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THE USE OF HIGH AND LOW PRESSURE WATER SPRAYS AGAINST FULLY DEVELOPED ROOM FIRES

by

D. Hird, R. W. Pickard, D. W. Fittes and P. Nash

Summary

This report describes extinction tests on fully-developed fires in furnished rooms, using a trigger-operated gun at nozzle pressures in the range 80-500 lb/sq.in^2 at rates of application from 5 to 25 gal/min.

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1. Introduction

The proportion of fires in buildings which are extinguished by hose reel jets has steadily increased since the war until now 75% of the fires in which water is applied by fire brigade equipment are extinguished in this way. This increased use has stimulated interest in obtaining the most efficient application of the limited amount of water which can be carried on the first aid appliance. The following factors might be expected to influence the amount of water used with hose reel equipment.

(a) The rate of application of water. For water, as for other extinguishing agents, there is a "critical" rate of application for a given size of fire, below which the fire cannot be extinguished. There may also be an "optimum" rate of application at which a given fire can be extinguished with the minimum amount of water.

(b) The method of application - by spray or jet. The cooling or smothering action of water in a fire depends on the rate at which heat can be taken up by the water. Since it may be possible to increase the rate of heat transfer by increasing the surface area of the water, it might be supposed that sprays would be superior to jets in some conditions.

(c) The nozzle pressure of sprays. Increasing nozzle pressure can be expected to reduce the droplet size of a spray, although most evidence suggests[(1)(2)] that there is little reduction for pressures greater than 100 - 150 p.s.i. Nozzle pressure also affects the throw of a spray [(3)].

Other less easily defined factors, such as the degree of control which can be exercised by the branchman, may also affect the efficiency of extinction.

Operational problems may be associated with variations in any of these factors. For instance, an increase in either pressure or rate of flow increases the reaction at the nozzle, which at some stage will affect the manoevrability; an increase in the rate of flow increases the pressure drop in the hose which may have to be offset by an increase in hose diameter or pump pressure.

When all these variables are coupled with the natural variability of fires attended by Fire Brigades, it is not surprising that it is difficult from operational experience to assess the separate effects of pressure, rate of flow and method of application. However, information is required on these separate effects to help in the design of more efficient equipment, and because of this the Joint Fire Research Organization, at the request of Chief Scientific Adviser and H. M. Chief Inspector of Fire Services, Home Office, undertook a series of tests designed to investigate the effects of pressure, rate of flow and method of application on the extinction of fires in buildings.

The extinction tests were made on fully-developed fires in rooms of a size chosen to represent approximately the upper limit of the present use of hose reel jets, at which any differences in efficiency are likely to become important.

2. Previous work

Surprisingly few controlled extinction tests have been made on fires in buildings so there is not very much information to draw on. The results of the most important large scale tests are summarised in Table 1.

Table 1. Summary of extinction tests in rooms

Type and size of fire	Rate of application gal/1000cu.ft/min	Jet or spray	Pressure p.s.i	Ventilation ft^2/ft^3	Water used to control fire gal/1000ft^3
National Board of Fire Underwriters(4)	60	spray	100	0.1	9.5
	19	spray	100	0.1	9.5
850 cu.ft room lined with fibre insulating board and containing wood and shavings	21	spray	600	0.1	13.0
	15	spray	300	0.1	11.8
	22	spray	600	0.1	10.0
	16	spray	300	0.1	5.4
	116	spray	50	0.1	12.6
	30	spray	200	0.1	4.3
	35	spray & jet	600	0.1	16
	61	jet	50	0.1	16.4
	9	jet	600	0.1	6.2
Wartime experimental fires at Building Research Station	2.4 (3 stirrup pumps)			0.015	22.5
1900 cu.ft rooom furnished with approx. 6 lb/ft^2	0.8 - 1.6 (1&2 stirrup pumps)			0.015	15
Wartime experimental fires 1424 cu.ft room	7.6	jet	100	0.04	15.5
	7.3	spray	100	0.04	14.8
	6.7	spray	100	0.04	not controlled
furnished with approx. 6 lb/ft^2	7.5	spray	100	0.04	14.8
Joint Fire Research Organization(5) 'Birmingham tests'	32	spray	100	0.01	8
	32	spray	100	0.01	8
1250 and 1750 cu.ft furnished with approx. 6 lb/ft^2	32	jet	100	0.01	8.5
	32	jet	100	0.01	5.8
	32	spray	100	0.01	5.3
	23	jet	100	0.01	8.6
	23	spray	100	0.01	5.7
Joint Fire Research Organization 512 cu.ft room lined with fibre insulating board and containing no furniture	4.4	spray	120	0.026	1.8
	3.0	spray	60	0.026	1.2
	4.4	spray	120	0.026	1.8
	4.8	jet	175	0.026	1.6
	4.8	jet	175	0.034	1.6
	4.8	jet	175	0.034	2.0

The amount and arrangement of furniture, type of nozzle, stage of the fire at which extinction was commenced and the ventilation and rate of application of water, differ widely in these tests. With the exception of the 512 cu.ft room, which was the only one unfurnished the amount of water used to control the fire does not vary very widely and it is not possible to discern any separate effects of the different factors. More information can be inferred from the results obtained by Thomas and Smart (6) on small scale models of burning rooms. The rooms were unfurnished and were lined with combustible material. The effects of ventilation, rate of flow and method of application were investigated and the results indicated that:-

(a) The amount of water required to extinguish a fully developed room fire is very small if it is applied efficiently, while control was achieved with as little as 2 gall/1000 cu.ft in the experiments, it was thought likely that this would be increased to 5 - 10 gall per 1000 cu. ft under full-scale operational conditions.

(b) The quantity of water required to extinguish the fires in the models increased with increasing ventilation, and also as the rate of application of water increased.

(c) The amount of water used by a spray was the same or less than that used by a jet to control the same fire. The difference became more marked as the rate of application of water was increased.

The only published information on the amount of water used to extinguish different types of fire under operational conditions is given by Mobius (7). One brigade reported the performance of two spray nozzles against 211 fires, not including small fires confined to furniture. The nozzles delivered between 25 and 30 gallons per minute at pressures between 60 and 85 p.s.i. The reports contained information on the type of fire, the nature of the combustible materials and the amounts of water used. The minimum amount of water used per fire was about 100 gallons; the amount of water increased with the ventilation and with the amount of "glowing" (fires in straw, textiles and upholstery etc. were defined as "glowing" fires). Mobius concluded that rapid extinction was obtained in rooms when the dimensions of the rooms were less than the throw of the spray. He also suggested that the ideal nozzle would be one in which the branchman could control the spray pattern and the rate of flow.

3. Test Programme

In the main test programme, it was required to investigate the effect of pressure on the amount of water, applied as a spray, necessary to control and extinguish a fully developed fire in a room. The range of pressures to be used was 80 - 500 lb/sq.in. for flow rates from 5 to 25 gal/min. During the course of the tests it was decided to include further tests to compare the effectiveness of water applied as a jet. These tests were made over the same range of flow rates at a pressure of 80 lb/sq.in. The main programme thus consisted of 50 tests:-

<u>SPRAY</u> 2 tests at 5, 10, 15, 20, 25 g.p.m. at each of the following pressures:- 80, 125, 225, and 500 p.s.i.) 40 tests

These tests were randomised.

<u>JET</u>. 2 tests at 80 p.s.i. at 5, 10, 15, 20 and 25 g.p.m.) 10 tests.

These tests were randomised amongst themselves.

Provision was also made for fourteen preliminary tests with three main objects; first to determine if any measurable property of the fire could be used to obviate a subjective assessment of the condition of the fire during extinction; second to develop a suitable test procedure; third to train the branchman so that he should have approached his maximum efficiency with this type of fire before starting on the main programme. Seven tests were made with a flow rate of 10 g.p.m. at 80 p.s.i. and seven at 25 g.p.m. and 500 p.s.i.

4. Test Fire

The test fires were designed to represent a fully developed room fire. A 1750 cu. ft room with ample ventilation (.035 ft^2/ft^3) was used and a plan of the room with details of the furniture is given in Figs. 1, 2 & 3. The fire load was $6\frac{1}{2}$ lb/ft^2 (52,000 B.Th.U/ft^2) and consisted of a floor of $\frac{1}{2}$ inch timber and simple "mock-up" furniture of 1 inch timber. All the wood was kiln dried but because of the large amounts used it was not possible to maintain the moisture content constant throughout the series of tests, and it varied from $9\frac{1}{2}$% to 15%. The fires were started in the two boxes shown in Fig. 1 by burning a $\frac{1}{2}$ pint of petrol in trays $\frac{1}{2}$ ft^2 in area. The fires were started in this way so that they would spread to involve the whole room as quickly as possible and in the majority of tests the room was fully involved in fire within $3\frac{1}{2}$ minutes. In some tests, however, the fire took longer to develop and this was generally, although not always, associated with a high moisture content of the furniture. The effects of this on the test results are discussed later. Temperature records for the tests were provided from nine 26 s.w.g. chromel-alumel thermocouples connected in series and mounted within an inch of the ceiling.

