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FOAM FOR AIRCRAFT CRASH FIRES (1)

by

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1. Introduction

Aircraft crash fires differ in many ways from other flammable liquid fires, such as those in petrol storage tanks. The time element is usually critical in that people must be rescued at the earliest possible moment, and the accent therefore lies in the rapid reduction of the intensity of the fire rather than on its extinction. It is unlikely that there will be any appreciable area of free petrol surface, and in order to obtain rapid coverage of the aircraft crash and the surrounding terrain, the foam must be applied directly to the burning areas.

Foam may be applied either as a jet or a spray, and opinions of operational officers differ on the relative merits of the two methods. While many tests have been made with sprayed foam on large spill fires, there is little information on the application of foam as a jet to this type of fire. An initial programme of tests was therefore planned to see whether there was any marked advantage in using one method of application in preference to the other, and at the same time the effects of varying the expansion and critical shearing stress of the foam were investigated.

2. Previous work on sprayed foam

Results of large-scale tests by the Engineer Research and Development Laboratories were reported in 1950 (1). A petrol fire 25 ft x 50 ft was tackled using a number of "fog foam" nozzles. The majority of these nozzles were water spray nozzles of the impinging jet type which, when used with a 6 per cent foam solution, gave a low expansion rapidly-draining foam. One of the nozzles tested was a self-aspirating nozzle similar to a branch pipe with a fan-shaped diffuser which appeared to give a foam of expansion about 6. The results of these tests are shown in Fig. 1.

Experimental work at the Naval Research Laboratories (2) was carried out at one rate of application, 0.083 gal/ft^2/min. Preliminary tests on an open-ended 2 ft diameter drum of petrol were followed by tests on a 400 ft^2 tray with about $\frac{1}{4}$ in. of petrol on a mud base. The spray was produced from a fixed nozzle with sixteen outlet pipes, the diameters of which were varied to obtain satisfactory performance with the foams of different expansion which were tested. The conclusions drawn from these tests were that there was an optimum expansion of 10-12 when foam was applied in a dispersed pattern and that variations in viscosity at a given expansion were of no direct importance.

3. Experimental procedure

3.1. Simulated aircraft crash fire

The test fire (Fig. 2) was arranged to simulate, in a simple manner, the main features of an aircraft crash fire. A 10 ft by 10 ft bund was constructed and two diagonally opposite quarters were built up with rubble and sand; the other two quarters were left unobstructed and a water level was maintained just below the sand surface. Four 40 gal. drums were placed symmetrically in the bund with their centre lines diagonally across the bund. About 15 gal. of petrol (motor spirit) was used for each test. The fire thus consisted partly of free petrol surface and partly of petrol-soaked sand, with a simple representation of an aircraft fuselage. Because of the symmetry of this arrangement the fire could be attacked from any side to suit the direction of the prevailing wind.

The foam was produced by a generator giving metered control of the foaming liquid and air flow rates. For the application of foam as a jet standard fire brigade nozzles were used, either $\frac{7}{8}$ in. or 1 in. diameter according to the foam flow rate. To produce a foam spray, a modified water diffuser (Fig. 3) was used. This was one of the type having serrations designed to give a solid cone of water spray. The original valve was replaced to give the increased clearance required for foam, two sizes of valve being used to suit the foam flow rate.

A 30-second preburn was allowed before fire-fighting was commenced. The progress of the fire control was recorded by means of radiometers arranged in the manner used in previous surface application experiments (3). The operator approached the fire from the windward side and moved round the bund to reduce the fire as quickly as possible. The criterion used to determine the efficiency of extinction was to measure the "90 per cent" control time, i.e. the time taken to reduce the radiation from the fire to one-tenth of its initial intensity. The size of the fire at this stage was considered to be such that a suitably clothed trained man could walk through the fire area to make a rescue attempt. No tests were carried out when the wind speed was more than 10 ft per sec.

Twenty-four tests were made, the order being selected to minimize the effect of the operator's learning factor. In half the tests, jet application was used and in the other half the foam was applied as a spray. For each method of application three liquid rates were used at two levels of critical shearing stress for each of two foam expansions. The two expansions were 7 and 14, the liquid rates of application were 0.05, 0.075 and 0.10 gal/ft^{-2}/min^{-1} and the two ranges of critical shearing stress were 300-450 dynes/cm^2 and 600-850 dynes/cm^2.

3.2. Free petrol and petrol-soaked sand fires

Following the twenty-four tests described above, a smaller number of tests were made to compare the use of jet and spray application on two of the basic elements of the aircraft crash fire, namely, fire on a free petrol surface and on petrol-soaked ground.

