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THE EXTINCTION OF FIRES IN ENCLOSED SPACES

by

P. H. Thomas and P. M. T. Smart

Summary

The first part of this report is a review of information derived from tests and actual fires on the amounts of water necessary to extinguish fires in rooms.

The second part of the report describes experiments made at the Joint Fire Research Organization in which the extinguishing capacity of sprays and jets have been studied under various conditions. At low rates of flow the amount of water required is the same with sprays as with jets and it increases with increasing rate of flow. This increase, however, is much less marked with sprays. The degree of manoeuvreability of the spray or jet affects the rapidity of extinction less with sprays than with jets.

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Introduction

The cooling or smothering action of water in a fire depends on rate at which heat can be taken up by the water. Since this rate of heat transfer can be increased by increasing the surface area of the water there are grounds for supposing sprays to be superior to jets in some conditions.

In 1944 some tests [1] were sponsored by the National Board of Fire Underwriters and the report included the statement that "No characteristics of spray or fog nozzles justify consideration of such streams replacing the volume available from standard fire department nozzles where fires have reached a stage producing a large amount of flame from well-involved combustible material". The report did state, however, "That sprays are of excellent worth in killing the heat of a large body of flame". On the other hand there have been published reports of tests, such as those in a Connecticut dwelling house [2] where most impressive results were obtained with sprays, and it would appear that there are certain conditions in which water spray is preferable to jets.

Against this background of contradictory views some experiments were made at the Joint Fire Research Organization in which fires in an 8 ft. cubic room lined with fibreboard were extinguished with jets and sprays [3]. At a later date experiments were made in a model room of 4½ cubic ft. This use of small-scale fires has permitted many more tests to be made than would otherwise have been possible and it is mainly the results of this work so far that are described below.

A survey of previous work

Reliable information of spray and jet performance under controlled and specified conditions is by no means plentiful. Reference can, however, be made to the results obtained in the series of tests sponsored by the National Board of Fire Underwriters [1], the dwelling house tests in Hamden, Connecticut [2] and some tests [4] and [5] made in Britain by the Ministry of Home Security during the war, to compare various nozzles. In addition the National Fire Protection Association have published some details of a few actual fires fought with sprays [6].

Tests by National Board of Fire Underwriters

Some tests were performed with wooden buildings 10 ft. x 10 ft. x 8-9 ft. high. The walls and ceiling were lined with fibreboard, one wall being open and a hole of 4 sq. ft. cut in the roof. The fire was allowed to burn for 5 minutes before applying water and the time to extinguish the flames was measured. The results of the tests, derived from the official report, are shown in Table 1.

TABLE 1

Results of tests by National Board of Fire Underwriters

Type of stream and nozzle	Nozzle pressure	g.p.m.	Total gallon	Extinction time (sec)
Cone spray 1	50	99	10·7	6·5
Cone spray 2	100	51·5	8·1	9·5
Impinging jet spray (A)	100	16	8·0	30
" " " (A)	200	25	3·7	9
" " " (applicator)	100	11·5	4·8	25
High-pressure gun jet 1	300	12·6	9·9	47
" " " " 2	600	17.7	10·9	37
" " " " 3(B)	300	13·9	4·6	20
" " " " 3(B)	600	19·2	8·6	27
Jet and spray †	600	41·8 19·2	13·6	25
Jet*	600	8·1	5·3	39
½ in. jet	50	52	13·9	16

†Reach of stream in fog (sic) position not sufficient. Full nozzle stream used.
*Attacked with full nozzle stream and changed to fog (sic) after about 15 seconds.

Although the type of spray may be the same in several tests the actual nozzle or adjustable opening of nozzles is different in all tests except those marked (A) and (B). In these tests there are no more than two tests at different pressures and rates of flow referring to the one nozzle and one position of opening, and from these tests an increase of pressure gives a reduction in water used for one nozzle (Tests A) and an increase for another (Tests B).

It would be unwise to draw any conclusion as to the effect of pressure, from tests of such limited scope.

Sprays in dwelling house fire tests

Test fires in a condemned dwelling house in Hamden, Connecticut[2] showed that rapid control would be achieved with impinging-jet sprays operated at no more than 100 lb. sq. in., an attic fire being extinguished with 7 gallons in about 2 seconds. The dimensions of the fires are not given, and the results are of little quantitative value.

Tests in the Fire Test Building of the Building Research Station

In 1943, and later in 1946, some tests were made in the Fire Test Building of the Building Research Station of the Department of Scientific and Industrial Research[4]. 550 lb. of wooden furniture of surface area 265 ft^2 in a room of 1,900 cubic ft. were ignited and the resulting fires were attacked with various nozzles. The ceiling was plasterboard and the floor was of plain-edged board. When the fires were fully developed and the temperature had reached 850°C to 1,000°C water was applied. The results give the total time for which water was applied and the total amount used (see Table 2). No consistent distinction is made, however, between water required to subdue the fire and that used to extinguish lingering fires in furniture, a corner or recess etc. The amounts quoted as being used do not all refer to complete extinction - in some fires this was achieved by the use of an additional appliance. The temperature records, however, of tests 3 and 4 and the result of test 2 suggest that about 15 gallons is sufficient to achieve control and at least twice this to achieve sure extinction. For a room volume of 1,900 cubic ft. this figure for control is equivalent to about 8 gallons/1,000 cubic ft. The ventilation was approximately 0·015 sq. ft. per cubic ft.

Ministry of Home Security Tests at Ladbroke Grove

The report of some tests,[5] in a ground floor and basement room of a house in Ladbroke Grove, London, is of interest in that apart from the total time and total amount of water required to extinguish the fire the time is also stated at which the fire could be said to have been "knocked-down", that is, major flame had been subdued. The results of these tests are given in Table 3.

Although the times to subdue the flames are only given approximately it can be seen that major control may be achieved with less than $\frac{1}{3}$ of the water actually used in these tests to extinguish the fire.

For these experiments the amount of water required to achieve major control was 20 gallons, equivalent to about 15 gallons/1,000 cubic ft. The ventilation of about 54 sq. ft. is equivalent to 0·039 sq. ft./ cubic ft.

Although in the conclusions of the report is is stated that "there is an advantage to be gained, at least in the early stages of firefighting operations, by applying water in a dispersed form (e.g. as a fan jet or spray) rather than in the form of a solid stream", the times for control and the amounts of water used are almost the same.

Summary of results

For the three series of tests described the quantity of water used to achieve control appears to have been between 8 and 15 gallons per 1,000 cubic ft. of fire. Although it is not practicable to analyse the data to correlate variations in quantity with variation in the time at which water was first applied or in the amount of furniture etc., it is possible to compare them with some results obtained under operational conditions. Lloyd Layman has described some fires in which sprays were used on fully-developed fires. The amount of water was estimated as approximately 7 gallons/1,000 cubic ft. in fires which ranged in volume from 3,500 to 33,000 cubic ft. This is equivalent to

TABLE 2

Results of tests at Building Research Station

Nozzle	Delivery g.p.m.	Delay before applying water (mins)	Time of application (mins)	Amount of water used (gals)	Remarks
½ in. Fog (sic) ⅛ in. jet	9·4 2·7	Flash-over + 3 mins.	) 18½)	50	Fire died down in vicinity of spray but not extinguished until after use of jet.
½ in. jet	24-30	"	½	12-15	Played intermittently.
1 stirrup pump	1·5 g.p.m. for 10 mins. 3·0 g.p.m. for remaining time	"	16	33 15 gals. to control	One pump used for first 10 mins. - after which two pumps were used. Control achieved with one pump.
3 stirrup pumps	4·4	"	.5	22	
3/16 in. Fan spray 90 lb sq.in.	8	"	5½	43½	Spray "rapidly subdued flames".