Before any extinction tests, a test fire was made to decide the stage at which extinction should be attempted and also to confirm that the fire would last long enough for the extinction tests at the lowest rates of application, when extinction might be expected to take a considerable time. The time-temperature curve of this preliminary fire is shown in Fig. 4.

5. Test Nozzles and Equipment

It was decided to use spray nozzles of the impinging jet type, on which much previous experience existed. In order that any effects of pressure on the droplet size of the sprays would not be masked, the orifice sizes were kept constant at 1/16 inch in all the nozzles. The rate of flow at a given pressure was therefore increased by increasing the number of pairs of impinging jets and not their size. Slight manufacturing differences, as well as the fact that the rate of flow per pair of impinging jets does not increase quite as rapidly with pressure as would be expected, produced some variations from the predicted flow rates. It was decided to keep the flow rates constant at the agreed levels for the test programme and to do this the pressures were adjusted around the four chosen levels. The numbers of pairs of impinging jets used for the different nozzles are given in Table 2 and the actual pressures used to give the desired flow rates are shown in parenthesis. Fig. 5 shows the final form of some of the nozzles.

Table 2. Details of Nozzle Design

No. of pairs of 1/16" impinging jets required				
pressure p.s.i. / Rate of flow (g.p.m.)	80	120	225	500
5	5 (78)	4 (128)	3 (232)	2 (490)
10	10 (79)	8 (125)	6 (250)	4 (485)
15	15 (81)	12 (121)	9 (210)	6 (510)
20	20 (73)	16 (130)	12 (213)	8 (495)
25	25 (85)	20 (121)	15 (240)	10 (520)

The angle of impingement of the jets was 60° and the angles of divergence of the two rings of impinging jets (Fig. 6) were chosen to give as uniform a distribution of water as possible in the 30° cone angle of the spray. The cone angle of a spray is generally taken as the angle of the spray at the nozzle. However, with small numbers of pairs of impinging jets this is not well defined and it was therefore decided to define the cone angle as that angle subtended at the nozzle by the area wetted by 90 per cent of the water on a plane perpendicular to the axis of the nozzle and at a distance of 8 feet. The cone angle was substantially the same for all pressures and rates of application.

The nozzles were fitted to a trigger-operated gun (Fig. 7) which was modified proprietary equipment. The trigger was fitted with a switch connected to a recorder so that the time for which water flowed through the nozzle could be recorded automatically.

6. Spray Properties

Variations in nozzle pressure and rate of flow can produce changes in a number of spray properties such as throw, velocity of entrained air, water distribution and droplet size. Rasbash et alia [8][9] and Fry and Smart [10] have examined some of these. It has been shown [9] that the force of the entrained air current of a spray increases with rate of flow and is approximately proportional to the square root of the nozzle pressure. Variations in a number of factors can affect the throw of a spray and an empirical formula has been derived [3] from the examination of many spray patterns which gives the throw of a spray (T) in terms of nozzle pressure (P), rate of flow (R) and cone angle (θ).

$$T = \frac{KR^{\frac{1}{2}}P^{\frac{1}{4}}}{\theta}$$

where K is a constant.

The mass median droplet size (D) of sprays of the impinging jet type designed to reduce coalescence to a minimum have been shown [8] to depend on both rate of flow and pressure. The droplet size increases with rate of flow, due to coalescence, and decreases with pressure in the following manner:

$$D = AP^{-x}$$

where A is a constant,

and the value of x depends upon the value of P, decreasing from 0.5 to 0.2 as the pressure is increased from 5 to 100 lb/in^2.

These measurements were made with nozzle pressures up to 150 lb/in^2 and since there is no information on this type of spray at higher pressures, the water distribution and mass median drop size were determined for a number of the sprays used in the extinction tests. These sprays were chosen to cover the range of variables used and the mass median droplet sizes are shown in Table 3.

Table 3. Drop size of sprays

Mass Median Drop Size mm			
Rate of flow gal/min \ Pressure lb/in^2	80	225	500
5	0.55	0.39	0.32
15	0.85	0.62	0.61
25	0.54	0.59	0.94

The effect of pressure on the mass median droplet size agrees reasonably with that suggested by Rasbash at the lower rates of flow. These relations are

$$D \propto P^{-0.3} \quad \text{at 5 gal/min.}$$
$$D \propto P^{-0.17} \quad \text{at 15 gal/min.}$$

At 25 gal/min however the droplet size increased with increasing pressure. The measurements of water distribution showed that the distribution of water in the sprays became less uniform as both pressure and rate of flow increased. The proportion of water in the centre of the spray increased with consequent increase of coalescence of the drops. This was most marked at 25 gal/min and 500 lb/in^2, and probably explains the high mass median droplet size found with this spray.

7. Preliminary Tests

The amount of water required to "control" the fire, that is, to reduce its intensity to a point at which a rapid redevelopment of the fire would not occur if the water application were stopped, had first to be determined. It was also decided to measure the amount of water required to "extinguish" the fire. The two terms "control" and "extinguish" were found to be unusually difficult to define for this type of fire. It was found in the preliminary tests that they could not be related to a given room temperature, as this temperature varied with the time taken to achieve control or extinction, presumably due to the cooling of the room. Typical temperature records of fires are shown in Fig. 8 and photographic sequences in Fig. 9. Radiation measurements proved unsatisfactory due to the screening effect of the smoke and steam produced in the early stage of the extinction and the very low values of radiation intensity when the fire neared control. It was necessary therefore to adopt an observer's assessment of "control" and "extinction".

The tests showed that the extinctions generally followed a similar pattern. The intensity of the fire was rapidly reduced when water was first applied, but if the application of water was stopped too early, the fire quickly regained its full intensity. This is indicated in the temperature record of Fig. 10 illustrating one of the preliminary tests in which the application of water was stopped when large volumes of steam were first seen issuing from the windows. The fire was considered to be "controlled" at a later stage when all the main flaming had ceased and only small pockets of flame were left which were unlikely to cause a rapid redevelopment of the fire. The later stages of the "extinction" consisted in putting out the smaller pockets of flame which remained. The room could be left for at least 10 minutes after "extinction" without any appreciable recurrence of flaming. Whilst the assessment of "extinction" by the observer and the branchman agreed, the branchman's assessment of "control" was generally a little later than that of the observer. However, since the branchman's estimate is the one which is important operationally, it was decided to use this during the main programme. It was evident after the first few preliminary tests that that the access of water would have to be improved to two of the boxes or a disproportionate time would probably be spent extinguishing the fire within them, and this might detract from the main objects of the programme. Boards were therefore removed from the rear face of boxes 1 and 2. (Fig. 1).

Finally, it was evident during these tests that extinction was much more difficult if the wind were easterly. With this condition, the branchman's vision was seriously impaired by hot air and smoke blowing out of the doorway. For this reason it was decided not to carry out any tests in the main programme with the wind in this direction.

8. Test Procedure in Main Programme

As a result of the preliminary tests the following test procedure was adopted in the main programme.

The rooms were furnished on the morning of the tests and the moisture content of the wood was measured. To obtain a mean value, the number of measurements made on the floor and furniture were proportional to the percentage of the total weight represented. The fire was started in the two boxes indicated in Fig. 1. Two minutes after the whole room had become involved ('flashover') water was applied continuously through the doorway until the branchman thought the fire "controlled". When the room had cleared of smoke and steam, water was reapplied, intermittently, at the discretion of the branchman until the fire was considered to be extinguished. A typical record of the water applied is shown in Fig. 11. No further water was applied for at least ten minutes, in order that any tendency to rekindle could be detected. In the fires which took longer to develop (Section 4) it was sometimes necessary to reduce the period between 'flashover' and the application of water to avoid complete destruction of some sections of the furniture.

The average wind speed and direction were measured during each test. Thickness and weight measurements were made on the furniture before and after the tests to determine the rate of burning.

9. Test Results for Sprays

The quantities of water used to "control" and "extinguish" the fires were determined for each test and the results are given in Table 4.

Table 4. Water used to control and extinguish fires

Flow rate Gal/min \ Pressure lb/in^2		Gallons							
		80		125		225		500	
5	Control	9.4	32.6*	3.6	35.6*	22.7+	7.3*	4.0	3.5
	Extinction	15.5	58.6	9.7	45.4	31.3	26.3	21.2	16.7
10	Control	7.7	5.3	7.7	6.5*	6.3	5.0	10.2*	4.8
	Extinction	12.8	14.2	18.5	25.7	6.3	9.9	22.3	16.5
15	Control	5.3	7.3	7.5	5.4	4.5	6.6*	5.8	5.4
	Extinction	10.2	23.0	17.3	12.5	6.3	28.5	12.9	20.8
20	Control	10.7	5.8	7.7	3.7	6.3	6.7	5.7	6.7
	Extinction	20.7	7.7	17.0	17.7	20.0	12.8	5.7	8.3
25	Control	14.6	7.3	4.2	9.8	11.3	10.2*	7.9	3.5
	Extinction	25.4	12.5	12.1	13.1	15.0	30.0	20.4	7.3

\+ Omissions were made in the preparation of this test which invalidated the results. The figures included have therefore been estimated.