The same 10 ft square bund was used. For the free petrol tests 15 gal of fuel was floated on water, while for the other tests the whole bund was filled with rubble and finished off with a level sand surface. The test procedure was similar to that used for the earlier experiments and foam of expansion 14 and critical shearing stress 450 dynes/cm^2 was used. For the free petrol fires the jet was always directed into the petrol, no use being made of the bund wall.

4. Experimental results and discussion

4.1. Simulated aircraft crash fires

The results of the twenty-four tests are shown in Table 1 and Fig. 4 and the results of the statistical analysis are given in Appendix 1. The analysis shows that of the four variables all but the expansion have a significant effect on the time taken to control the fire, the rate of application and critical shearing stress of the foam having a greater effect than the method of application. The "most likely" results can be calculated using only the significant effects and these are plotted in Fig. 5.

TABLE I

EXPERIMENTAL RESULTS OF TESTS ON 100 SQ. FT MOCK AIRCRAFT FIRE

EXPANSION	CRITICAL SHEARING STRESS	METHOD OF APPLICATION	1/10 CONTROL TIME (SECS.) RATES OF APPLICATION: GAL.ft^{-2}min^{-1}		
			0.10	0.075	0.05
7	LOW 400	JET	43 .0715	48 .060	45 .0375
		SPRAY	47 .073	42 .052	55 .046
	HIGH 700	JET	29 .048	56 .070	77 .064
		SPRAY	46 .077	45 .056	103 .086
14	LOW	JET	28 .047	34 .042	48 .040
		SPRAY	37 .062	36 .045	48 .040
	HIGH	JET	42 .07	43 .054	60 .050
		SPRAY	56 .093	44 .055	88 .073

The effects of the foam properties on the control time were similar for both jet and spray application. In both cases there was no significant effect of expansion and at the lower rates of application the more fluid foams controlled the fire more rapidly than the stiff foams. As the rate of application from the jet increased, the control time decreased as would be expected. However, the shape of the control time/rate curves for spray application, particularly with the low critical shearing stress, show that it tended to take longer to control the fire at the high rate of application than at the medium rate. To interpret this and the difference between the two methods of application it is necessary to consider what happens as the foam passes through the flames.

Water will be lost from the foam by evaporation as it passes through the flames, and this loss will depend on the expansion of the foam, the flake size and the time the foam takes to pass through the flames. These evaporation losses have been estimated in Appendix 2. The way in which they depend on the properties of the foam spray can be seen by making an approximation to equation 3 of Appendix 2. This can be re-written -

$$\frac{M}{M_o} = \left(1 - \frac{B.t.E}{r_o}\right)^3$$

where $\frac{M}{M_o}$ = fraction of the water in foam reaching the petrol surface

t = time for which flakes are in the flame

E = expansion

r_o = initial radius of foam flakes

B = constant

Now $t = \frac{\text{length of path through flame}}{\text{velocity of foam flakes } (v)}$

It it is assumed that the flakes are travelling with their terminal velocity then for flakes less than about 1 cm in diameter

$$\frac{M}{M_0} = \left[\frac{1 - B' E^{1.7}}{r_0^{2.14}}\right]^3$$

and for flakes greater than about 1 cm in diameter

$$\frac{M}{M_0} = \left[1 - \frac{B'' \cdot E^{1.5}}{r_0^{1.5}}\right]^3$$

where B' and B'' are constants.

It can be seen that the evaporation losses from the foam in the form of a jet would be insignificant but in a spray would depend on both the expansion and the flake size of the foam. For flakes less than about 1 cm diameter the losses are more dependent on the flake size than on the expansion. The percentage of water reaching the petrol surface under the conditions of the tests have been estimated and are shown in Fig. 6.

Because of the importance of the flake size in the foam sprays samples of the sprays were collected on glass plates and photographed. About one hundred flakes of each spray were sized and the mass median flake size estimated; these are shown in Table 2.

Table 2. Mass median flake size of foam sprays

Expansion	Critical shearing stress	Rate of application gal/ft^2/min	MASS MEDIAN flake diameter (cm)
7	Low	0.1	0.8
		0.075	1.3
		0.05	*
	High	0.1	0.5
		0.075	1.2
		0.05	*
14	Low	0.1	0.4
		0.075	0.6
		0.05	1.0
	High	0.1	0.5
		0.075	0.4
		0.05	0.75

*The sprays produced with foam of expansion 7 at the lowest rate of application were really a series of small jets and no estimate of the flake sizes were made.

It can be seen from Table 2 that the flake sizes tended to decrease as the rate of application increased and also that the smaller flakes were generally obtained with the high expansion foam.

