140,000	450	0.3	14	3.2	100	19	1	
45 (2,700)	4,500	730	16	80	3.5	390	21	2	
5 (300)	145	36	25	6	1.6	260	6	3	
60 (3,600)	44,000	11,000	25	26	39	93	85	4	
30 (1,800)	40,000[3]	34,000[3]	85[3]	30[3]	240[3]	210[3]	180[3]	5	
40 (2,400)	16,500	5,400	33	60	29	320	320	6a	Fire incidents
15 (900)	220,000	1,800	1	6	26	86	86	6b	
80 (4,800)	116,000	28,600	25	110	77	310	35	7	
30 (1,800)	113,000	113,000	100	90	810	620	620	8a	
210 (12,600)	2,540,000	510,000	20	200	520	210	210	8b	
180 (10,800)	7,200,000	3,740,000	52	450	4,500	540	440	9	

3 Bitumen covered roof timbers formed the fuel

(Cont'd)...

Cont'd ....

Est^{d} fire duration min (s)	FUEL							Incident or test Ref.	Fire
	Est^{d} total wood equivalent of fuel present kg	Est^{d} fuel consumed kg	Fuel cons^{d} %	Est^{d} fire load cons^{d} per unit fire area kg m^{-2}	Est^{d} total rate of burning MW	Est^{d} burning rate per unit area of			
						Fire kW m^{-2}	Comp^{t} kW m^{-2}		
19 (1,140)	218	218	100	25	2.5	290	88	K	
20 (1,200)	436	436	100	50	4.7	550	165	D	Fire tests
22 (1,320)	872	872	100	100	8.5	980	300	F	
28 (1,680)	1,744	1,744	100	200	13	1,550	470	L	
6.7 (402)	408	408	100	47	13	1,550	470	Cardb'd	
6	7	8	9	10	11	12	13	Column number	

TABLE 3. EFFECTS OF FIRE AND DAMAGE

Incident No.	Fire area / Compt.area %	Depth of		Duration of fire fighting arrival to control min	Comments on fire fighting	Structural damage apart from roof cladding
		Clear layer above floor m	Hot gases beneath ceiling[1] m			
1. H.53	19	2.7	0.6	57[3]	No smoke problems.	None.
2. B.48	6[2]	2.7	0.6	29	No smoke problems.	Localised charring of roof frame. One timber roof support above fire collapsed.
3. B.26	3[2]	0 2.3	3.3 1.0	10	Building smoke logged to floor level until GRP rooflights failed. Smoke then no further problem.	No significant damage.
4. S.7	90	0	4.8	88	Rapid fire spread through most of building before lined roof failed. Fire fighting prevented further spread.	Building collapsed over area of fire.
5. B.75	85	0	6.6	73	Timber roof remained intact (and hence delayed discovery) until most of roof involved. Fire fighting prevented further spread.	Most of roof collapsed. Minor damage to walls.
6. H.11	100	0	6.7	34	Corrugated iron roof remained in position until fire had passed partition into open store. Whole area involved when fire fighting commenced.	Complete collapse.
7. B.93	100	0	7.0	81	Late discovery. Whole building involved. Roof vented on FB arrival. Fire fighting prevented fire spread to adjoining compartment.	Unprotected steel frame badly damaged.
8. S.1	100	0	16.0	324[3]	Rapid fire spread over whole building. Fire fighting limited to damping down and preventing spread.	Total collapse of roof structure. Walls suffered major damage.
9. S.8	82	0	6.0	213	Rapid fire spread overwhelmed sprinklers. Fire fighters driven out by worsening conditions. Had great difficulty escaping in zero visibility. Equipment abandoned.	Complete collapse of roof. Walls still standing after fire.

1 Calculated from Technical Paper No.7 - see Appendix 3.
2 Fuel covered limited area of floor.
3 Includes time for extinguishing fire in adjacent building.

The discussion in Section 3 following the tables outlines the points of interest and comments upon the features of the fires in buildings and the experimental fires. Figures 1-9 illustrate the building layout and disposition of the fuel.

The salient features of the fires in buildings and the experimental fires are presented as conclusions in Section 4.

The following items are given in Appendices to this note.

Appendix 1 Comments on general information presented in the tables.

Appendix 2 Estimation of fire duration.

Appendix 3 Calculation of depth of hot gas layer in incidents 1-3.

Appendix 4 Calculation of horizontal length of flames under the roof in incident 9.

3. DISCUSSION

3.1. Effectiveness of roof venting.

3.1.1. Damage and fire spread

The effectiveness of roof venting in restricting fire damage is confirmed by the limited spread of fire and the absence of significant damage to the structural frames of the buildings in incidents 1-3. The roof finishes and whether they were effective or not in venting the fires are listed below.

Incident No.	Roof finish	Burning rate per unit area of fire kW m^{-2}	Venting effect	Notes
1	Asb.Cem-PVC	100	Very Effective	Roof vented early in fire
2	Asb.Cem.	390	Effective	"
3	Corr.Iron-GRP	260	Effective	Building completely smoke logged until GRP rooflights failed
4	Asb.Cem/FIB lining	93	Ineffective	Extensive fire spread
5	Bitumen on timber	210	"	"
6	Corr.Iron	320	"	"
7	Asb.Cem/ Plasterboard - GRP	310	"	"
8	Asb.Cem.	620	"	Rapid fire spread through cardboard cartons regardless of roof.
9	Slate on timber	540	"	Extensive fire spread

Corrugated asbestos cement and PVC[4] rooflights were both particularly effective in venting the fires except in incident 8 where cardboard cartons formed the fuel as fire will spread rapidly through these regardless of the roof. The GRP rooflights which did finally vent the fire in incident 3 cannot however be relied upon to vent in most situations. They only failed in incident 3 after being subjected for 5 minutes to strongly burning petrol from a vehicle being repaired, whereas in incident 7 the GRP rooflights withstood a growing fire and remained in position for more than one hour when the fire became starved. Although the average rate of burning given above for incident 7 exceeds that for incident 3, it should be noted that the rate for incident 7 includes the rate of burning after flashover occurred (see comments on incident 7 in appendix 2). Before flashover, the burning rate would have been less than in incident 3.

The structural frames of the buildings were undamaged in incidents 1 and 3, and only one timber roof support directly above the fire collapsed in incident 2. In these three incidents the roofs vented fairly quickly and fire spread was limited to less than 20 per cent of the area of each building. In all the other incidents fire spread exceeded 80 per cent of the buildings which were badly damaged and would need to be rebuilt. Where present, the brick walls remained standing and did prevent fire spreading to adjacent sections or adjoining buildings. Even the corrugated iron walls in incident 6 probably prevented ignition by radiation of the contents of an open-sided store 7 metres away.

Unusual features of fire spread were noted in incidents 1 and 8. Goods inside the warehouse (incident 1) were ignited when an external fire penetrated the timber doors. In 8 the fire in the single storey warehouse ignited the contents of a 4-storey warehouse 5 m away. This warehouse had windows which faced the fire and these allowed the contents to be ignited by radiation from the single-storey building.

3.1.2. Depth of smoke-free air above the floor

Clear air above the floor enables fire-fighters to find and tackle the fire. The depth of such a layer was estimated from nomogram 6 of FR Technical Paper No.7[2] for the first three incidents listed. It was not possible to determine this layer depth visually as smoke had blackened the walls before the roofs had vented. However, the calculated values agree with estimates by eye witnesses at each incident. These values and the method for calculating the layer depths are given in Appendix 3.

3.2. Comparison of burning rates with experimental fires

Only one fire incident burned at a greater rate than the largest crib fire (see 7.2.3.). The fuel involved was assembled cardboard cartons which are known to burn very quickly. The wood crib fires are therefore representative of amany fire situations encountered in practice.

The rates of burning quoted are the averages for the whole duration of each fire. Within that period the burning rate might have varied considerably, and would have been reduced when fire-fighting commenced. Before brigade arrival the burning rates could have been several times greater than those listed, but it is unlikely that a fully-developed fire in a building would be allowed to burn for very long without the fire brigade taking action to contain and extinguish it.