* In these tests the fire took longer to develop (Section 8) and a considerable amount of the furniture had collapsed before the fire was tackled. This meant that instead of readily accessible surfaces, there were heaps of burning material which appeared to be more difficult to extinguish.

10. Analysis of results with sprays

In the analysis the logarithms of the quantities of water were used as being of a more normal distribution than the quantities themselves.

It is first necessary to decide whether the "starred" tests in Table 4 can be included in determining the effects of pressure and rate of application or whether they must be considered as tests carried out under different conditions from the unstarred tests. There is no apparent reason why the collapse of the furniture should affect the amount of water required to control the fire although there are good grounds for assuming that it would affect the amount of water used to extinguish it. Whereas there are two starred tests in which appreciably more water was used to control the fire than in the unstarred tests, more water was used to extinguish the fire in all the starred tests. Analysis shows that there is a highly significant difference (1% level) between the means of the amounts of water used to extinguish the fire in all the starred and unstarred tests.

Thus in analysing the results of the amount of water used to extinguish the fire there are good grounds for omitting the starred tests whereas they might be included in the analysis of water used to control.

The analysis has therefore been made with the starred tests both included <u>and</u> excluded, for <u>control</u> of the fire, but only with the starred tests <u>excluded</u> for extinction of the fire.

(1) <u>Water used to control the fire</u>

(a) All the results were analysed and none of the factors were significant at levels higher than 10%. A linear effect of $\frac{1}{\sqrt{P}}$, where P is the nozzle pressure, and a quadratic effect of rate of application appear as significant at the 10% level. If it is assumed that these are an expression of real physical laws then these laws can be represented by the following regression equation, which also gives the 95% confidence limits.

$$\text{Log}_{10} W = (0.854 \pm 0.074) + (0.044 \pm 0.044)(r^2-2) + (0.03 \pm 0.034)(2p) \quad \text{–(1)}$$

where W is the quantity of water used in gallons.

$r = \frac{R - 15}{5}$ and R is the rate of application in gal/min.

$p = \frac{P - .078}{.022}$ and P is the nozzle pressure in lb/in^2.

If the effects are real effects the expected saving in water under the test conditions which can be achieved, together with the range of expected results, can be obtained from equation (1).

These are shown in Table 5.

<u>Table 5. 95% confidence limits of water likely to be used to control the fire if effects of rate and pressure are real effects</u>

WATER USED TO CONTROL FIRE (GALLONS)

Rate of application gal/min \ Pressure lb/in^2	80	500
5 and 25	5.1 - 19.8	3.4 - 13.1
10 and 20	4.2 - 13.2	2.8 - 8.7
15	3.4 - 13.2	2.2 - 8.7

(b) A further analysis was then made on the first series of 20 tests only, containing only one "starred" test. The thirteen tests in which satisfactory repeats were obtained were used as estimates of error.

Only an interaction between a quadratic effect of rate and a cubic effect of $\frac{1}{\sqrt{P}}$ appeared significant at the 5% level. A linear effect of rate approached significance at the 10% level. Since there are no physical grounds for the interaction (shown in the analysis to be significant at the 5% level) to be any more probable than the other 18 effects tested, the test for significance for the largest F-ratio (11) ought to be applied. If this is done the interaction is not significant at the 5% level and probably not at the 10% level.

2. Water used to extinguish the fire

The analysis was made on the results obtained in the first series of tests only, as in 1(b). Only a complex interaction between pressure and rate of flow approached significance at the 10% level and this can be rejected by the test for significance of the largest F-ratio.

11. Test results for jets

Ten tests were made in which the water was applied to the test fire in the form of a jet. A nozzle pressure of 80 lb/in^2 was used and the tests were made over the same range of rates of application as with the water sprays. The results are shown in Table 6.

Table 6

Water used to extinguish fire by jet

	FLOW RATE - GAL/MIN									
	5		10		15		20		25	
		*	*		*			*	*	*
Control	13.2	11.0	28.0	7.0	7.3	6.0	7.7	14.4	10.0	7.5
Extinction	20.2	16.0	39.5	25.7	18.1	11.5	18.1	19.4	24.6	15.6

* In these tests the time to flashover was delayed and some of the furniture had collapsed before the application of water.

There appears to be no significant difference in the amount of water used either to control or extinguish the fire in the starred and unstarred tests and all the results can therefore be used in a comparison with sprays. Such a comparison shows no significant difference between sprays and jets in the amount of water used to control or extinguish the fire.

A further comparison between sprays and jets may be made for the "starred" results only. This shows a significant difference in the amount of water used to extinguish the fire, less water being required with the jets. The 95% confidence limits of the mean amount of water used to extinguish the fire in the starred tests with sprays are 22.9 - 45.7 gallons compared with 14 - 31.3 gallons using jets.

12. Summary of results

(1) Water used to control fire - sprays

The analysis shows that neither pressure nor rate are significant at the 5% level but effects of pressure and rate are significant at the 10% level. If the "starred" tests are not included in the analysis then only an effect of rate of application approaches significance at the 10% level.

(2) Water used to extinguish fire-sprays

Neither pressure nor rate of flow appear significant at the 10% level.

(3) Water used - jets

There is no significant difference between the performance of sprays and jets against the test fire, but the results with the starred tests only, indicate that less water might be used in "mopping up" with jets.

13. Branchman's Observations

After each test the branchman recorded his impressions of the fire and the efficiency of extinction.

The gun was found difficult to manoeuvre at 500 p.s.i. with rates above 15 g.p.m. particularly when operating the trigger. The protection against radiation afforded by the sprays made fire-fighting easier than with jets, though this effect was not noticed with the tests carried out at 80 p.s.i. Further, it appeared to the branchman that 'control' was achieved more rapidly with sprays than with jets under the same conditions though the directional properties of a jet appeared to make easier the extinction of more deep-seated pockets of fire beneath collapsed furniture.

14. Discussion of Results

The mean amount of water used with sprays or jets to 'control' the fire was 7 gallons, equivalent to 4 gallons/1,000 ft^3. This is of the same order as that used in previous tests (Table 1). The mechanism by which fires of this type are controlled is discussed in the Appendix.

More protection was afforded to the branchman by the spray than by the jet and this is probably the reason why he thought 'control' was achieved more rapidly, although the results do not show this to be so. It is possible, however, that under operational conditions 'control' could be achieved more rapidly with the spray since less manipulation is required. This may not have been shown in these tests since the branchman had tackled the same fire many times when he came to use the jets and knew the position of the main centres of burning.

The total amount of water used to extinguish the fire was about 15½ gallons; thus rather more water was used to subdue the small pockets of flaming and to prevent the fire from re-establishing itself, than was used to control the fire. It would appear that the amount of water used in this stage of the fire is more sensitive to the method of application and the type and arrangement of combustibles than is the amount of water used to control the fire. This was emphasised by the tests in which the furniture collapsed, where considerably more water was used for this second phase of extinction with sprays than with jets. This is presumably because the water needs to be applied to a relatively small area and the spray is wasteful. Most fires in practice are likely to have features of this type, upholstered furniture and materials arranged so that supporting radiation would make the final fires more difficult to extinguish. It would seem then that operationally a jet would be better than a spray for the second stage of the extinction.

The fact that the results with water applied as a jet were very similar to those when a spray was used indicates that droplet size is not a factor affecting efficiency of extinction

15. Practical implications of the results

Although levels of significance cannot be chosen arbitrarily without considering the implications and consequences of taking action on them, it would be difficult under most circumstances to interpret a significance at the 10% level as anything more than an amber light, indicating that if the suggested improvements are large enough to merit action, assuming the effects are real effects, then further selected tests should be made to clarify the significance.

The improvements in the amount of water required to control this type of fire which may be gained when the nozzle pressure is increased from 80 p.s.i. to 500 p.s.i. can be seen from Table 5. At the rate of flow of 8 - 10 gal/min used on present hose-reel equipment the amount of water needed might be expected to be in the range 4.2 - 13.2 gal at 80 lb/in^2 and at 500 lb/in^2 within the range 2.8 - 8.7 gal. The difference between these ranges is small compared with the amount of water carried on a tender. However, of more importance is the fact that this effect of pressure is lost when the total amount of water required to extinguish the fire is considered. Since this is the quantity of practical importance, there would seem to be no grounds for using high nozzle pressures against this type of fire.

There are no pronounced effects of rate of flow on the amount of water required to control or extinguish the test fire. This means that the fire can be controlled more rapidly at the higher flow rates without using additional water.

16. Conclusions

The results of the experiments described in this report have led to the following conclusions.

(1) A small amount of water, about 7 gallons, was required to control the fully-developed test fires in the 1750 cu.ft. room. About 17 gallons was required completely to extinguish the fire.

(2) It is doubtful whether there is any real effect of either nozzle pressure or rate of application, within the ranges tested, on the amount of water used to control the fire. If either does, in fact, have an effect, the saving of water is unlikely to be of practical importance.