Considering then the results obtained with sprayed foam (Fig. 5) the increase in control time as the rate increases from 0.075 to 0.1 gal/ft^2/min may well be explained by the reduction in flake size increasing the evaporation losses and reducing the rate of application to the petrol surface. However, one would expect an increased evaporation loss from the high expansion foam on two

counts; firstly, theory suggests that for the same flake size the evaporation losses are greater with the high expansion foam, (Fig. 6), and secondly, at the same rate of application the flake sizes of the high expansion foams were found to be less than those of the low expansion foams. Despite this the total effect of expansion was not significant. This indicates that if the spray consisted of larger flakes, with which the evaporation losses would be negligible, the high expansion foam might control the fire more rapidly than the low expansion foam.

The tests showed, therefore, that when foam was applied to the fire as a jet the control time decreased as the rate of application increased and the fluid foams controlled the fires more rapidly at the two lower rates of application than did the stiffer foams. There was no significant difference between foams of expansion 7 and expansion 14.

When the foam was applied as a spray the fluid foam again controlled the fire more rapidly at the lower rates of application and the effect of expansion was insignificant. However, since the flake sizes of the foam were in the region where considerable losses by evaporation were possible, it would be unwise to draw any firm conclusions on either the effects of expansion or the relative merits of spray and jet application had the spray consisted of flakes large enough for the evaporation losses to be negligible.

One other factor may affect a comparison between the application of foam as a jet and as a spray. A jet of foam breaks up to some extent and by manipulation a dispersed pattern can be achieved over a reasonable area. It may be, however, that there is an effective limit to this, and the advantages of spray would show up more when large areas are involved.

4.2. Free petrol surface and petrol-soaked sand

The control time rate of application relationships for these tests are shown in Fig. 7. On the free petrol surface there is little indication of any difference in the two methods of application, although the reservations given above will apply particularly as a high-expansion foam was used. In the tests with petrol-soaked sand the jet took much longer to control the fire than did the spray. The foam was rapidly broken down in contact with the sand when applied as a jet and after extinction little foam remained. This effect may have been largely mechanical.

Conclusions

At this stage of the investigations it is difficult to come to any very definite conclusions as to the influence of the method of applying foam to this type of fire. There is some indication that spray application may be better if the flakes are of comparatively large size, so that most of the foam reaches the petrol surface.

The most important foam property when foam is applied as a jet is the critical shearing stress; a fluid foam controlling the fire more rapidly than a stiff one. With this method of application there was no significant difference between foams of expansion 7 and 14.

A fluid foam is also an advantage with spray application but in these tests the effects of expansion may may well have been shrouded by the variation of flake size with expansion.

Acklowledgments

Thanks are due to Mr. C. R. Theobald who acted as branchman for the tests and to Mr. D. W. Millar for his help in planning the tests.

References

(1) Engineer Research and Development Laboratories Report No. 1166. Fort Belvoir, Virginia, 1950.

(2) Tuve, R. L. and Peterson, H. B. Naval Research Laboratory Report No. 3725.

(3) French, R. J., Hinkley, P. L. and Fry, J. F. Chemistry and Industry. pp. (200-268) 1956.

(4) Heat Transmission. W. H. McAdams. McGraw Hill.

APPENDIX I

RESULTS OF STATISTICAL ANALYSIS

Statistic	Mean result sec.	Standard error of observations	Coeff. of variation %	Mean Values of significant effects					
				Linear Effect of R (R_1)	Curvilinear effect of R (R_2)	Linear effect of M-(M_1)	Linear effect of S-(S_1)	Interactions	
								R_2M_1	R_1S_1
Control Time	50	± 8.2	16.4	- 12.25**	+ 3.25*	+ 3.9*	+ 7.42**	+2.84*	-7.15**

Factor R. Effect of Rate of Application r_o = 0.05 gal/ft^2/min r_1 = 0.075 gal/ft^2/in r_2 = 0.1 gal/ft^2/min.
Factor M. Effect of Method of application m_o = jet m_1 = spray.
Factor S. Effect of fluidity s_o = 300-450 dynes/cm^2 S_1 = 600-850 dynes/cm^2.
Factor E. Effect of expansion e_o = 7 e_1 = 14.

Levels of significance ** 1 per cent * 5 per cent.

APPENDIX 2

Estimation of evaporation losses from foam spray

The loss of water by evaporation as the foam passes through the flames will depend on the foam expansion and particle size and the time taken for the foam to pass through the flame.