An American booklet[5] lists some heat release rates for the following materials:

	Material	Heat release or burning rate kW/m^2
1.	Gasoline	1,880
2.	Wood pallets piled 8 ft (2.4 m) high	4,700
3.	Simulated packed stock with 8 in (0.2 m) gap between piles 8 ft high	3,000
4.	As in 3, but piles 12 ft (3.6 m) high	8,500

These burning rates are much greater than those in Table 2. The source of the American figures is not given, but they may have been determined for fuels burning in the open. If this was so, then the difference between these results and those in Table 2b is probably due to both the effect of the buildings on the fires and the application of water by the fire brigades.

3.3. Wind

Only in incident 9 where staff leaving the building had left all doors open did wind have any effect. When firemen were forced to evacuate the building, a wind of 7.5 m/s blew smoke along in their direction of escape.

3.4. Fire resistance of roof frame and cladding

The combination of corrugated asbestos cement cladding and PVC rooflights was particularly effective in venting the fire in incident 1. The concrete frame supporting this roof had much greater fire resistance than the cladding and was undamaged. The nominal fire resistance of this frame would be at least 30 minutes whereas that of the rooflights and cladding would be unlikely to exceed 2 or 3 minutes. The fire resistance of the frame therefore exceeded that of the cladding by at least a factor of 10. When the roof frame has less fire resistance than the cladding large areas of the roof will collapse when the frame fails. This is dangerous to firemen, may cause increased damage within the building and greatly increases the task of clearance and reinstatement. An example of this was the timber boarded roof supported by a 'Belfast' truss in incident 5 in which 85 per cent of the roof collapsed. The main structural members were composite and consisted of several deep but thin timbers bolted together. As the gaps between the timbers were unstopped, the fire resistance of the composite beam was little more than that of each of the component parts and was less than that of the cladding.

3.5. Roof linings

When a corrugated asbestos cement roof is lined internally to reduce thermal losses the cladding may remain in position for an appreciable period and this occurred in both incidents 4 and 7. The lined roof and the GRP rooflights in incident 7 withstood a slow burning fire for over an hour and even after flashover 60 per cent of the cladding and rooflights were still in place. PVC rooflights would have failed much sooner and would probably have prevented flashover. A notable exception to this is where cardboard cartons and similar materials are present. These materials burn and spread fire so rapidly that a fire will become large whether the roof vents or not.

3.6. Fire sub-divisions

All the buildings listed in Table 1 lacked internal sub-divisions except incidents 4 and 6 where 'makeshift' or flimsy partitions were present. The cardboard cartons in incident 7 were stored in the folded flat state on a mezzanine floor. Here they were in a position to be ignited by hot gases collecting under the roof from a fire in any part of the building. Assembled cartons were present in incident 8. In both cases, these materials should have been separated from the rest of the building by some form of sub-division.

3.7. Height of roof

The temperature of the hot gases reaching the roof determines the time taken for roof venting to occur. The plume of hot gases rising from a fire is cooled by entrainment. The degree of cooling is thus dependent upon the distance between the burning fuel and the base of the layer of hot gases under the roof. Once flames approach and reach the roof the structure will be subjected to very high temperatures. Failure to vent the hot gases at this stage will result in extensive heating of the structure and rapid spread of fire in the contents caused by the formation of long flames beneath the roof. Such flames were seen by firemen in incident 9 (see Appendix 4) and were also present in incidents 6 and 8. Only in incident 7 did the fire at floor level fail to produce flames tall enough to reach the roof. The roof remained in position and when fire spread to the cardboard stacked on the mezzanine floor the fire had become starved which resulted in lower temperatures within the building (see Appendix 2).

3.8. Sprinklers

The warehouse in incident 9 was fitted with sprinklers at roof level. Although these may have retarded fire growth and spread, they were ineffective as the upper racks of stacked goods shielded those beneath (see Section 10.2.2. incident 9). This situation was represented in some experimental tests on water curtains[6] which showed that a relatively low water application rate of 0.1 l m^{-2} s^{-1} (0.12 gal/ft^2/min) per unit area of wetted floor prevented fire spread in continuous fuels at both high and low levels when used in conjunction with a roof vent. These tests indicate that although the sprinkler system in incident 9 would now be classified as sub-standard, the sprinklers would probably have confined the fire to the stack of origin if the roof had vented effectively.

4. CONCLUSIONS

1. This exercise confirms that roof venting can effectively retard fire growth and spread in many occupancies. The main exception to this is where cardboard and similar rapid burning materials are stored. Such materials should be kept away from the main building or at least in a section separated from it. These goods should not be kept on a mezzanine floor.

2. Although corrugated asbestos cement will fail and vent most fires, this does not happen if the roof is lined, in which case a correctly designed venting system will be required.

3. Incidents 4-9 confirm that unless the structural roof supports are so designed that their fire resistance exceeds that of the roof cladding, then the roof will collapse over a large area.

4. The crib fires used in the experimental programme were well chosen as they gave burning rates representative of fires in many occupancies. Cardboard cartons are an exception to this.

5. The depths calculated for the layer of hot gases in incidents 1 to 3 agreed with estimates by eye witnesses.

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7. APPENDIX 1. COMMENTS ON THE TABLES

7.1. Table 1. Building construction

The roof constructions in Table 1 range from unlined corrugated asbestos cement with PVC rooflights[4], both of which vent readily in a fire, to slates on timber boarding and wired glass rooflights. The latter combination has sufficient fire resistance for the roof to remain in position until a fire has grown large. In between these two extremes are various combinations of roof claddings and internal roof linings. Their behaviour during the fire is described in Section 7.2.2. In two instances glass fibre reinforced plastic (GRP) rooflights were present and these behaved differently in each case. In incident 5 the timber roof formed the bulk of the fuel present.

7.2. Table 2.

7.2.1. Compartment and fire area

These areas illustrate the size of the fire and its environment and indicate the extent to which fire has spread. In six of the incidents the contents occupied most of each building but in three instances (incidents 2, 3 and 7) most of the fuel was present in a well-defined area only and was not distributed throughout the building. In each of these cases fire involved the whole area of fuel.

7.2.2. Fire ventilation

Only in the first three incidents did roof venting occur early enough to aid fire-fighting. The combination of asbestos cement cladding and PVC rooflights was particularly effective in venting the burning crates of furniture in incident 1, and corrugated asbestos cement alone vented the timber fire in incident 2 before the fire had spread. In incident 3 the GRP rooflights failed in about 5 minutes when subjected to a strongly burning liquid fire, but before failure, the building was smoke logged.

Although corrugated asbestos cladding was present in the fourth incident it was lined throughout with fibre insulation board. This served to protect the cladding while fire spread rapidly along under the insulation board, which also added significantly to the fire load. The bitumen covered timber roof on a 'Belfast' truss (incident 5) formed a high fire load in the most favourable position to be ignited by a fire occurring anywhere within the building. The timber roof supports were similar in thickness to the cladding and this resulted in the frame collapsing before the cladding burned through.

Incident 6. The corrugated iron roof remained intact until fire had spread past a 'makeshift' partition into the chipboard store.

Incident 7. Although corrugated asbestos formed the roof and part of the walls it was lined with plasterboard to reduce thermal losses. The lining protected the cladding which remained intact for more than 1 hour. GRP rooflights similar to those in incident 3 were present, but in this case the fire burned relatively slowly as the cardboard cartons were stacked flat. The hot gases under the roof were at a lower temperature than in incident 3, and the lined roof and GRP rooflights remained in position until flashover which coincided with the arrival of the fire brigade.

Incident 8. The warehouse contained more than 100,000 assembled cardboard cartons each holding 12 corrugated paper separating wraps for bottles. Also present were more than 2000 tons of cardboard reels in stacks. When ignited the cartons burned and spread fire very rapidly and although the roof was of corrugated asbestos cement, roof venting did not occur soons enough to prevent the fire spreading to all the contents of the building.

Incident 9. This building was a central warehouse for a large chain of retail stores. Wrapped and packaged consumer goods were stored on racks up to 3.6 m high. Staff saw the fire while it was still small but their attempts to tackle it with extinguishers and hose reels were unsuccessful. Fire spread very quickly over the goods wrapped in paper and corrugated cardboard so that when the sprinklers operated several minutes later the fire was already large in area; twenty heads opened in rapid succession. The upper racks of goods shielded those beneath from the sprinklers. The slate roof on timber boarding and the wired glass rooflights remained intact for about 10 minutes, and when the roof did fail it vented slowly and progressively. Hence at any time the vent area was insufficient for the corresponding fire area and eventually resulted in the formation of long flames under the roof (see Appendix 4). A major factor which contributed to the final size of this fire was that the fire brigade was not called until about 10 minutes after the fire was first seen. According to data analysed by Melinek[7], the known delay of 10 minutes in summoning the fire brigade increased the probability that the loss would exceed £10,000 by almost a factor of two.