TABLE 3

Results of tests in Ladbroke Grove

Nozzle	Pressure lb sq.in.	Delivery rate (gal/min)	Delivery before applying water	Time to subdue major flame (min)	Amount used to subdue major flame (gal)	Final extinction time (min)	Amount used (gal)	Remarks
3/16 in. plain jet.	100	10·9	Flash-over + 3 mins.	2	20	8	87	
3/16 in. plain jet and plate "Fanspray".	100	10·4	"	2	20	6½	67	
½ in. 'fog' nozzle.	100	9·6	Flash-over + 6 mins.	-	-	-	-	Unable to extinguish fire.
½ in. 'fog' nozzle + ⅛ in. jet.	100	10·7	Flash-over + 3 mins.	2	20	7	65	⅛ in. jet only used after 4¼ mins.

a volume of steam approximately twice the room volume. The rates of application used were sufficient to produce control in less than three minutes, and in two fires in less than one minute.

Experiments at the Joint Fire Research Organization in the 8 ft. cubic room

The first experiments were conducted by J. F. Fry and one of us (P.M.T.S.) in a room 8 ft. x 8 ft. x 8 ft., the ceilings and walls of which were lined with fibreboard. The room was ventilated by an open doorway and an open window the total area being 13·3 sq. ft. or 0.026 sq. ft. per cubic ft. of volume. For two of the tests a trap door was also open increasing the ventilation to 17 sq. ft., or 0·034 sq. ft. per cubic ft. The room was set alight by burning $\frac{1}{2}$-litre of petrol in a corner. In all tests except one the water was applied 2 minutes after ignition of the petrol, i.e. between $\frac{3}{4}$ and $1\frac{1}{4}$ minutes after the room had become fully-developed. In the other test water was applied 4 minutes after ignition. The spray or jet was carried by hand and moved about to extinguish the fire as rapidly as possible. The results of the tests are shown in Table 4.

TABLE 4

Fires in 8 ft. cubic room lined with fibreboard

Mode of application of water	Pressure (lb. sq. in.)	Delivery (g.p.m.)	Delay* before application of water (mins)	Extinction (secs)	Amount of water used (gals)
Spray - 1/16 in. jets impinging at 30°.	120	2·2	2	25	0·91
" "	60	1·5	2	25	0·62
" "	120	2·2	2	25	0·91
Jet - 0·0885 in. diameter.	175	2·4	2	20	0·80
‡ " "	175	2·4	2	20	0·80
‡ " "	175	2·4	4	25	1·00

*Flash-over at about 1 minute.
‡Tests in which the 4 sq. ft. trap door was open.

These results do not show any significant difference between spray and jet. The delay in applying water in the last test would also appear to have had little effect on the amount of water required, a result differing from that obtained in the tests in Ladbroke Grove. A comparison between the third and fourth test in Table 3 suggests that in those tests a delay of a few minutes in applying the water affected the capacity of the spray to control the fire. This question is the subject of further investigation. Thus, since all the results may be lumped together we can obtain an average figure for the amount of water required. This is 0·88 gallons or 1·72 gallons per 1,000 cubic ft; the average ventilation is 0·028 sq. ft./cubic ft.

Tests in 4·5 cubic ft. model room

As a result of the above experiments it was thought that any difference between sprays and jet application might among other things depend on the rate of application of water. As the number of experiments required in this work might be large in view of the many factors involved it was decided to continue experiments on a small-scale and accordingly a model room with walls of asbestos board was constructed, (see Figure 1). The walls etc., were not tied together but were held in a metal frame and the whole room could thus easily be dismantled and lined with ¼ in. fibreboard. Over a circular hole at one end was pivoted a plate which could be lifted to allow spray to enter and the height of the four windows could be reduced from 3 in. by partially covering with slats. In the experiments in which the spray was used two 1/32 in. jets were fixed to impinge at 90° and when the jets were used separately two operators moved one each by hand.

The fibreboard linings used for these tests were conditioned at a humidity of 60 per cent at $40^{\circ}C$ - the moisture content of some boards was measured and was found to be about 5 per cent. The temperature at a point about 3 in. into the room at the level of the top windows was measured by a chromel alumel thermocouple and whilst this was too slow in responding to give much information about the fall in temperature, it indicated the value of the maximum temperature reached before water was applied. This was found to be about $900^{\circ}C$ with the largest ventilation and about 700° for the least ventilation used.

A little petrol, spilt along the base of the wall opposite the circular window, was used to ignite the room which became fully involved in fire after 1½-2 minutes. About 5 seconds after the temperature had become steady and the flames had reached a maximum height, the water was turned on and the time taken to extinguish all flame inside the room was measured with a stop watch.

Such experiments were made with sprays over a range of pressures from 5 lb/sq.in. to 100 lb/sq.in. and at four conditions of ventilation, the water being applied through the hole in the end wall of the room. In view of the difficulty of manoeuvring jets effectively through the side windows when these were partly closed, it was not possible in these small-scale tests to use the jets at low values of ventilation. Some experiments with jets were made, however, in which one side of the room was removed. These were performed with nozzles of different sizes to find any large variation in performance due to the separate effects of rate of flow, pressure and the use of one jet, instead of two. Also with the model room in this condition comparative experiments were made between a movable spray and separate jets.

Experimental results

Sprays

In Figure 2 the extinction times are shown for various water pressures, when using water spray. Since only one size of nozzle was used the effect of rate of flow and pressure are not separable here. The results for the ventilation of $0{\cdot}67\ ft.^{-1}$ refer to the extinction of a fire in the model with one side removed but in which the spray was applied through the opening at one end of the model.

It may be noted that the reasons for the limits to the range of experiments are that below 5 lb/sq.in. it is not possible to get a spray at all with 1/32 in. nozzles, while at high pressures, especially at low ventilations, the fire is extinguished so rapidly that it is difficult to determine the time of extinction accurately.

The stages of extinction with water spray at intervals of ¼ second is shown in Figure 3.

It is seen that extinction is very rapid with flows of about 50 g.p.m. per 1,000 cubic ft. The listed extinguishing times are for the disappearance of flame inside the room, but the major collapse of the fire occurs within 1 second (Figure 3). There is a rate of flow, or pressure, below which complete extinction is not possible with a fixed spray even though a major collapse of the fire may still occur. This limiting flow is seen to decrease with lower ventilation and it will presumably be lessened as would the extinction time if the spray could be moved about.

If the extinction time is multiplied by the flow, a measure is obtained of the amount of water used. This is shown in Figure 4. The amount of water used when the flow is above the critical value is practically independent of pressure and this suggests that drop size might be less important than the total amount of water at flows which are greater than the critical rate. This is still being studied.

Jets

The times and the corresponding amounts of water necessary to extinguish the model fire by two jets of water applied through the fully open windows are given in Figures 5 and 6. It was thought that because of the limited accessibility of the fire through the windows the above results might not represent the most efficient use of jets and accordingly experiments were made with one side of the model removed. Results given in Tables 5 and 6 show these separate effects of rate of application, pressure, and the use of one jet instead of two.

TABLE 5

Quantity of water in gallons required to extinguish fire in model room with one side removed

Pressure	One jet		Two jets	
	Nozzle diameter 0·044 in. Rate 0·25 gpm	Nozzle diameter 0·062 in. Rate 0.5 gpm	Nozzle diameter 0·031 in. Rate 0.25 gpm	Nozzle diameter 0·44 in. Rate 0·5 gpm
30 lb sq.in.	0·022	0·039	0.016	0·026
100 lb sq.in.	0·023	0·037	0·023	0·042

Doubling the rate of flow reduces the extinction time by 15 per cent and thus it increases the consumption of water by about 70 per cent. In this connection it is interesting to note a similar effect of rate of flow in the three tests with jets by the National Board of Fire Underwriters (see the last three results in Table 1).