(3) There is no evidence of any effect of nozzle pressure or rate of application on the total amount of water used to extinguish the fires.

(4) It appears that the ideal equipment would enable the fire to be controlled with a spray, and finally extinguished with a jet. The trigger-operated control was found to be a great convenience in extinguishing the fire.

Acknowledgments

These tests were planned in co-operation with the Fire Service Department and the Chief Scientific Adviser's Branch of the Home Office, and many helpful discussions were held with them both during the tests and in the preparation of this report.

Such a series of large-scale tests as is reported here required the co-operation of many people and the authors would like to thank those, including carpenters, electricians, labourers, office and workshop staff, as well as scientific staff, who helped to ensure the smooth running of the test programme.

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APPENDIX

Discussion of Mechanism of Control of Fully Developed Room Fires

The mechanism by which fully-developed room fires may be controlled by the application of water has been discussed by Thomas and Smart (6). The results of their tests with small scale models ($4\frac{1}{2}$ cu.ft) suggested that the gaseous contents of the room were expelled and replaced by steam. In other large scale tests, however, the amount of water required (per unit volume) to control the fire was two or three times greater than with the small scale rooms (Table 1). The mean amount of water used with sprays or jets to control the fires in the tests described in this note was 7 gallons, or 4 gall/1,000 ft^3, a figure comparable with the results of the $4\frac{1}{2}$ cu. ft. model.

To help in interpreting the results, a number of measurements were taken to enable estimates of the rate of burning and the heat content of the fire to be made. The thickness of selected pieces of timber from the furniture and the floor was measured before the test, and after the fire had been extinguished the charcoal was removed and the thickness of the wood remaining measured. Other pieces of timber were weighed before and after the fire, and the weight of charcoal as a percentage of the weight of wood burnt was determined.

The following are the mean results of these determinations together with other details of the fire load.

Mean depth of char - 3/16 in.

Percentage by weight of wood burnt remaining as charcoal - 14%

Area of wood exposed - 727 ft^2

Mean density of wood 35.4 lb/ft^3.

The fire was allowed to burn for 2 mins. after flashover before water was applied and the fire was controlled by a mean amount of 7 gallons of water, representing about $1\frac{1}{2}$ minutes at 5 gall/min and about 15 secs. at 25 gall/min. In calculating the rate of burning, a time of $2\frac{1}{2}$ minutes would seem to be a reasonable estimate of the time during which the majority of the loss in weight occurred. Although this gives a rate of charring of 3/40 in/min compared with the value of 1/40 in/min obtained with timber beams in a furnace (12), other measurements (13) would seem to corroborate this higher rate of burning under these conditions. Taking this figure, the rate of production of heat in the room before the application of water, assuming 100 per cent efficiency of burning, would be 3.8×10^6 cal/sec. If the water applied to the fire was vaporized immediately then the rate of cooling would be

at 5 gal/min - 2×10^5 cal/sec.
and at 25 gal/min - 1×10^6 cal/sec.

Since approximately the same amount of water was used to control the fire at the two rates of flow, extinction is not achieved by cooling at a rate greater than that at which heat is produced. This was also shown to apply to the extinction of freely burning crib fires (14), where the amount of water required to extinguish the fire depended on the thermal content of the combustible crib. The thermal content of the floor and furniture can be estimated from the measurements of the weight of the charcoal taken during the tests. At the commencement of water application, assuming the charcoal was at a uniform temperature of 800°C, the thermal content would be 6.9×10^6 calories.

The fire might be controlled by reducing the temperature of this charcoal to a point at which a rapid redevelopment of the fire would not occur, say 200°C. Another consideration is that a relatively high level of radiation, about 0.6 cal/cm^2/sec, would be required for the wood to continue burning when covered with a thick layer of charcoal. The intensity of radiation would fall below this level if the temperatures of the surfaces in the room, including walls and ceilings, were reduced to 500°C.

About 2 gallons of water would have to be vaporized to cool the charcoal to 200°C, and considering the efficiency of application of the water, this is at least of the same order as the amount of water actually used. However, some heat transfer to the combustible material takes place during the process of extinction and this would tend to re-establish burning in parts of the fire which had been extinguished. At the lower flow rates, where extinction took a proportionately longer time, there would be a greater opportunity for the re-establishment of burning and therefore one would have expected more water to be required at the lower rates of flow. Since this was not found, it is difficult to attribute extinction simply to the cooling of the combustible material.

It has often been suggested that the atmosphere in a burning room is inerted by the presence of steam and that this plays an important part in the control of the fire. If the concentration of oxygen is to be reduced from 21 per cent to 15 per cent, the concentration which would inhibit flaming, then assuming that there is mixing of steam with air and combustion products the concentration by vol. of steam in the room would have to be 28 per cent. The rate at which steam must be produced to achieve this concentration will depend on the degree of mixing of the steam with the gases in the room.

If there were no mixing then about 8 gallons of water if vaporized would completely fill the room. Under these ideal conditions there would be no effect of the rate of application on the amount of water used to control the fire. If on the other hand there was intimate mixing of the steam and gases in the room then the concentration of steam, c, is given by

$$V \frac{dc}{dt} = W - x\,Vc \qquad \text{.........(2)}$$

where V = volume of room
W = volume of steam produced per sec. by vaporization of water.
x = volume of gas removed per sec. as a fraction of the total room volume.

After a time t secs

$$c = \frac{W}{xV}\left(1 - e^{-xt}\right) \qquad \text{.........(3)}$$

Assuming the temperature of the gases leaving the room is 100°C an approximate value of x of $^1/_{30}$ can be obtained by the method outlined by Kawagoe.* If it is further assumed that all the water applied to the fire is immediately converted into steam, an approximation which is doubtful particularly at the higher flow rates, then the effect of the rate of application on the amount of water required to control the fire can be obtained from equation (3). This shows that the equilibrium concentration of steam would not be high enough to produce an inert atmosphere at flow rates below about 5 gall/min. and that only about a 25% reduction in the amount of water required would result from increasing the flow rate from 7 to 25 gall/min. Since this small reduction might be outweighed by the less efficient vaporization of water at the higher flow rates the test results could be considered to be consistent with the theory that the fire is controlled by inerting the atmosphere in the room.

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* Kawagoe. 'Fire Behaviour in Rooms', Building Research Institute of Japan, September 1958.