7.2.3. Fuel. Comparison of burning rate data from fire incidents and experimental fire tests

Data obtained from experimental fires in compartments[3] are included in this section for comparison. The total wood equivalent and the fuel consumed were estimated from the owners descriptions of the contents and from photographs taken after the fire. These figures are, of necessity, approximate. The figures for fuel consumed do not include material that was spoiled by heat, smoke or water.

The percentage of the total fuel consumed is included as it provides an indication of the salvable contents.

The estimated rate of burning is the total rate of heat output in megawatts (10^6W) of the whole fire area and is a measure of fire size.

The equivalent fire load density consumed is the mass of fuel burned, divided by the fire area. This ratio is often quoted for experimental fires.

The final columns list the estimated burning rates for the building and experimental fires. A net calorific value of 13 MJ per kilogram was assumed for the cellulosic fuels to determine these. The figure in column 13 was calculated on the basis that the fire load was evenly distributed over the whole floor and is applicable to most of the fire incidents where racks or stacked goods formed the fuel and fire involved more than one stack. Only the fire involving cardboard cartons (incident 8a) burned at a greater rate than the largest crib fire. That cardboard cartons burn very quickly was confirmed quantitatively from observations of flame height and duration of burning in an ad hoc test carried out by the author in 1966. In this test long cardboard cartons were stacked in a manner similar to the wood cribs in the same compartment used for the crib tests. The results are listed under 'cardboard' at the bottom of tables 2a and 2b. The rate of burning estimated for the cardboard fuel was similar to that of the largest crib fire (column 12). In three incidents (2, 3 and 7) the fuel was present in a specific area only and for these cases the burning rates and crib results listed in column 12 should be compared. These figures are burning rates per unit floor area of each fire or crib alone and are representative of fires in discrete piles of fuel.

7.3. Table 3. Difficulties during fire fighting and the effects of fire on the buildings

7.3.1. Percentage of compartment area involved in fire

The percentage of the compartment area covered by the burning fuel shows whether roof venting was effective in preventing fire spread. In incidents 2 and 3 the bulk of the fuels present covered a small area only and venting did prevent combustibles remote from the fire being ignited. In incident 3, however, the whole building became smoke logged before the GRP rooflights failed. Although most of the fuel was in a relatively small part of the building in incident 7, the fire filled the building with smoke and hot gases which started many small secondary fires over the whole of the floor area.

The buildings in incidents 4 to 9 were all smoke logged and this can affect ease of escape. The civilian who discovered the fire in a room at the end of a corridor (incident 4) saw flames burst through the ceiling lining between him and the exit. He was only able to escape by crawling beneath the rapidly deepening layer of smoke and hot gases. Firemen had great difficulty in leaving the very large warehouse in incident 9 as conditions inside became suddenly worse when the tops of many stacks of goods were ignited by long flames under the roof. (The length of these flames is calculated in Appendix 4 of this note). The men had to find their way out of a strange building containing many obstacles in zero visibility.

7.3.2. Duration of fire-fighting

The duration of fire-fighting is the time from arrival of the brigade to the time when the fire is under control. This may be less than or it may exceed the duration of burning although when many incidents are considered the two averages may be similar. The duration of fire-fighting should not however be used as fire duration in calculating rates of burning for specific incidents as individual variations may be sufficiently great to render such results meaningless.

7.3.3. Comments on fire-fighting

One of the principal benefits of roof venting is the formation of a smoke-free layer above the floor. The comments on fire-fighting are those of fire brigade personnel with direct knowledge of each fire and describe the problems arising from the absence of effective venting.

8. APPENDIX 2. ESTIMATION OF FIRE DURATION

This figure is the period for which the fire was burning strongly and does not include the time when the fire was small. When possible it was derived from the depth of charring of timber subjected to the fire for the full duration. For example, in incident 1 a piece of wood surrounded by flames was charred to a depth of about 20 mm ($\frac{3}{4}$ in). The rate of char quoted[8] for these conditions is 11×10^{-6} m/s (approx. $^1/40$ in/min).

$$\text{Hence duration} = \frac{\text{char depth (m/s)} \times 10^6}{11}$$

$$= \frac{20 \times 10^{-3} \times 10^6}{11} = 1820 \text{ s}$$

$$= 30 \text{ minutes}$$

In the same incident a wood door about 4.5 m from the fire was irradiated by the flames but not immersed in them, and therefore a different rate of char applies. The char depth observed was about 32 mm ($1\frac{1}{4}$ in) for a duration of about 30 min. The rate of char was therefore 18×10^{-6} m/s. For these circumstances the charring rate is related to the intensity of radiation and according to Butler[9] is given by (in S.I. units)

$$R = 3.67 \times 10^{-2} \ H \quad \text{where} \quad R = \text{rate of char m.s}^{-1}$$

$$H = \text{intensity of radiation W.m}^{-2}$$

$$\text{Hence } H = \frac{R}{3.67} \times 10^{-2}$$

$$= \frac{18 \times 10^{-6}}{3.67 \times 10^{-2}}$$

$$= 4.8 \times 10^{-4} \text{ W.m}^{-2} \ (4.8 \text{ W cm}^{-2})$$

In the first seven incidents timber was present in the hot gases from the fire and the former rate of char used to determine duration. In addition, in incident 5, timber doors 2.5 cm thick were charred through. In the early stages of the fire these doors were exposed to radiation in circumstances similar to incident 1, then as the building became smoke logged the doors became immersed in the hot gases. An average of the two char rates produced a duration of about 30 minutes. This agreed with the duration determined from the roof timbers which were subjected to hot gases until collapse.

The fire conditions in incident 7 were different from those of the other incidents as fire spread rapidly in the early stages and then became starved of air as the building was smoke logged before the lined roof or windows failed. This resulted in a slow rate of burning. Messrs Colt Ventilation Ltd suggested that a leakage rate of between one and two air changes per hour might be appropriate for this construction producing an air flow rate of about 10 kg/s. By extrapolation from Table 3 of Hinkley's paper[10] this gave an equivalent window area of about 10 m^2. The fire load, the area of the internal surfaces of the building and the equivalent window area enabled the equivalent furnace time to be estimated using the relationship quoted by Margaret Law[11].

$$\text{Equivalent furnace time} = \frac{\text{fire load}}{(A_W \times A_T)^{\frac{1}{2}}}$$

where A_W = window area m^2

A_T = area of internal surface of building m^2

$$= \frac{28.5 \times 10^3}{(10 \times 5.65 \times 10^3)^{\frac{1}{2}}}$$

$$= 120 \text{ min}$$

To withstand the actual fire the steelwork would have required a fire resistance of about 2 hours. It would appear from the construction of the building that its fire resistance was considerably less than this which is confirmed by the fact that partial collapse occurred.

The actual fire duration determined from the depth charred of some roof timbers was about 80 minutes, but since fire duration and furnace time cannot be equated directly this is not inconsistent with the furnace time calculated above. However, the air flow into this building was very low and may have been insufficient to maintain flaming combustion. The value of $A_T/A_W\sqrt{H}$, where H is the window height in metres, was about 230 $m^{-\frac{1}{2}}$ which is much higher than the value of 100 $m^{-\frac{1}{2}}$ suggested by Thomas[12] as being an upper limit for the production of high temperatures.

In incidents 8 and 9 people became aware of the fire in its early stages or were present at the start of the fire, so the durations were known for these incidents.