TABLE 6

Rate of application 0·5 gpm
Quantity of water in gallons required to extinguish fire in model room with one side removed

One jet		Two jets	
30 lb sq.in.	120 lb sq.in.	30 lb sq.in.	120 lb sq.in.
0·036	0·026	0·033	0·027
0·031	0·027	0·032	0·030

The results in Table 6 show that for a given rate of flow an increase of pressure from 30 lb sq.in. to 120 lb sq.in. reduces the extinction time and thereby the amount of water by about 20 per cent. Clearly then for a given nozzle diameter an increase of pressure will not be an advantage since the effect of the increased flow outweighs the advantage of the higher jet velocity. There is thus a flow at which water consumption is a minimum.

Although these experiments indicated little, if any, difference between the use of one jet and two jets of equivalent total flow, it was felt that manoeuvrability must be a factor at some stage. Experiments were therefore conducted at a pressure of 10 lb sq.in. and these showed that at this small flow the use of two jets was significantly superior to the use of one, there being an improvement of 15-20 per cent in extinction time. Results are shown in Table 7.

TABLE 7

Extinction times with equal rates of flow at 10 lb sq.in.

One jet 0·044 inch diameter	Two jets 0·031 inch diameter
(sec)	(sec)
7·7	6·2
7·3	6·4
6·7	5·9
	5·6

A comparison of jets and sprays

A comparison of the results in Figures 2 and 5 shows that when the two jets were used separately the extinction was achieved less rapidly than with the spray. The critical rate, however, was less with the jets. This difference in critical rate is presumed to be largely due to the use of a fixed spray (see below). The results of the experiments comparing fully manoeuvrable jets and sprays are given in Figure 7, where it is seen that jets can be as efficient as sprays at low rates of flow. Sprays become increasingly superior as the rate of flow is increased. The results of the experiments in the 8 ft. cubic room are also shown in Figure 7 and it is seen that they correspond to a rate of flow at which sprays and jets would not be expected to behave markedly differently.

A comparison of Figures 5 and 7 shows that the amount of water used when the spray is fixed and directed from the side, through the opening in the end wall, is no more than about twice that used when it is movable and directed into the fire from the open side. The difference between the behaviour of jets between the two sets of experiments (Figures 4 and 7) is about the same, though the difference in the degree of manoeuvrability between the two sets of experimental conditions was clearly less for the jets than for the spray. It is therefore reasonable to conclude that manoeuvrability is less important for sprays than for jets.

By increasing the rate of application of water the amount of water used to control a fire by jets or movable sprays is increased but that used by a fixed spray is unchanged and may even be reduced. One would expect that at high rates of flow the amount of water used to control a fire would be the same for movable and fixed sprays.

Ventilation

The effect of ventilation is two-fold: it affects the intensity of the fire by controlling the rate of burning when the fire is not "fully-ventilated" and it also allows the gaseous contents of the room to be expelled and the steam to escape.

It may be seen in Figure 6 that decreasing the ventilation decreases the minimum rate of application to extinguish the fire and also the time to extinguish one. The effect of the ventilation on the quantity of water required to extinguish a fire is shown in Figure 8 which is derived from Figure 6. Although a fire with zero ventilation would not develop beyond a certain point and would eventually die out it does not follow that a fire of small but finite ventilation would require only a proportionately small amount of water to extinguish it. The curve in Figure 8 has not therefore been extrapolated to the origin.

The amount of water required

For values of ventilation normally encountered in full-scale rooms the amount of water corresponds approximately with the amount required to replace the gaseous contents of the fire with steam and this might suggest that the extinguished gaseous contents of the room are expelled and replaced by inert steam.

If the action of the steam were only to reduce the concentration of oxygen from, say 21 per cent to about 15 per cent by volume, the concentration inhibiting flame, a lesser amount of steam would suffice. This, however, would depend on the degree of mixing of the steam and air, etc. as some steam is lost from the fire. Clearly if only air and combustion products were expelled and the remaining atmosphere contained 15 per cent of oxygen, the amount of water required would have to be sufficient to generate steam to fill at least 'x' per cent of the space

$$\text{where } 0{\cdot}21\left(1 - \frac{x}{100}\right) = 0{\cdot}15$$

$$\text{i.e. } x = 28 \text{ per cent} \qquad \ldots\ldots \quad \text{(i)}$$

while if the gases expelled were safely mixed and contained 15 per cent of oxygen 'x' would be given by

$$0{\cdot}21 = \left(1 + \frac{x}{100}\right)0{\cdot}15$$

$$\text{i.e. } x = 40 \text{ per cent.} \qquad \ldots\ldots \quad \text{(ii)}$$

TABLE 8

The heat content, minimum necessary cooling, and amounts of water used in practice to extinguish fires in various tests

Test reference	Volume ft.^{3}	Estimated surface area ft.^{2}	Time of burning after flash-over heating time T_h (sec)	(a) Calculated heat content - (gal)	(b) Calculated minimum cooling necessary to prevent reignition (gal)	(c) Calculated amount of water to fill room with steam (gal)	(d) Minimum amounts of water actually used in practice (gal)
J.F.R.O.	4·5	13	5	0·027	0·005	0·020	0·006
J.F.R.O.	512	320	120	3·14	0·3	1·9	0·81
J.F.R.O.	512	320	240	4·56	0·3	1·9	1·0
N.B.F.U.	900	570	300	9·1	1·3	3·4	9·9
N.B.F.U.	900	570	180	7·1	1·2	3·4	8·1
Ladbroke Grove	1400	*1020	180	12·8	1·1	5·2	20
B.R.S.	1900	*1180	180	14·7	1·3	7·1	15

*Inclusive of furniture.

It is this quantity which is used in Figure 8 as the limiting amount of steam required. These estimates assume some degree of mixing to occur. If none took place, flame could only be completely extinguished when x was 100 per cent. In practice some steam would be lost by ventilation and the value of x could be more than 100 per cent. In the tests performed by the National Board of Fire Underwriters, and at the Building Research Station, as well as in the actual fires reported by Lloyd Layman, the amount of water used to gain control corresponded to a value of x of about 200 per cent, if evaporation is assumed to have been complete, and was about twice to three times that in the small-scale tests. In the Ministry of Home Security tests, however, the amount used was about four times that in the small-scale tests.

<u>The vaporization of water and the cooling of the fire</u>

From the results of the small-scale tests we have found that extinction can occur when the amount of water applied is about 0·015 - 0·02 gallon for a $4\frac{1}{2}$ cubic ft. room. For this all to be turned into steam the heat required would be 42,000 - 56,000 calories. Now the heat content of the gaseous contents of the room, measured in excess of 100°C is

$$H_1 = \rho c V \theta$$

where ρ is density of the gases at the elevated temperature
c is specific heat at constant pressure
V is the room volume
and θ is the excess temperature.

From the appropriate values we calculate H to be about 8,000 calories which will vaporize no more than one-fifth of the water and since in practice the gases are partly if not wholly expelled the available heat may be very much less than this. The source of the heat which vaporizes the water must therefore be the walls, floors, etc. and the solid contents of the room.

If the temperature of the solid surfaces in the room were instantaneously raised to 900°C we can calculate the approximate amount of heat that would enter the solids by thermal conduction alone. In addition to this there will be the heat produced by the exothermic reactions within the burning material.