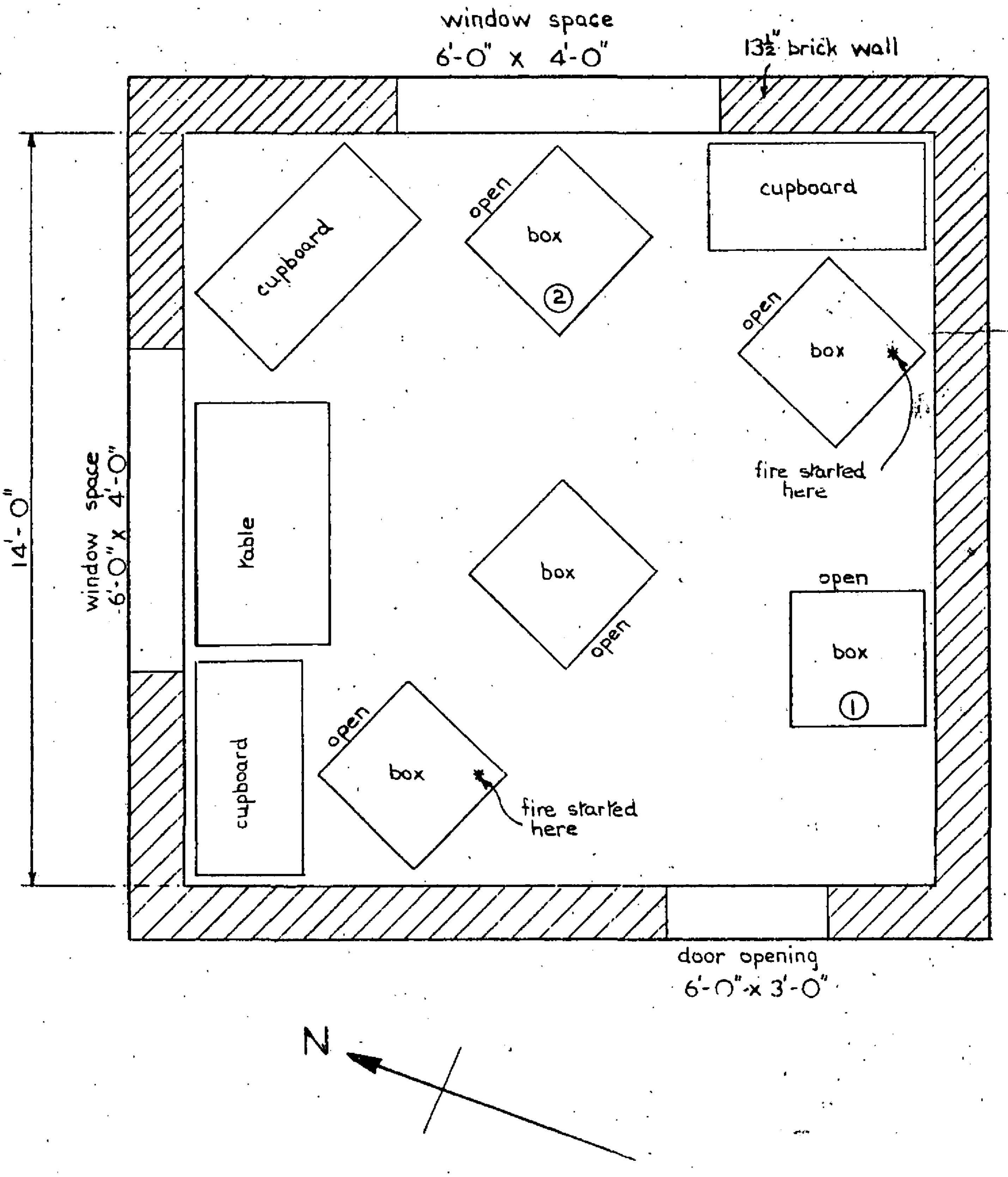


FIG.1. PLAN OF ROOM AND FURNITURE

1/3947. F.R.342.7 F.R.388

1/2948 F.R. 342 + F.R. 388

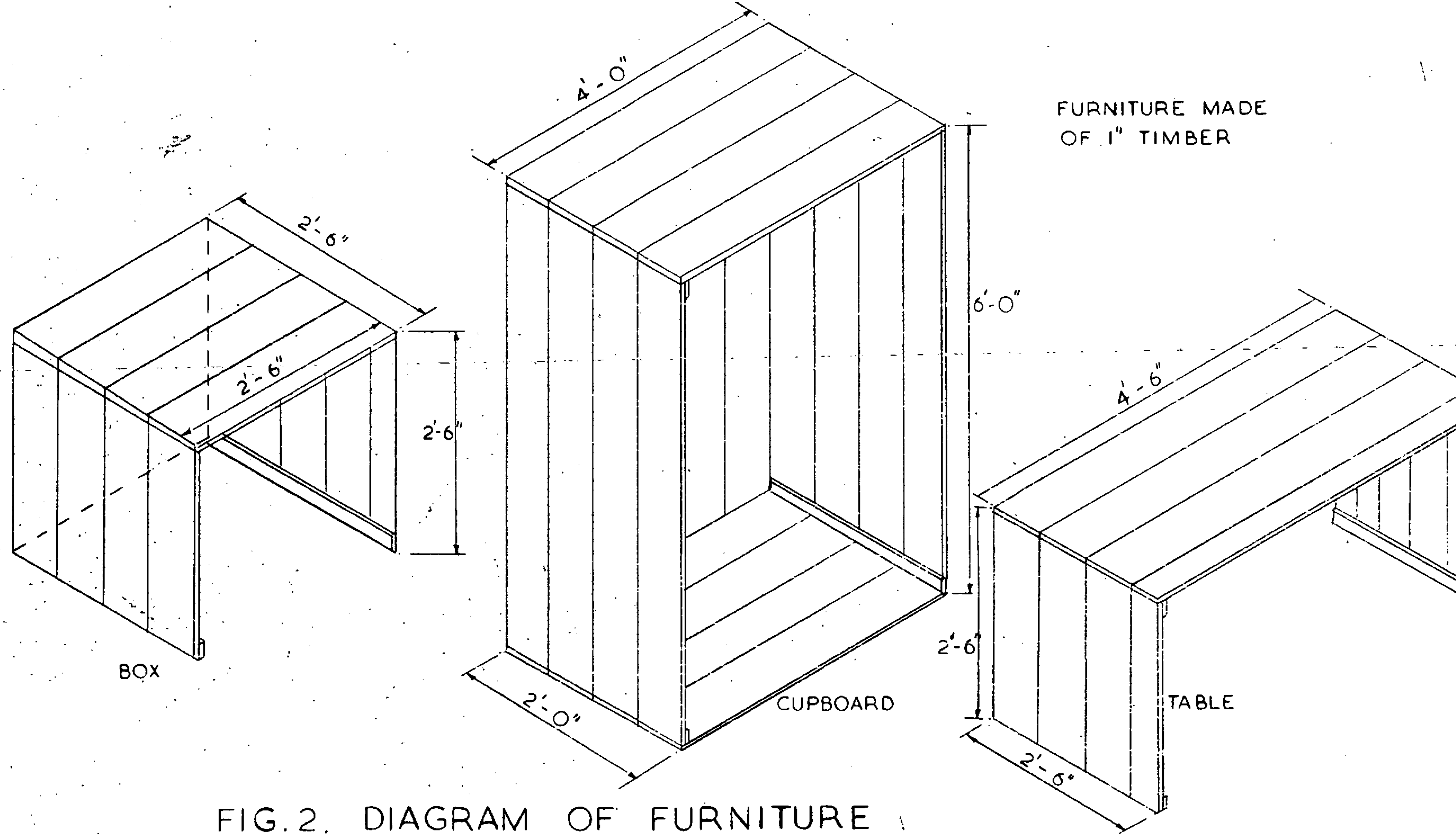


FIG. 2. DIAGRAM OF FURNITURE

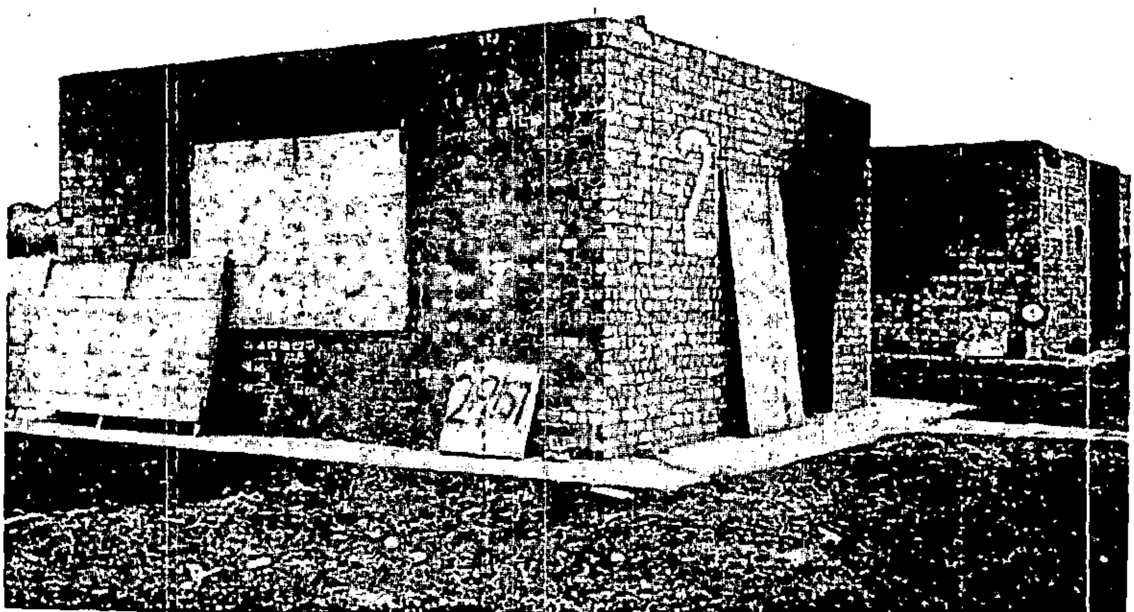


FIG. 3. FIRE TEST ROOMS