9. APPENDIX 3. CALCULATION OF DEPTH OF HOT GASES, INCIDENTS 1-3

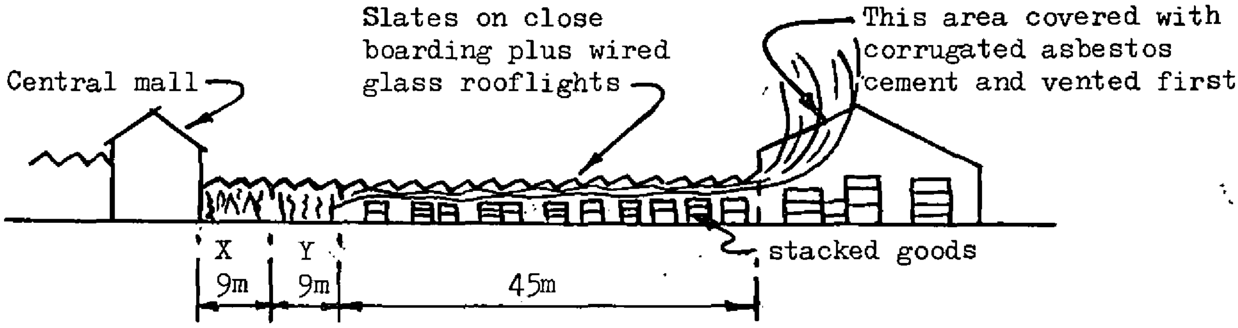
To use nomogram 6 of FR Technical Paper No.7[2], the ceiling height h_c, the perimeter of fire w_f and the square root of the effective vent area $(a_v)^{\frac{1}{2}}$ are required. A discharge coefficient of 0.6 was assumed for the vent areas. These are listed below with the depth of layer of hot gases, d_b, obtained from the nomogram. Also given are values assessed by witnesses at each incident. As the values expressed in f.p.s. units for these incidents could be used directly in the nomogram, the layer depth is given in feet with the metric equivalent.

Incident No.	Perimeter of fire w_f (1)	Ceiling height h_c	Effective vent area a_v (2)	$(a_v)^{\frac{1}{2}}$	Depth of layer of hot gases (calculated)		Depth of layer of hot gases (observed)	
	ft	ft	ft^2	ft	ft	m	ft	m
1	40	11	225 x 0.6	11.6	2	0.6	2.5	0.75
2	54	12	300 x 0.6	13.4	2	0.6	2	0.6
3	34 (3) 68	10 (3) 20	70 x 0.6	6.5 (3) 13	3.3 6.6	1.1	3	0.9

1. From observed floor area damaged by fire.
2. From photographs of area of roof damage.
3. For this incident the value for perimeter of fire was off the scale of the nomogram. As these scales are dimensionless, the values of w_f, h_c and $(a_v)^{\frac{1}{2}}$ were doubled which gave double the layer depth for the hot gases (lower line in table). The corresponding layer depth for the original values of w_f, h_c and a_v is therefore half the value determined from the nomogram.

10. APPENDIX 4. CALCULATION OF HORIZONTAL LENGTH OF FLAMES UNDER THE ROOF IN INCIDENT 9

In FR 712[13], Hinkley, Wraight and Theobald gave formulae for calculating horizontal flame lengths. Incident 9 supplied an opportunity to test this method of calculation. Firemen saw long flames under the roof from the bay of origin to the region roofed with asbestos cement sheet.



Assume flames produced by fire in bay Y, 9m across.

From column 10 Table 2b, burning rate, $m^1 = 450\ kg/m^2$ in 3 h

$= 0.0417\ kg/m^2/s$

From FR 712, for unit width of flame,

$$l = 220 \left(\frac{m^1}{\rho_o}\right)^{\frac{2}{3}} \times \frac{1}{g^{\frac{1}{3}}}$$

l = horizontal flame length

ρ_o = density of air at ambient temperature

g = gravitational constant

$$= 220 \left(\frac{0.0417 \times 9}{1.2}\right)^{\frac{2}{3}} \times \frac{1}{(9.81)^{\frac{1}{3}}} \text{ in S.I. units}$$