If the solids are regarded as semi-infinite, initially cold, and subjected to a constant raised surface temperature, then the temperature θ at a point "x" from the surface at time "t" is given by

$$\theta = \theta_S \operatorname{erfc} \frac{x}{2\sqrt{kt}}$$

where θ_S is the surface temperature 900°C
and k is the thermal diffusivity.

This approximation is valid for a finite lining as long as $\sqrt{kt}$ is much less than the thickness of the lining. The heat content of the solid for a surface area A is then given by

$$H_2 = \int_0^{\infty} \theta \rho_w c_w . A . dx = 2 A \rho_w c_w \theta_S \sqrt{\frac{kt}{\pi}}$$

From this equation we can estimate the total heat content of the fires described above. For convenience this is quoted as the quantity of water which, if evaporated into steam, would absorb this heat.

The results of such calculation are given in Table 8 column (a) and the amounts of water actually used to extinguish these fires are given in column (d). These latter varied somewhat with the different conditions of application and, while many experiments were made for a variety of conditions in the $4\frac{1}{2}$ cubic ft. room, the date for some of the other fires are perhaps relevant to only one condition of application of water. However, a comparison between the calculated heat content and the amounts of water used does show that, relative to the estimated heat content, the amount of water used tends to increase with the size of the fire. The rate at which this heat can be extracted may be estimated by assuming that the heated surfaces are everywhere reduced to zero ambient temperature, during the time the water is applied but if this is done a difficulty is introduced in that the calculated heat extracted depends on the cooling or extinction time whereas the amounts of water necessary do not vary greatly with a decrease in extinction time brought about by increasing the rate of flow.

A different approach is to calculate the minimum amount of cooling that need be applied. A suitable criterion of minimum necessary cooling is that the surface temperature must not exceed a critical value for reignition after the removal of cooling. For simplicity, this calculation again assumes uniform cooling over the entire surface but within this and other limitations, the theory shows that if the temperature of reheating is assumed not to exceed 300°C a minimum necessary value of the cooling time T_c can be calculated for any given heating time T_h. The heat extracted in this time can then be found and is given by Tauxe and Stoker [8] as equivalent to a layer of water of thickness about 10^{-3} in. Their results were obtained with an electrical analogue which took account of the difference in the properties of charcoal and wood. In another report by one of us (P.H.T.) it will be shown that results very similar to those obtained by Tauxe and Stoker are obtained if the material is assumed to be homogeneous, a simplification allowing an analytic approach to be made. The results appropriate to the fires described above are also listed in Table 8 (column (b)), from which it is seen that relative to this minimum cooling the amounts of water used in extinction increase with the size of the fire. Column (c) Table 8 gives the amounts of water which if completely evaporated could fill the room with steam. For burning times of a few minutes there is more than enough heat available for making this steam. Even so, the attribution of extinction wholly or partly to smothering by steam as a volume effect does not alter the view that extinction is achieved less efficiently the larger the fire.

A possible explanation of this decrease in efficiency with size is that extinction is achieved by a combination of cooling and smothering but that since the bulk of the steam is formed at the hot surfaces of the room the larger the room the more steam must be formed per unit area of surface to produce a volume of steam a given fraction of the room volume. Since the amount of steam that can be formed per unit surface area is limited the contribution of smothering decreases as the rooms become larger.

Conclusions

(1) Experiments with small-scale models have demonstrated that the amount of water required to extinguish a fully-developed fire of short duration is very small if applied efficiently. The extinction of flame sufficient to allow entry to be made after the clearance of steam may require as little as 2 gallons of water for 1000 cubic ft. of fire. Under full-scale conditions both experimental and operational this figure may be 5-10 gallon/per 1000 cubic ft.

(2) The quantity of water required to extinguish an enclosed fire increases with increasing ventilation.

(3) Under the conditions of these experiments the amount of water used by a spray is the same or less than that used by jets to control the same fire. The difference becomes more marked as the rate of application of water is increased.

(4) Since the efficiency in terms of water consumption can decrease with increasing rate of flow, particularly when using jets, there would seem to be a most efficient rate of application of water. In practice this is probably not much greater than the minimum rate that can be used to extinguish the fire where differences between sprays and jets may not be very large. If the time of extinction is to be reduced, it can best be done by increasing the rate of flow and sprays are then more efficient than jets.

(5) Differences in the degree of manoeuvrability of a nozzle are less important with sprays than with jets.

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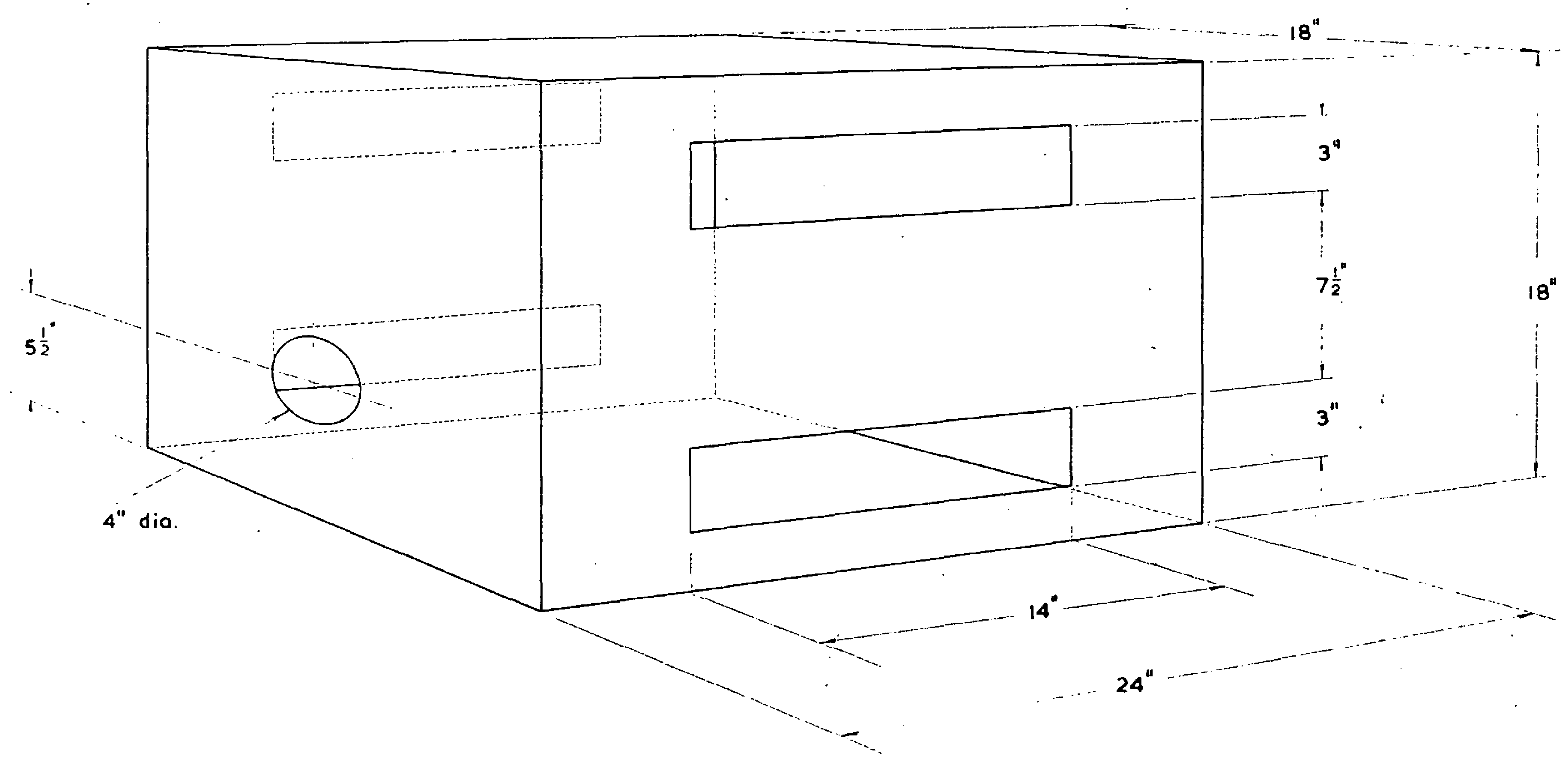


FIG. I. DIAGRAM OF MODEL ROOM.