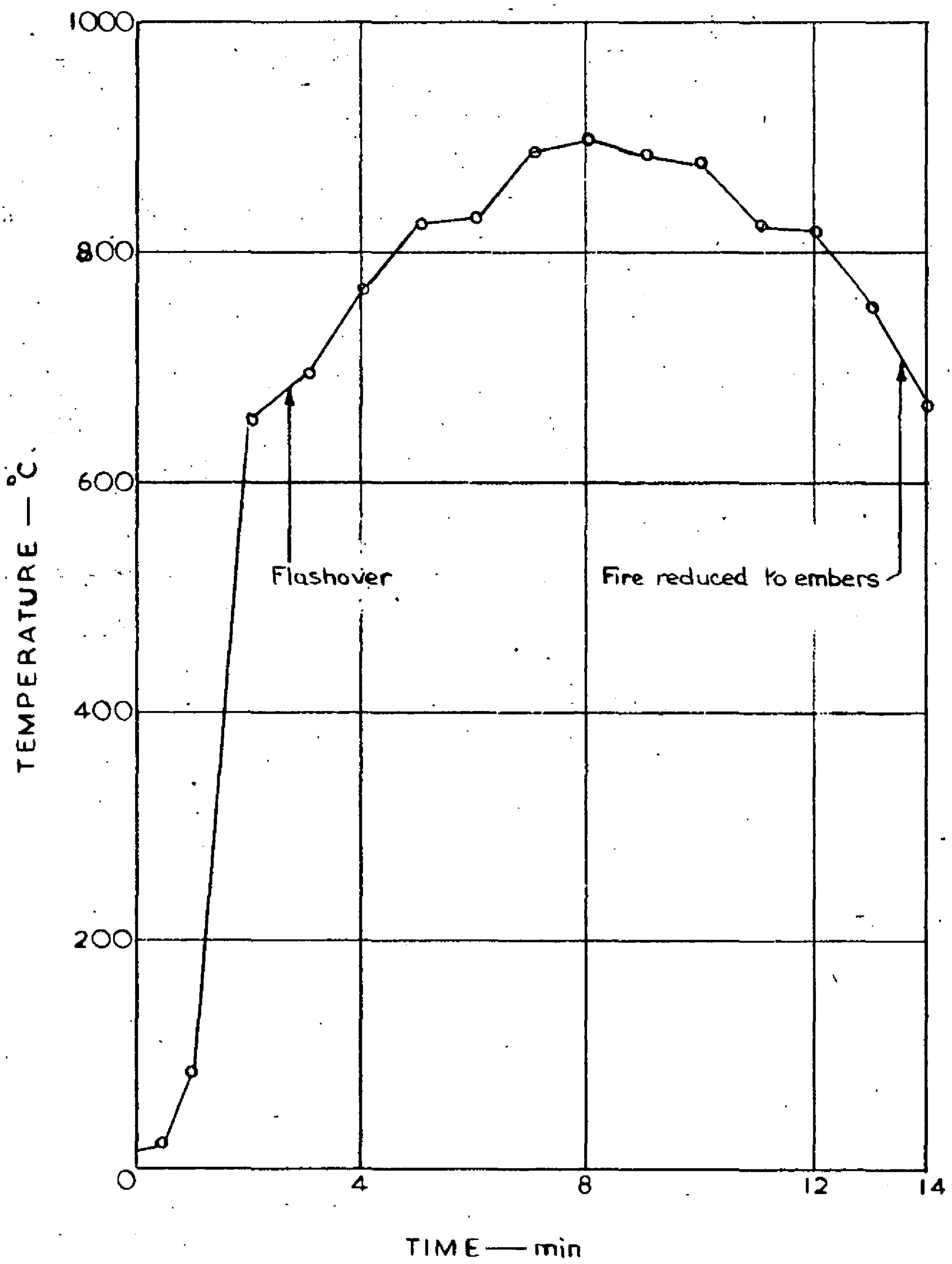
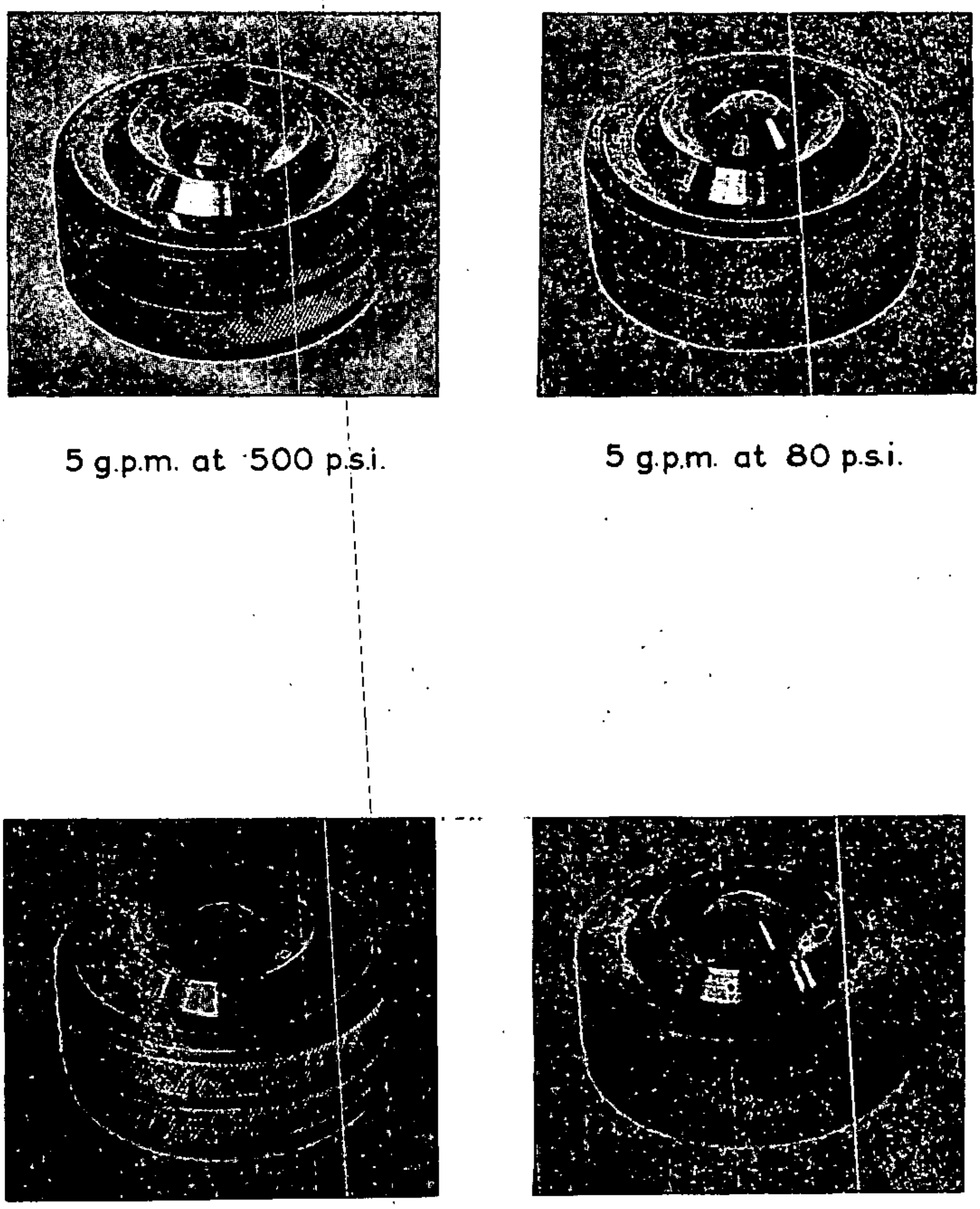


FIG. 4. TIME-TEMPERATURE RECORD OF FIRE TEST

1/2949 F.R. 342 + F.R. 388



5 g.p.m. at 500 p.s.i.

5 g.p.m. at 80 p.s.i.

10 g.p.m. at 80 p.s.i.

25 g.p.m. at 500 p.s.i.

25 g.p.m. at 80 p.s.i.