$$= 220\ (0.312)^{\frac{2}{3}} \times \frac{1}{2.1}$$

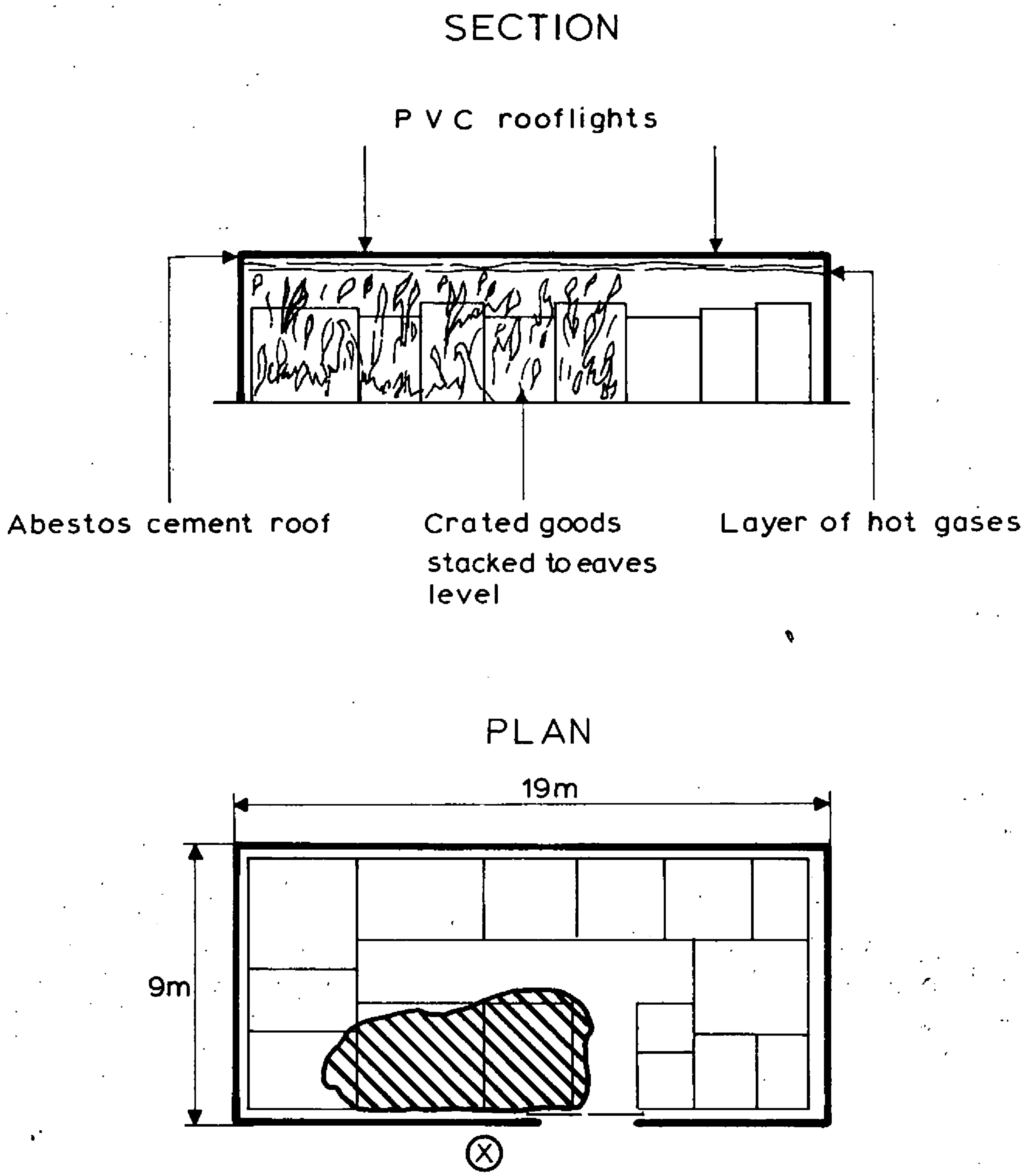
$$\simeq 50\ m$$

If the flames were air-rich

$$\frac{m^1}{\rho_o \cdot g^{\frac{1}{2}} \cdot d^{3/2}} < 0.025$$

Flames under the roof were about 1 m deep, i.e. d = 1

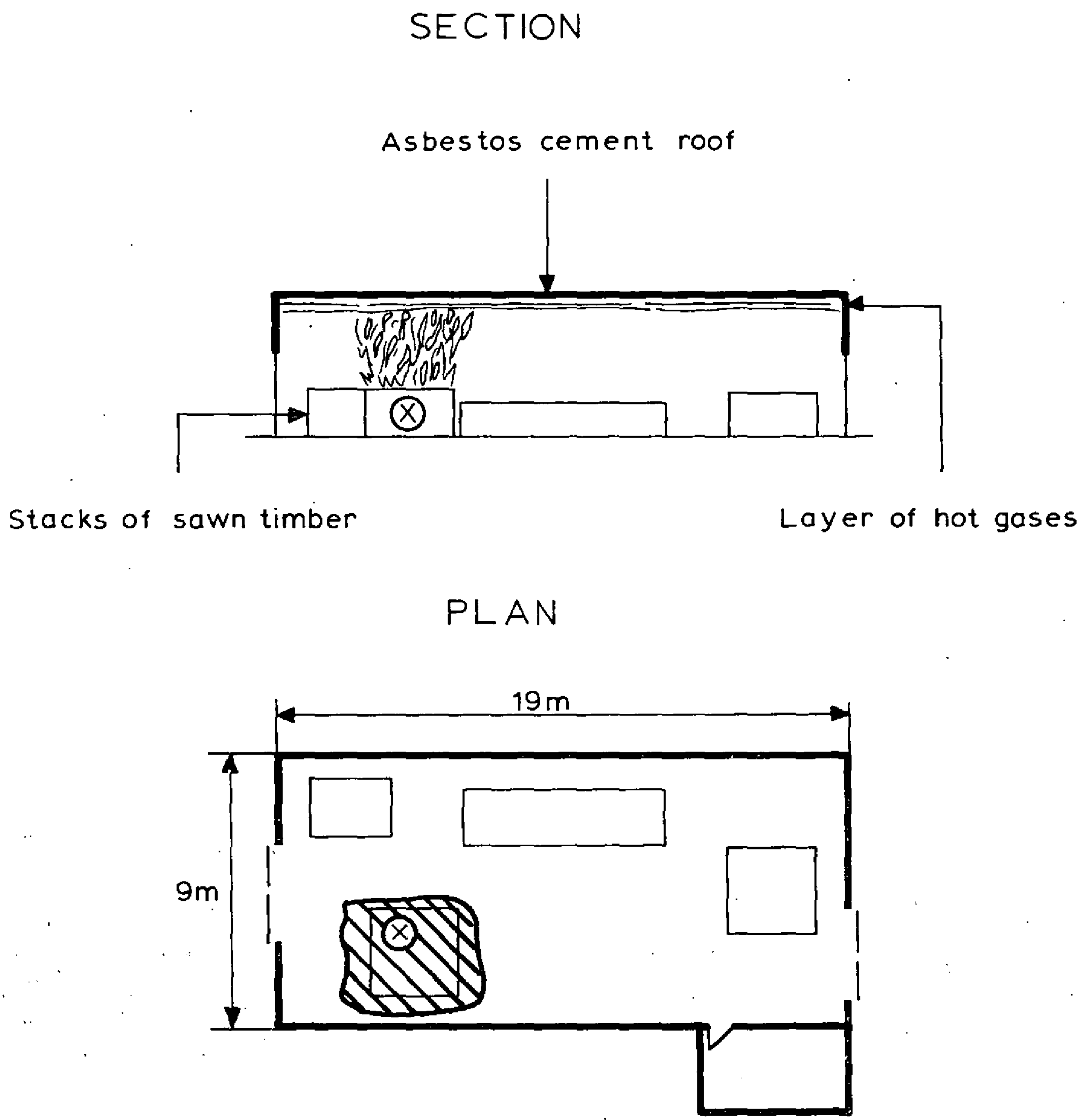
$\frac{0.0417 \times 9}{1.2 \times 3.24 \times 1^{3/2}} = \frac{0.376}{3.89} = 0.097$: this value exceeds 0.025, therefore the flames under the roof were fuel-rich and would have been much longer than the length of 50 m calculated assuming the flames were air-rich.