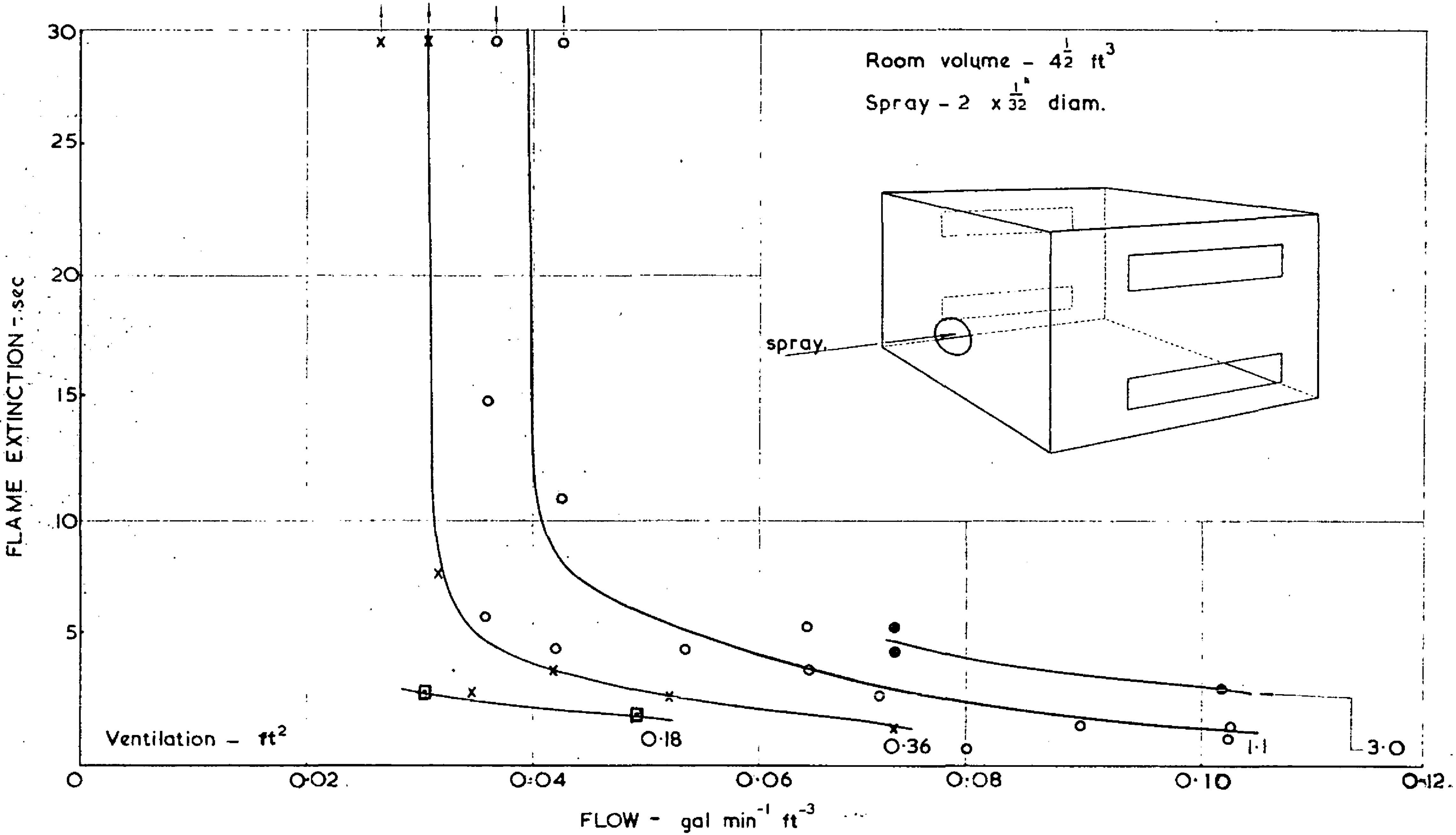
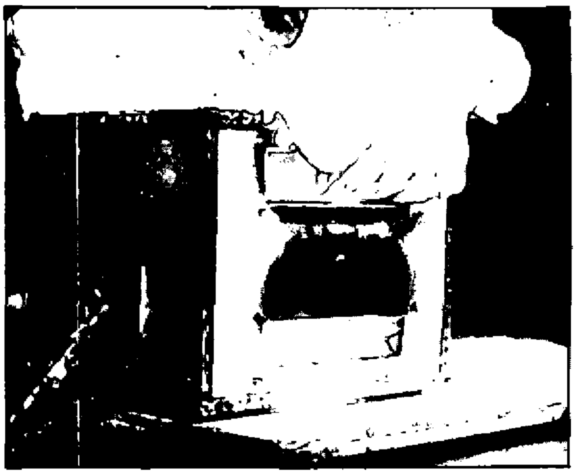
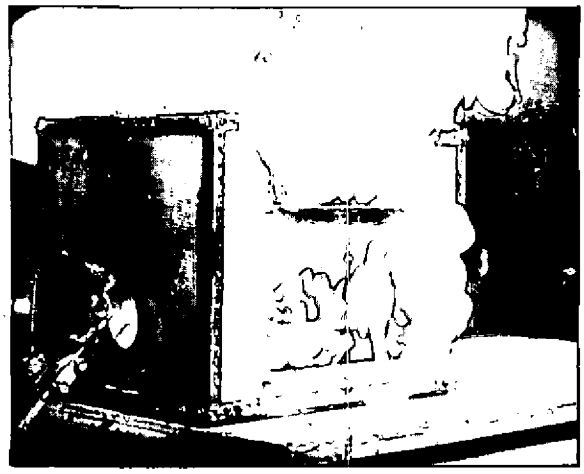


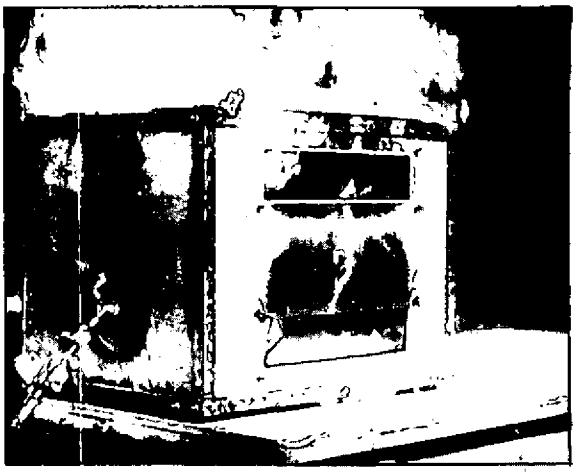
FIG. 2. EXTINCTION TIMES FOR VARIOUS RATES OF FLOW FROM SPRAYS.