FIG.5. TEST NOZZLES

1|2950 F.R. 342 & F.R.388

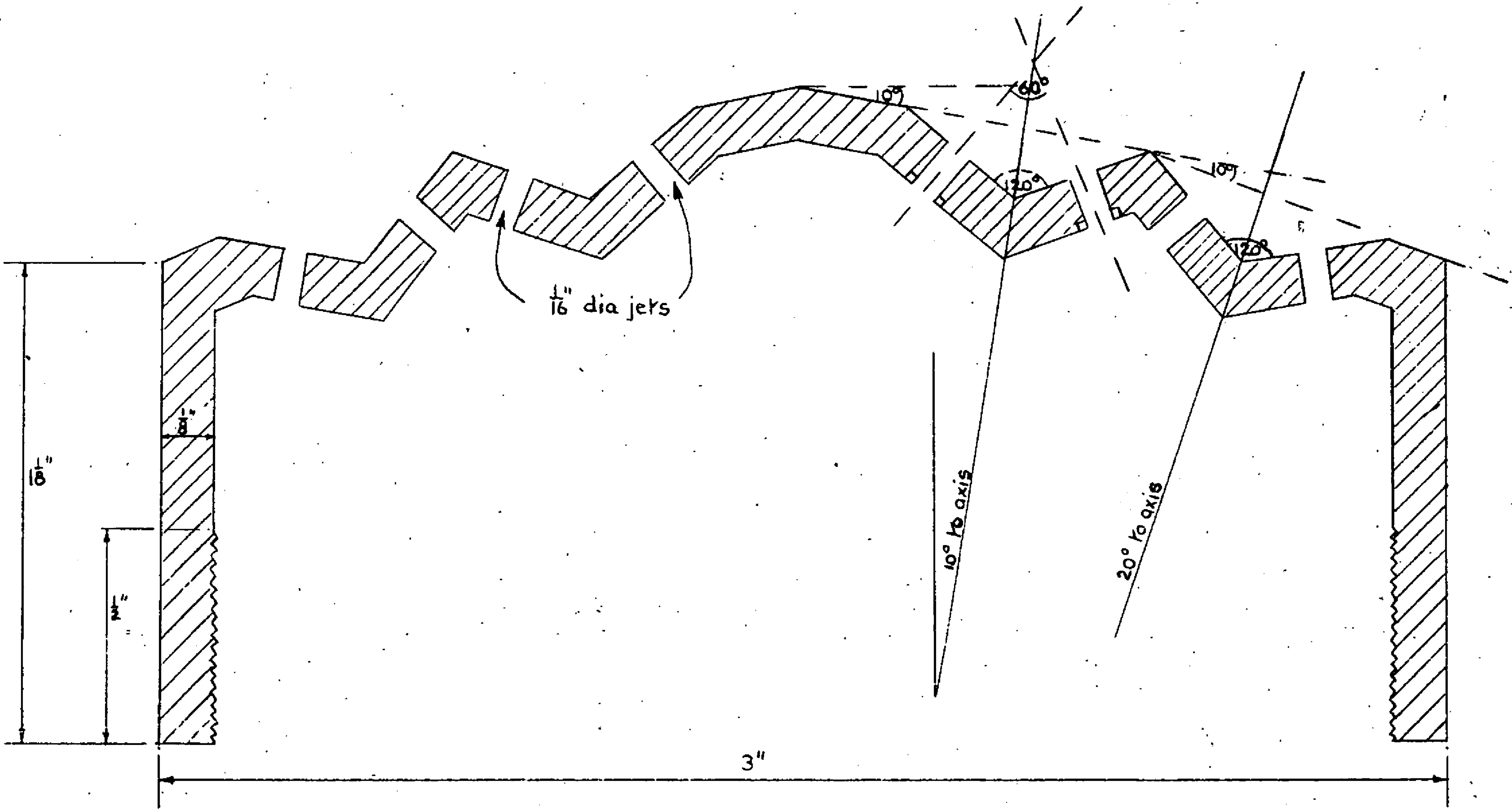


FIG. 6. DIAGRAM OF SPRAY NOZZLE

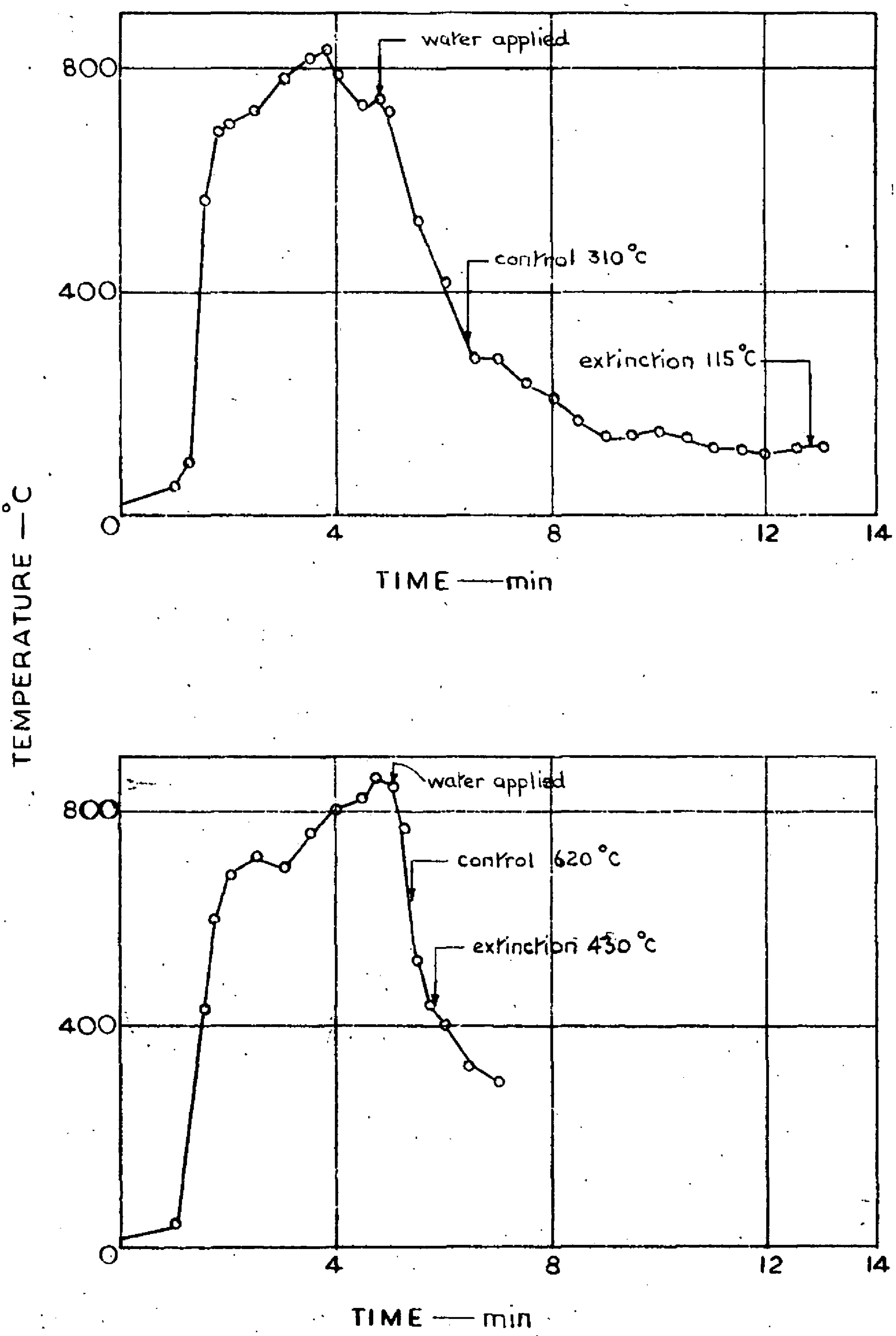
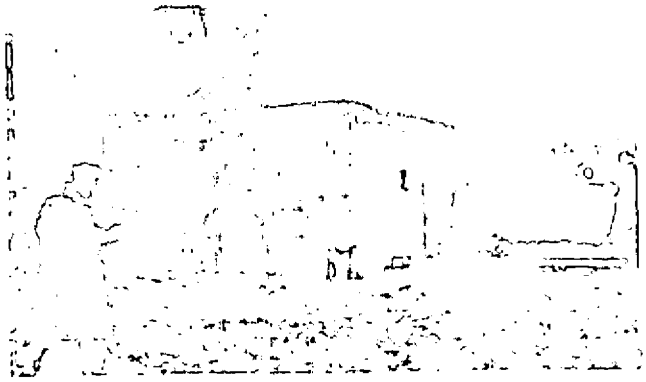


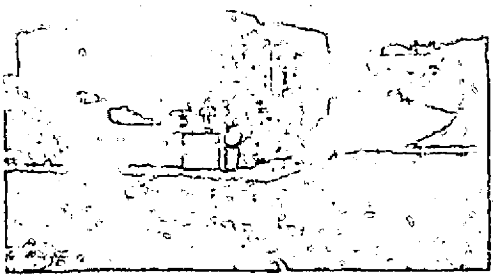
FIG. 8. TYPICAL TIME-TEMPERATURE RECORDS OF EXTINCTION TESTS

F.R. 342 & F.R. 388

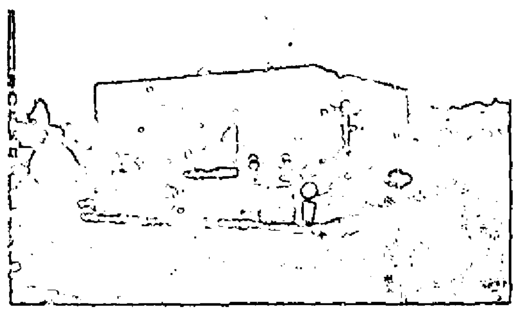
1/2951



(a) 2 seconds before water application



(b) Water applied



(c) Marked reduction in intensity

(d) Control

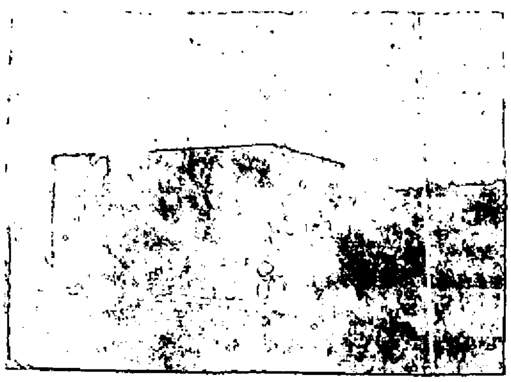
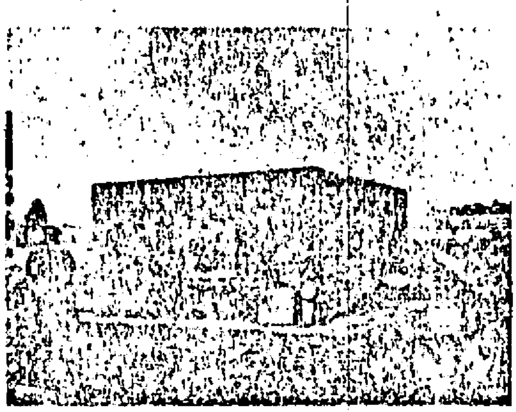