Total fire load 140 000 Kg
Fuel consumed 450 Kg
Fire duration 30 min
Scale 1/200

Fire origin ⊗
Area affected by fire

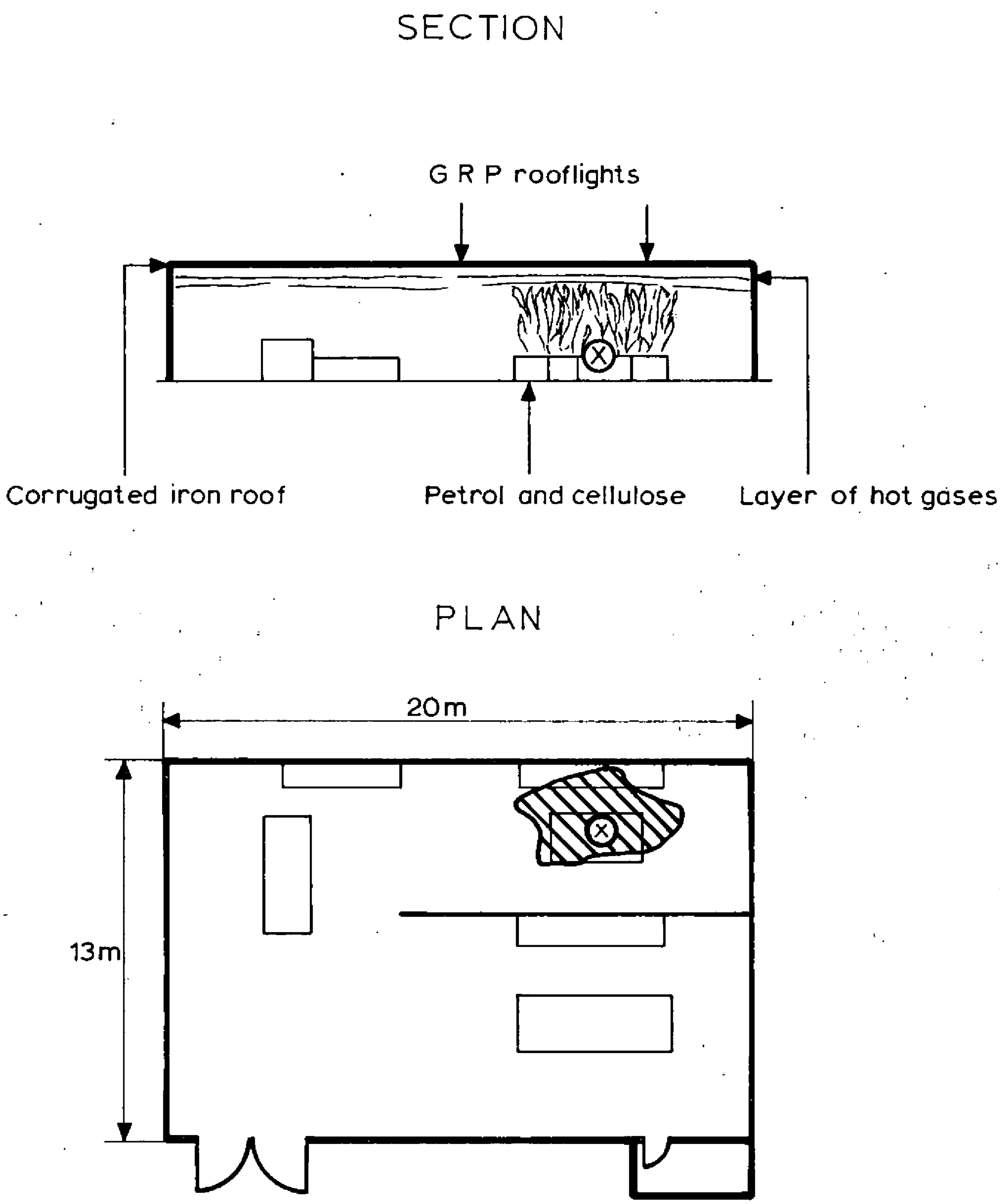
FIG 1 STORAGE BUILDING



Total fire load 4500 Kg
Fuel consumed 730 Kg
Fire duration 45 min

Fire origin ⊗
Area affected by fire \\\
Scale 1/200

FIG 2 WORKSHOP

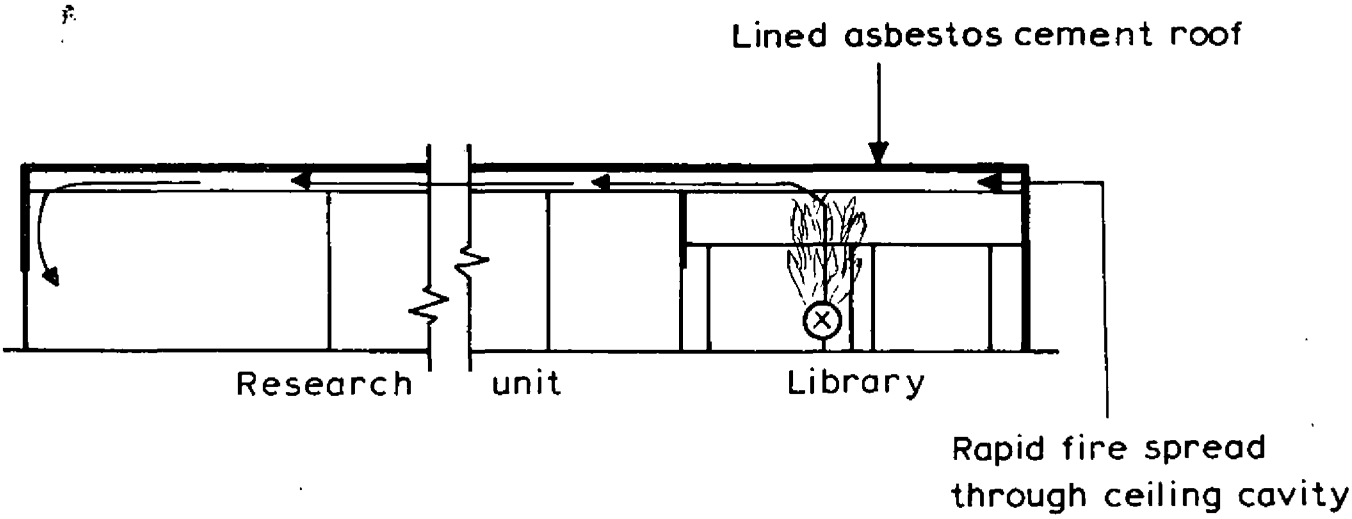


Total fire load 145 Kg
Fuel consumed 36 Kg
Fire duration 5 min

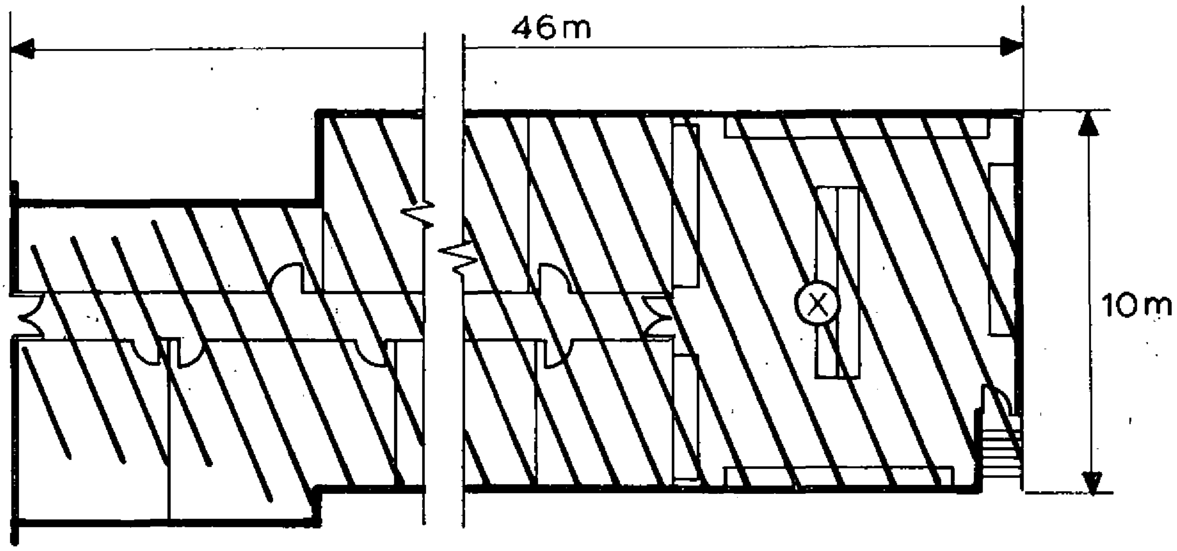
Fire origin ⊗
Area affected by fire ///
Scale 1/ 200

FIG 3 WORKSHOP

SECTION



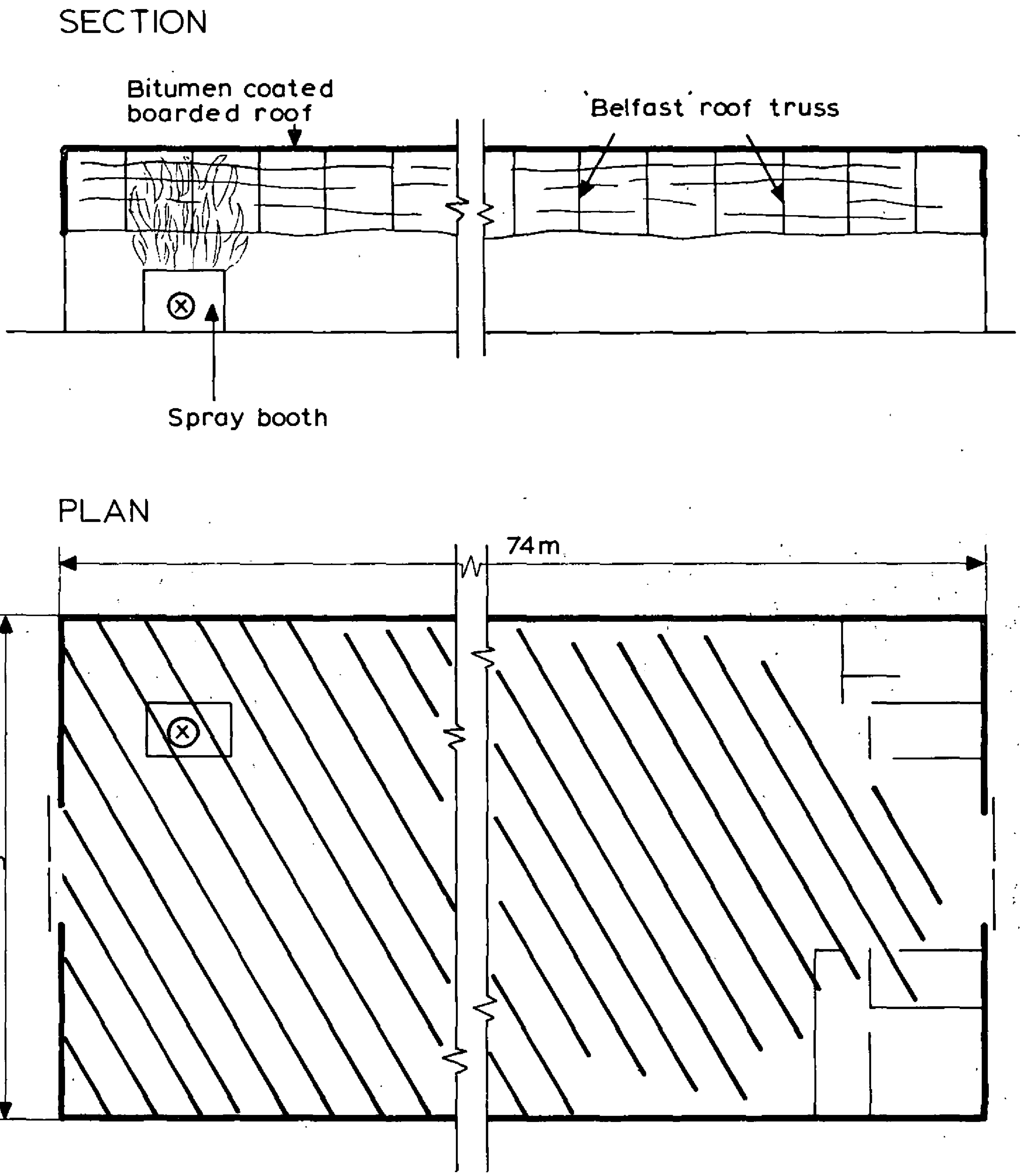
PLAN



Total fire load	44 000 Kg
Fuel consumed	11 000 Kg
Fire duration	60 min
Fire origin	⊗
Area affected by fire	\\\