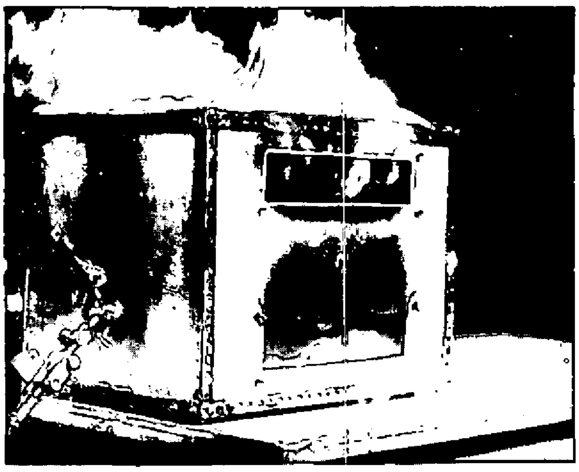
Immediately prior to application of water.
(0 sec)



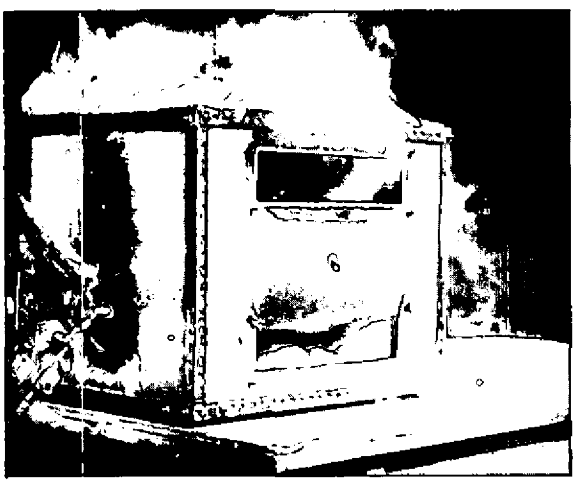
Flames driven out of all windows after entry of water.
(¼ sec)



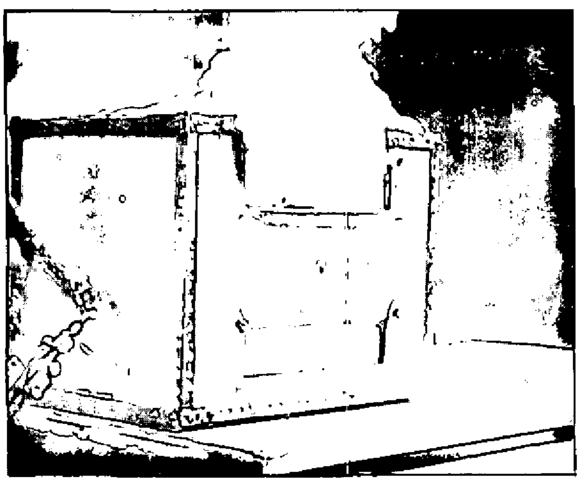
Collapse of flame.
(½ sec)



Wisps of steam appear from windows.
(1 sec)



Increasing amount of steam.
(1¼ sec)



Large clouds of steam. Flame extinguished.
(3 sec)

FIG. 3. SUPPRESSION OF FLAME BY WATER SPRAY.

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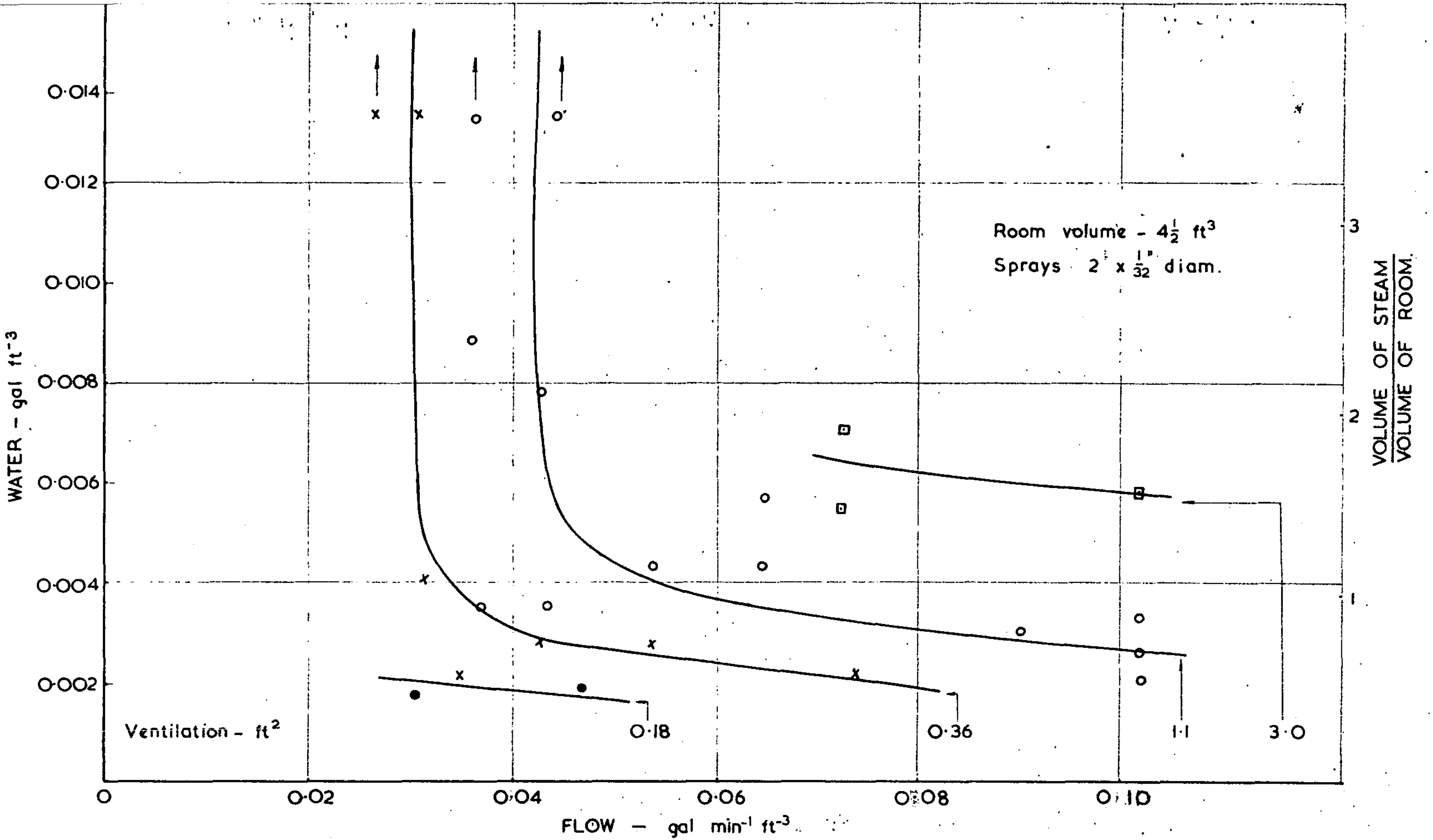

FIG. 4. QUANTITIES OF WATER USED AT VARIOUS RATES OF FLOW FROM SPRAYS.