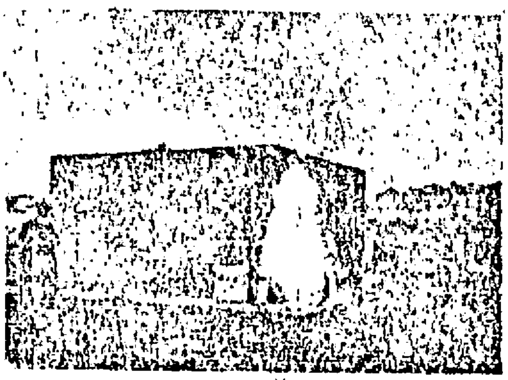
FIG. 9. SEQUENCE OF EXTINCTION

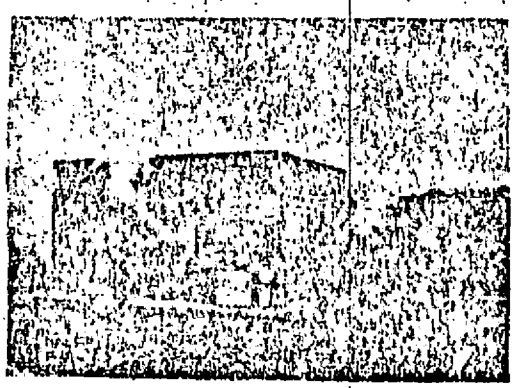
(a) 2 seconds before water application

(b) Water applied



(c) Marked reduction in intensity





(d) Control

FIG. 9. SEQUENCE OF EXTINCTION

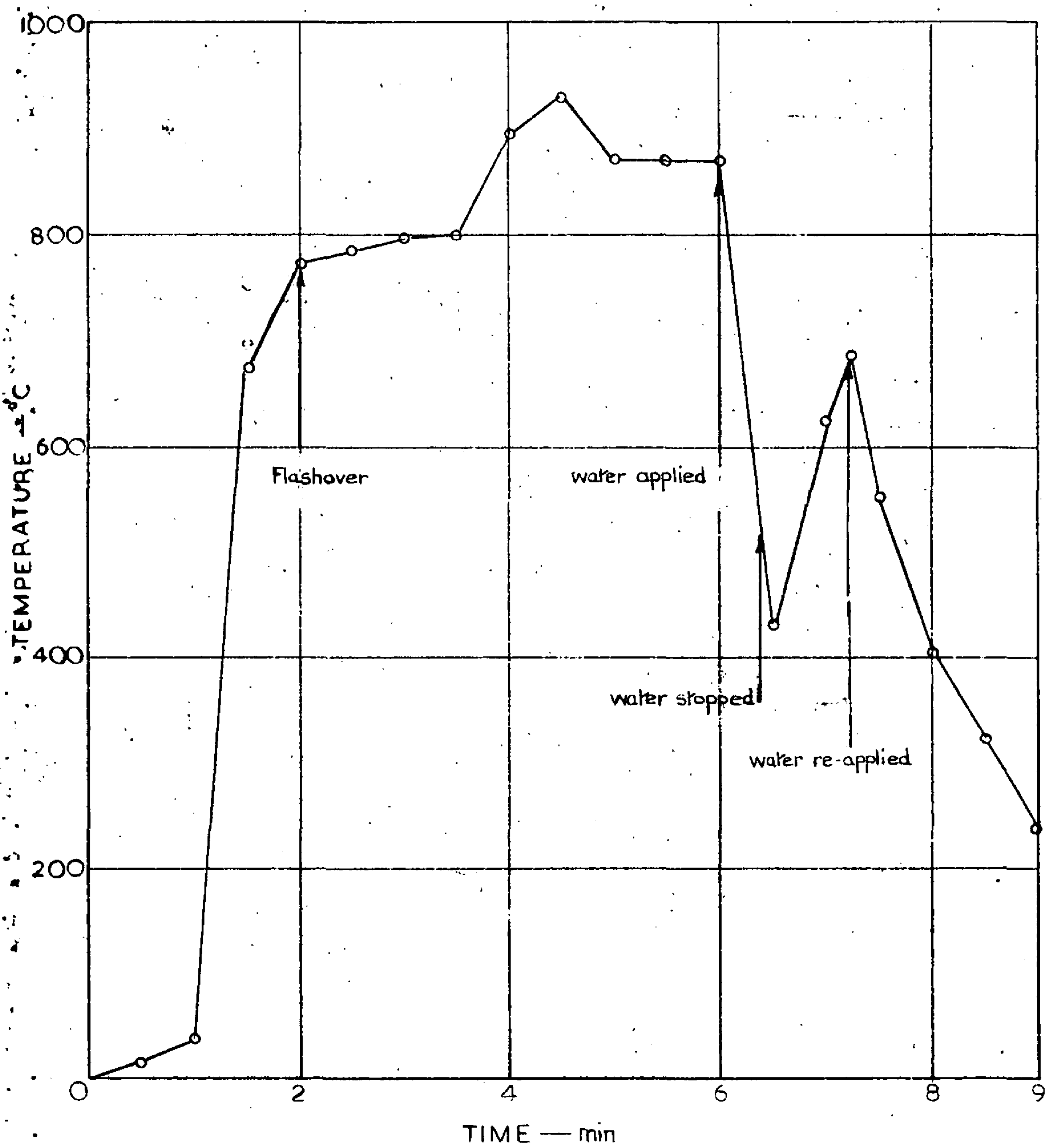


FIG. 10. TIME-TEMPERATURE RECORD OF EXTINCTION TEST IN WHICH FIRE IS RE-ESTABLISHED

1/2952 · F.R.342 + F.R.388

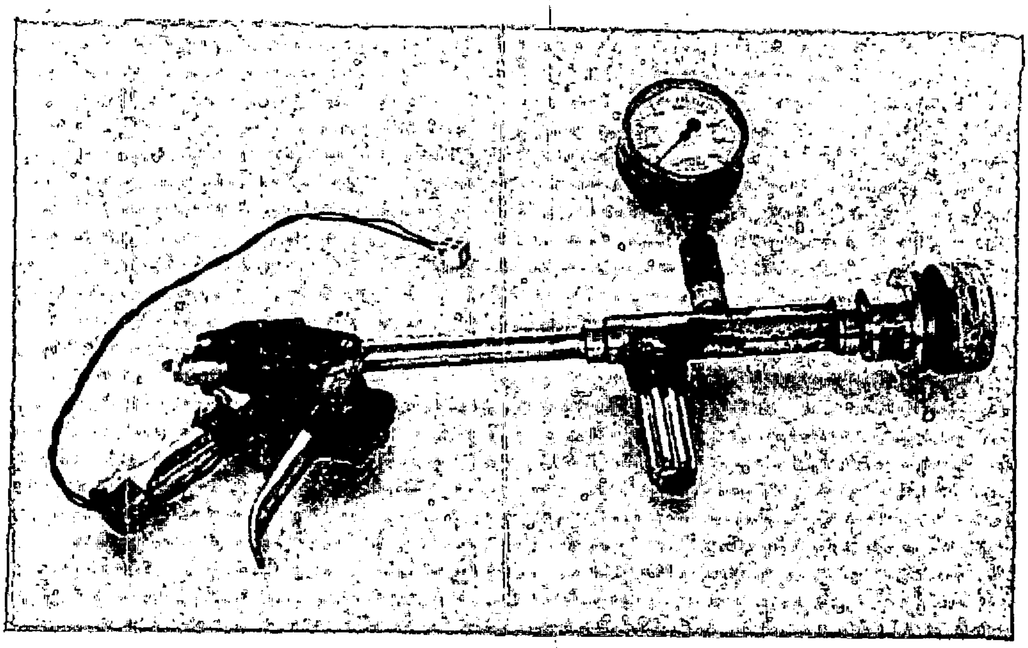


FIG.7. NOZZLE AND GUN ASSEMBLY

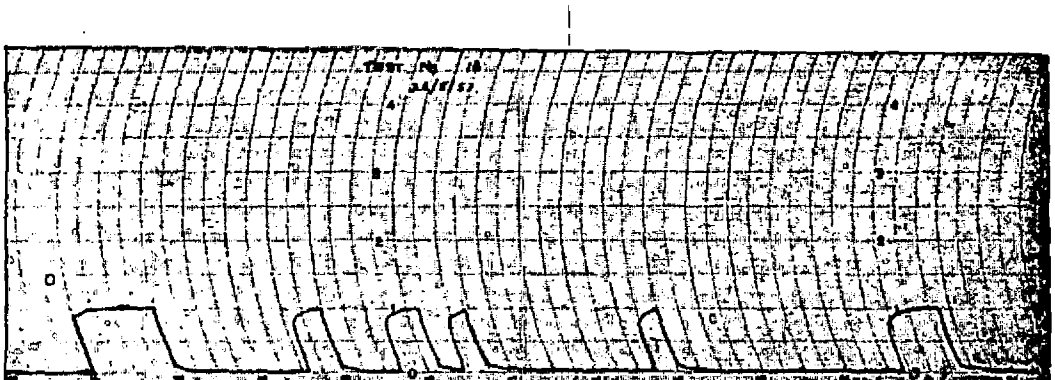


FIG.11. RECORD OF WATER APPLIED