Scale: 1/200

FIG 4 LIBRARY AND RESEARCH UNIT

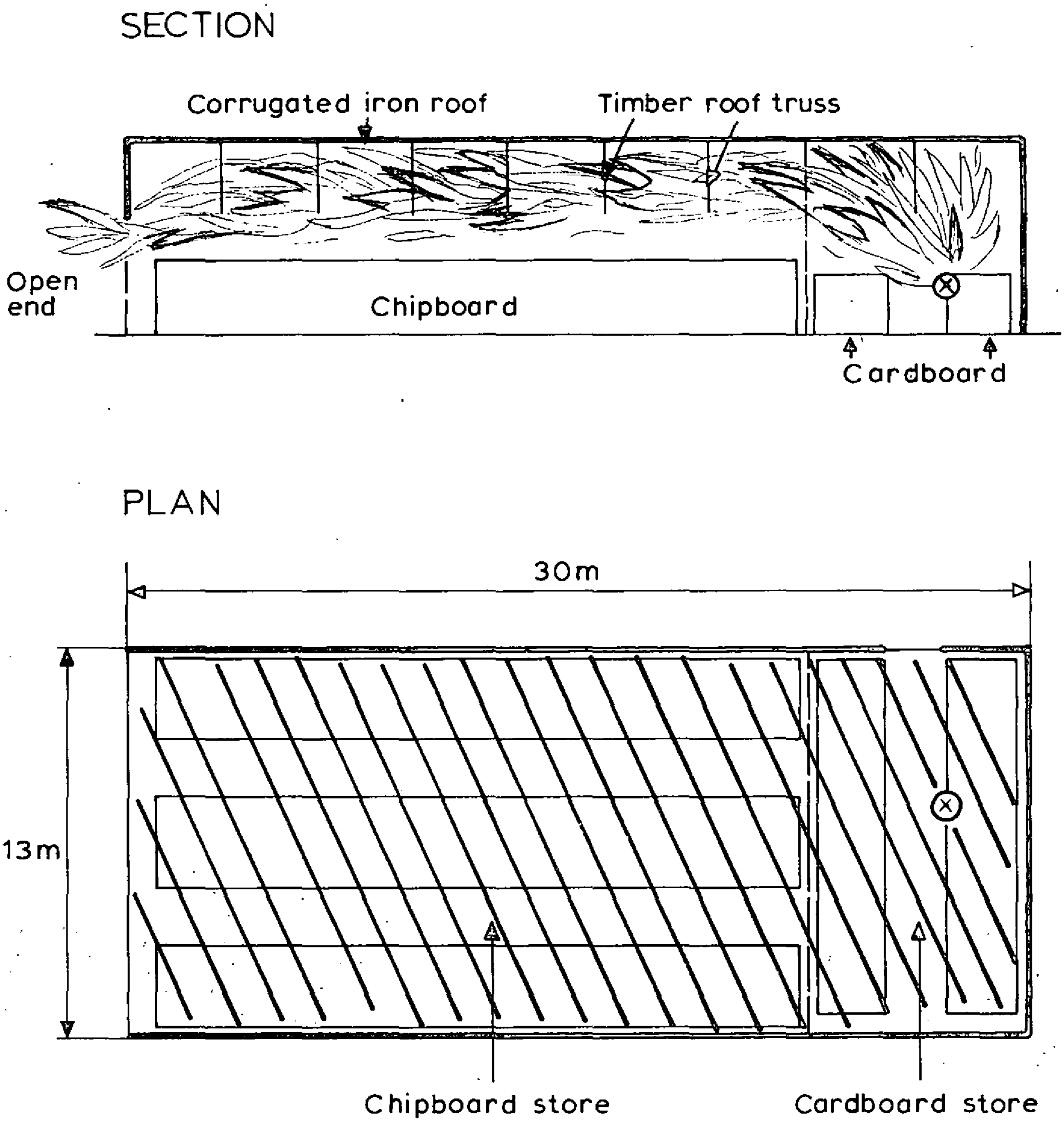


Total fire load (timber roof) 40 000
Fuel consumed 34 000
Fire duration 30 min

Fire origin ⊗
Area affected by fire ///

Scale 1/200

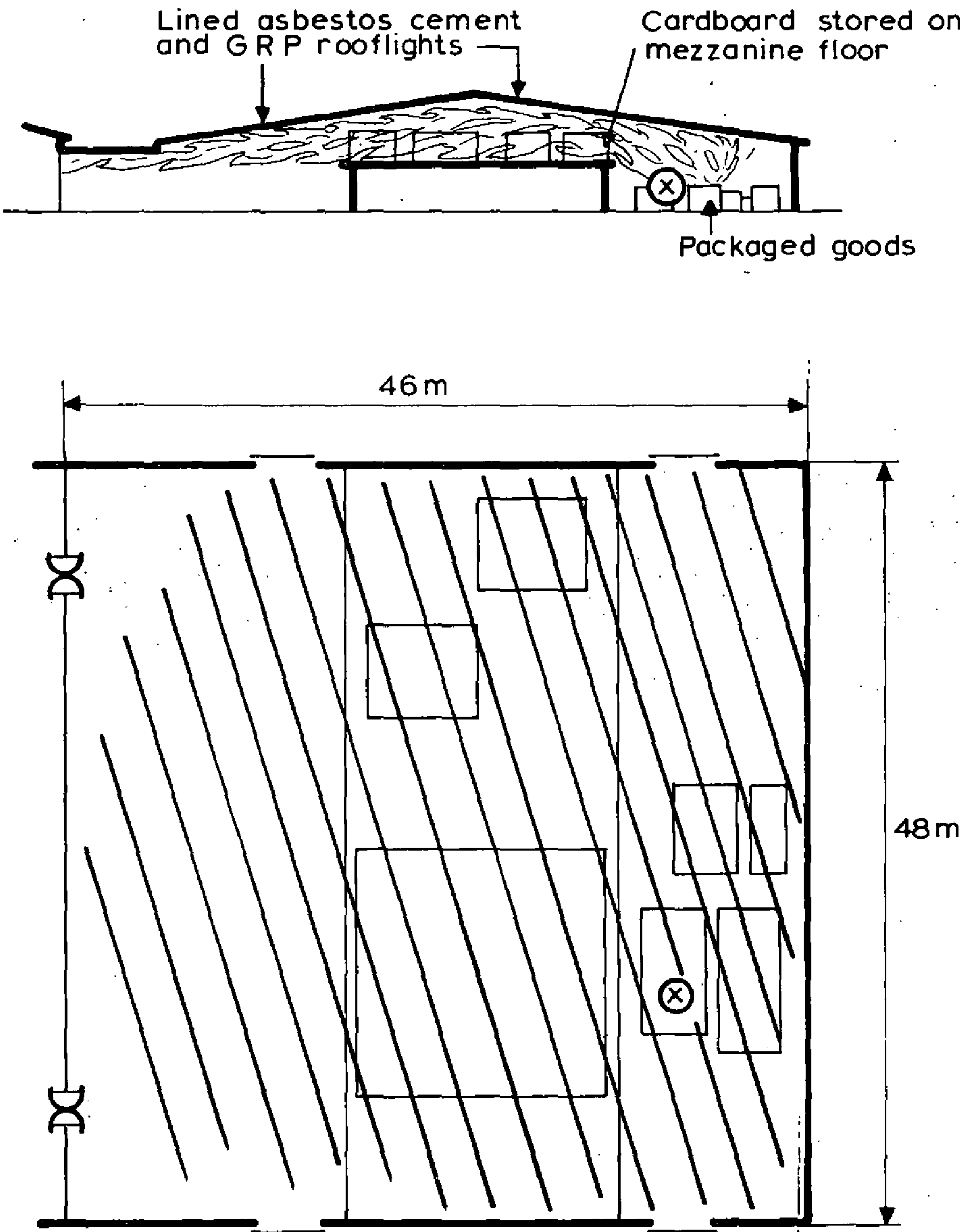
FIG 5 FACTORY



	Chipboard store	Cardboard store
Total fire load	220 000 Kg	16 500 Kg
Fuel consumed	1 800 Kg	5 400 Kg
Fire duration	15 min	40 min