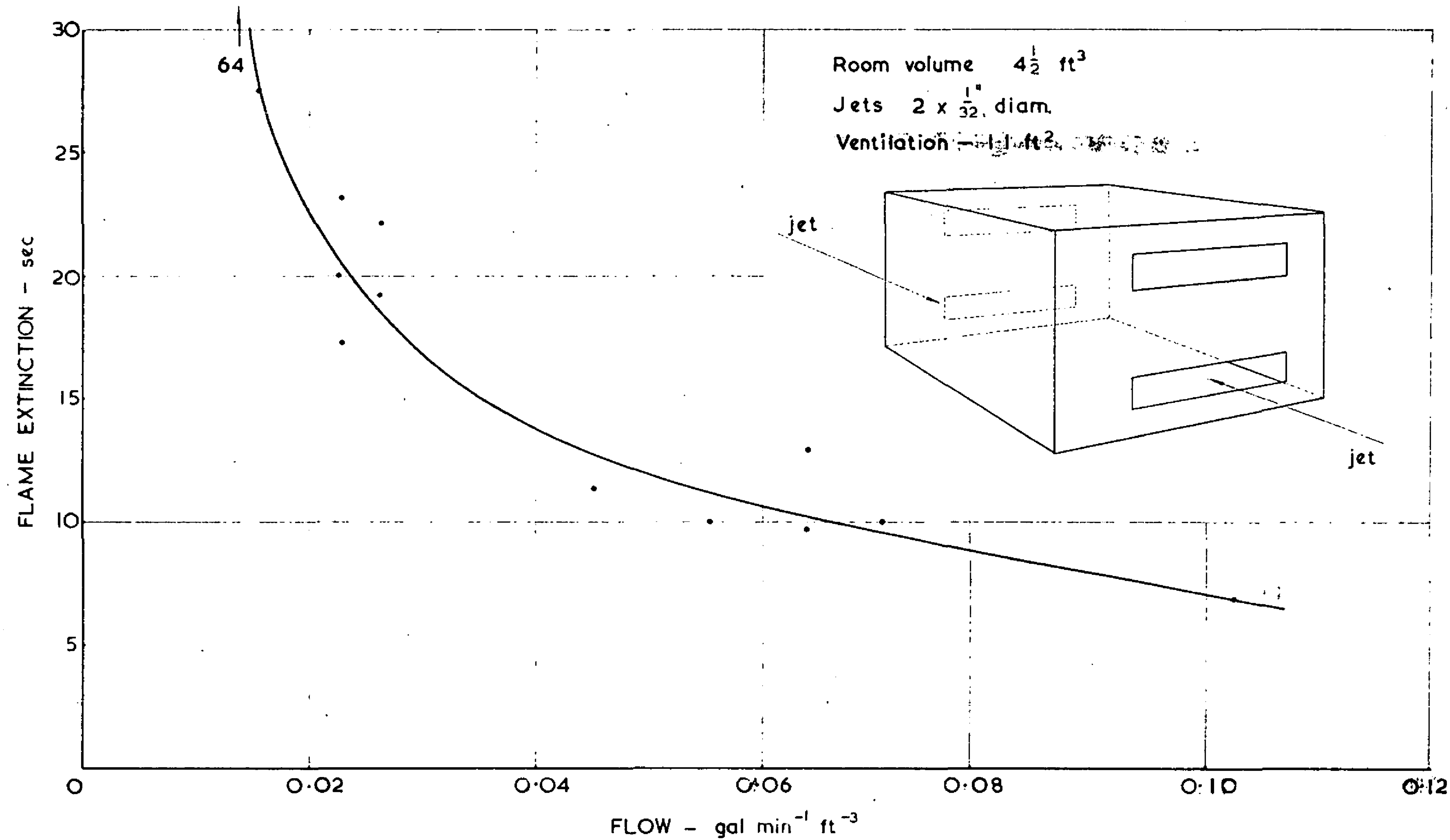

FIG. 5. EXTINCTION TIMES FOR VARIOUS RATES OF FLOW FROM JETS.

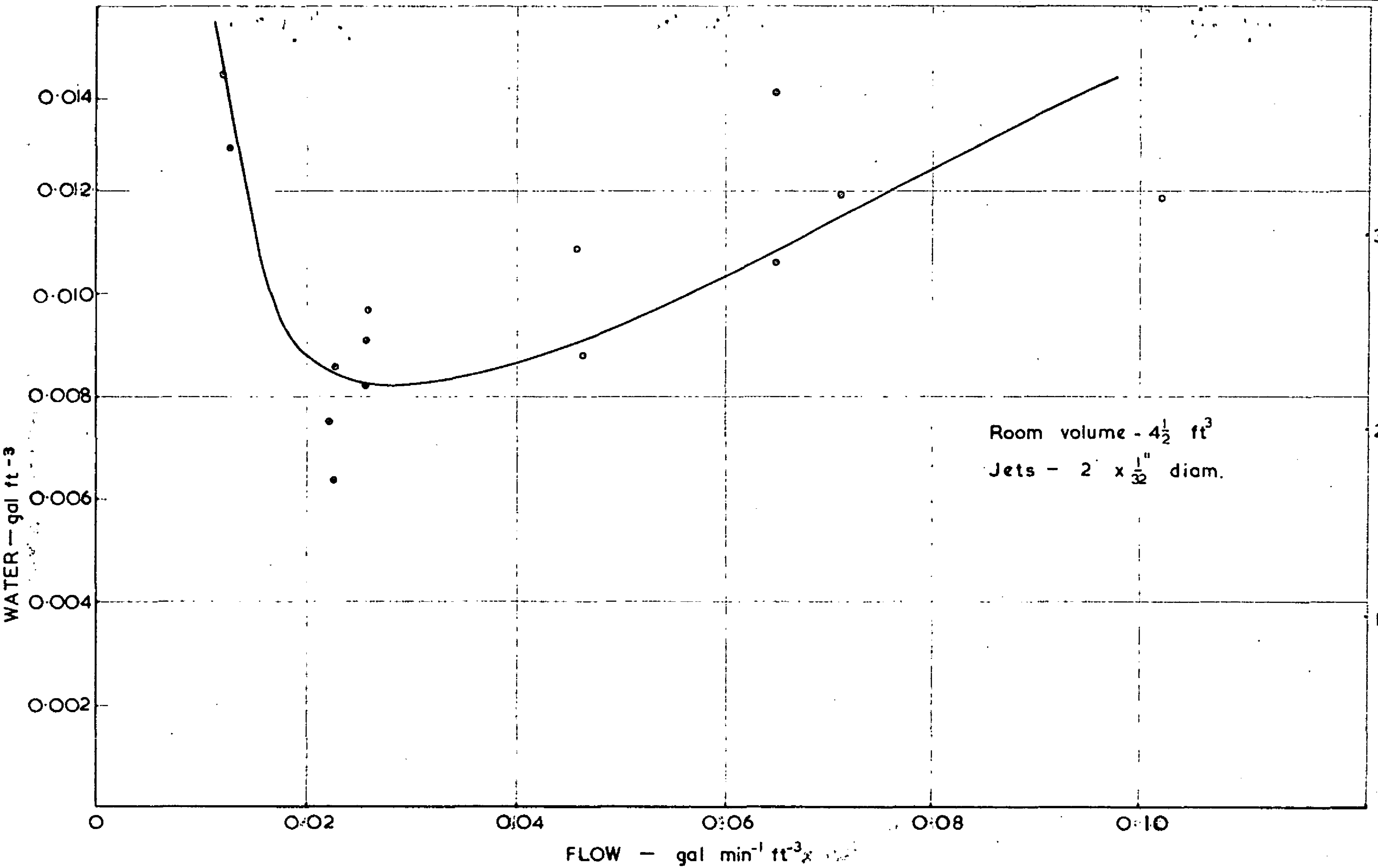

FIG. 6 QUANTITIES OF WATER USED AT VARIOUS RATES OF FLOW FROM JETS.