Fire origin ⊗
Area affected by fire ///
Scale 1/200

FIG 6 STORE



Total fire load 116 000

Fuel consumed 28 600

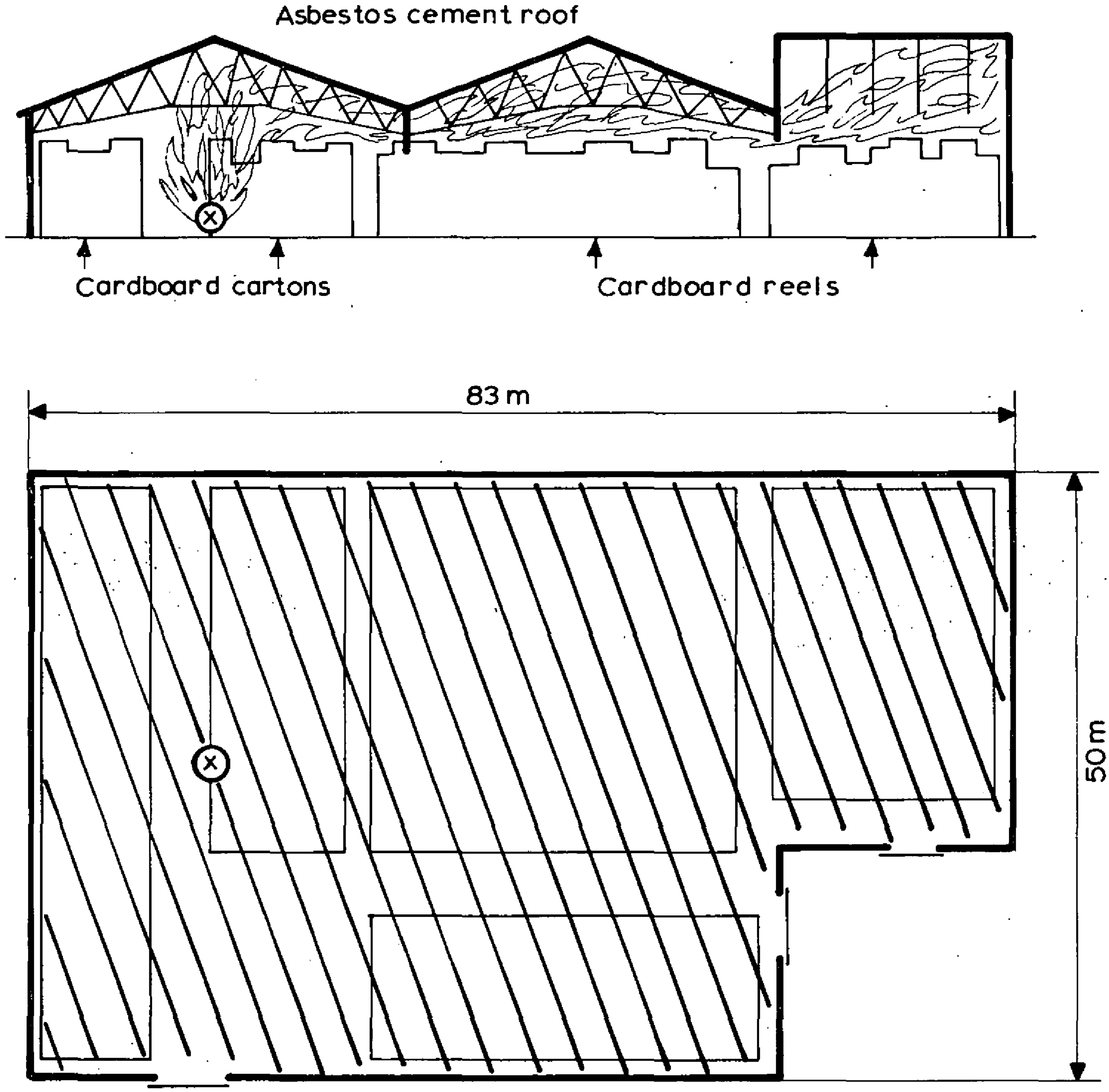
Fire duration 80 min

Fire origin ⊗

Area affected by fire ///

Scale 1/400

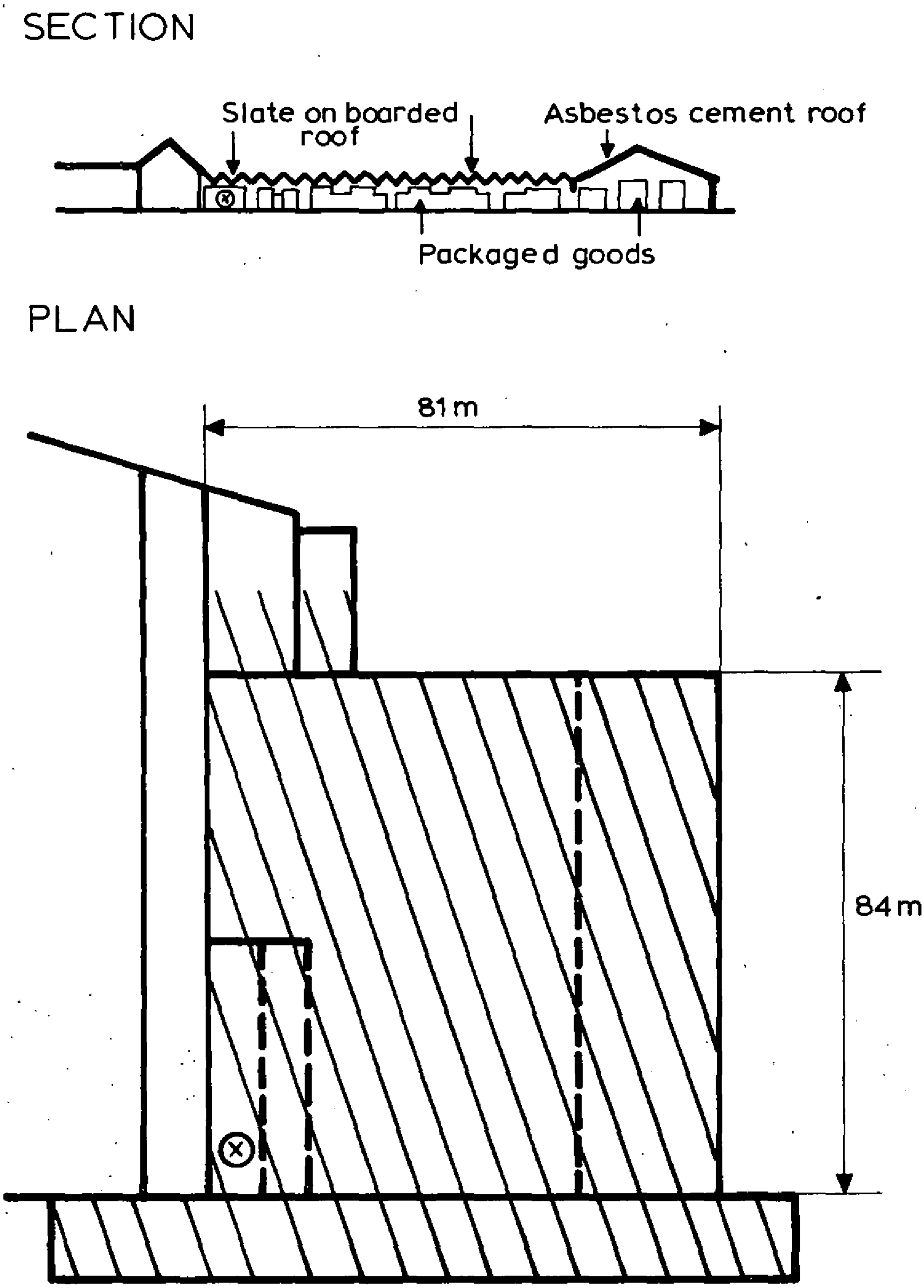
FIG 7 FACTORY



	Cardboard cartons	Cardboard reels
Total fire load	113 000 Kg	2 540 000 Kg
Fuel consumed	113 000 Kg	510 000 Kg
Fire duration	30 min	210 min

Fire origin ⊗
Area affected ////
Scale 1/500

FIG 8 WAREHOUSE



Total fire load	7 200 000 Kg
Fuel consumed	3 740 000 Kg
Fire duration	180 min
Fire origin	⊗
Area affected by fire	///

Scale 1/1000

FIG 9 WAREHOUSE