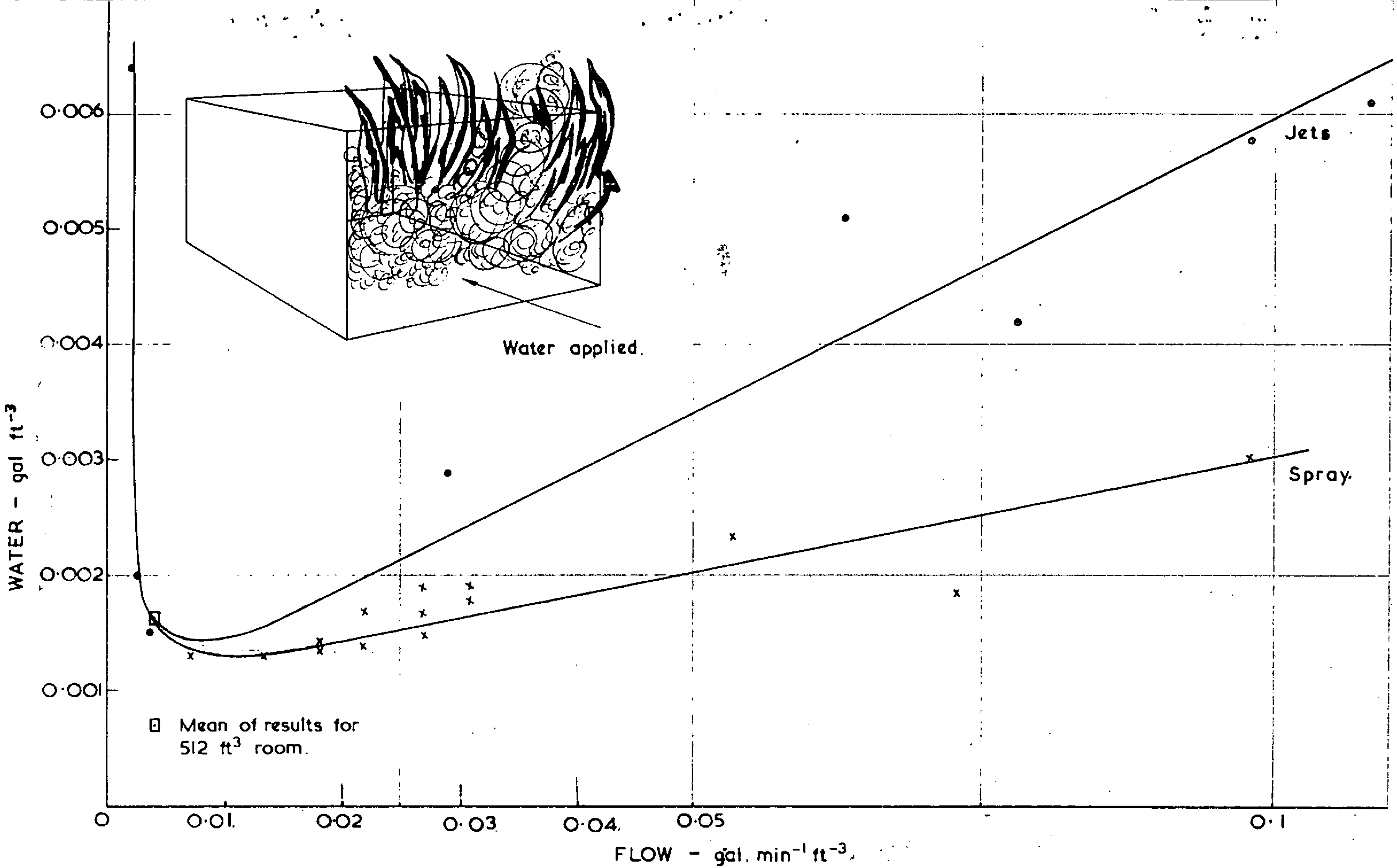

FIG. 7. QUANTITIES OF WATER USED BY SPRAYS AND JETS.

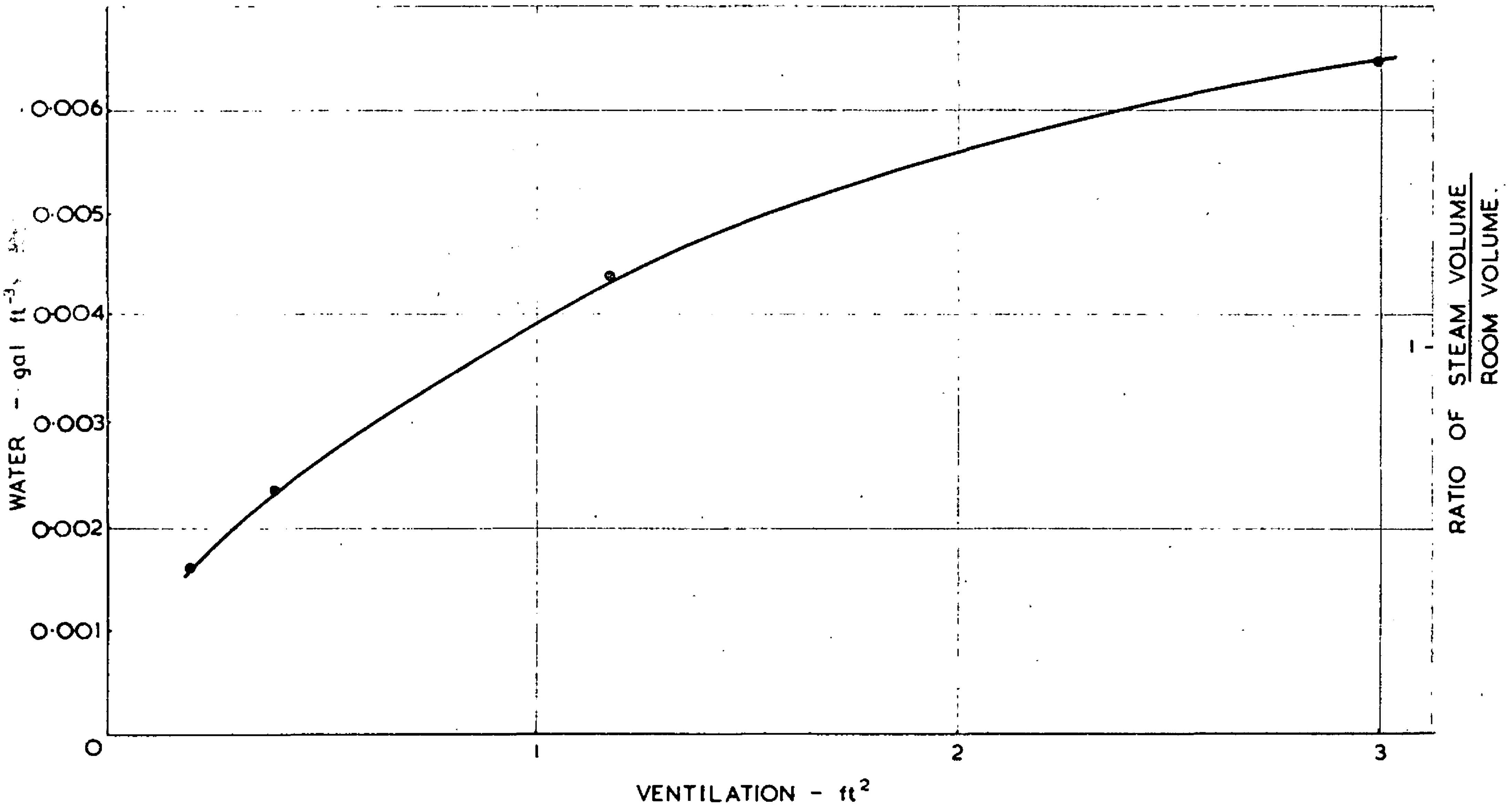

FIG. 8. EFFECT OF VENTILATION ON QUANTITY OF WATER REQUIRED TO EXTINGUISH FIRE IN ROOM $4\frac{1}{2}$ ft^3