Consider unit mass of foam comprising N spherical flakes of initial radius r_o. The rate of loss of weight is given by

$$-\frac{dM}{dt} = \frac{hNS\theta}{L} + \frac{INS}{L} \qquad \text{.....(1)}$$

where
- h = convective heat transfer coeff.
- N = number of flakes in unit mass of foam $= \frac{3}{4\pi r_o^3 \rho_F}$
- ρ_F = density of foam
- S = surface area to which heat transfer occurs $= 4\pi r^2$
- r_o = initial radius of flakes
- r = radius at time t
- θ = flame temperature
- L = latent heat of steam
- I = intensity of radiation

Data on heat transfer coefficients between spheres and air have been correlated in terms of the Reynolds No. (Re) and the Nasselt No. (Nu) [4]. To simplify the integration of equation (1) the following correlation will be used -

$$Nu = 0.63\ Re^{0.5}$$

This gives a good correlation over the range of Re from (20-2,000) which is the range concerned in this problem.

Substituting in Equation (1)

$$-\frac{dM}{dt} = \frac{0.63K}{2r}\left(\frac{2vr\rho}{\mu}\right)^{0.5}\frac{3r^2\theta}{r_o^3\rho_F L} + \frac{3r^2 I}{r_o^3\rho_F L} \qquad \text{.....(2)}$$

where
- K = thermal conductivity of the hot gases
- ρ = density
- μ = viscosity
- v = relative velocity between the foam flakes and the flame.

It is reasonable to assume that the flakes will be travelling at their terminal velocity through the flames. The terminal velocity $V \propto \rho_F^{0.7} r^{1.4}$ (Re < 500) and $V \propto \rho_F^{0.5} r^{0.5}$ (Re > 500)

The range of flake sizes up to about 1 cm diameter would be in the first range of Re. In determining the residence time of the flakes in the flames calculated values of settling velocity will be used, but since in equation (2) V appears only as $V^{0.5}$ the following approximation will be used -

$$V = A\rho_F^{0.7} r \quad \text{where} \quad A = 9.9 \times 10^3$$

Substituting in equation (2)

$$-\frac{dM}{dt} = \frac{0.63K}{2r}\left(\frac{2A\rho}{\mu}\right)^{0.5}\frac{r\rho_F^{0.35}3r^2\theta}{r_o^3\rho_F L} + \frac{3r^2 I}{r_o^3\rho_F L}$$

$$= \frac{r^2}{r_o^3\rho_F L}\left[3I + \frac{0.945K\theta\rho_F^{0.35}}{}\left(\frac{2A\rho}{\mu}\right)^{0.5}\right]$$

Now $r = r_o M^{1/3}$

$$-\frac{dM}{dt} = \frac{M^{2/3}}{r_o\rho_F L}\left[\ \ldots\ldots\ldots\ldots\ldots\ldots\ \right]$$

Integrating gives

$$M^{1/3} = 1 - \frac{t}{3 r_0 \rho_F L}\left[3I + 0.945 K \theta \rho_F^{0.35}\left(\frac{2A\theta}{\mu}\right)^{0.5}\right] \quad \ldots\ldots(3)$$

If it is assumed that the flakes always traverse the same distance through the flames the residence time in the flames (t) will depend on the terminal velocity with respect to the petrol surface ($\bar{V}$) which depends on the flame velocity (V_F) and also on r_0 and ρ_F.

$$\bar{V} = V - V_F$$

Since r will vary as the flakes pass through the flames the terminal velocity will be continually varying. However, a 50% loss in weight of the foam flake would only result in a 16% reduction in r and thus a 16% decrease in velocity and a proportional increase in residence time. A reasonable approximation can therefore be obtained by taking the terminal velocity as that appropriate to the initial flake size.

The evaporation losses for foam sprays of expansion 7 and 14 will be computed assuming the following values for the constant in Equation (3).

L = 620 cal/gm.
θ = 1000°C
$K_{1000°C}$ = 1.3×10^{-4} c.g.s. units
$\rho_{1000°C}$ = 2.8×10^{-4} c.g.s. units
$\mu_{1000°C}$ = 4.8×10^{-4} c.g.s. units
I = 3.6 cal/cm²/sec. (assumes an emissivity of 1).
A = 9.9×10^3

$$t = \frac{\text{length of path of flakes thro' flame}}{V - V_F} \text{ secs}$$

Assuming the flakes traverse 10 ft (305 cms) and V_F = 305 cm/sec.

$$\text{then } t = \frac{305}{V - 305} \text{ secs.}$$

Substituting in Equation (3) gives

$$M^{1/3} = 1 - \frac{0.165}{(V-305) r_0 \rho_F}\left[10.8 + 13.2 \rho_F^{0.35}\right]$$

Thus for foams of expansion 7 -

$$M = \left[1 - \frac{20.1}{(V-305) r_0}\right]^3$$

and for foams of expansion 14

$$M = \left[1 - \frac{37.15}{(V-305) r_0}\right]^3$$

Values of M have been computed from these two equations for values of r_0 up to 1 cm and are shown graphically in Fig. 6

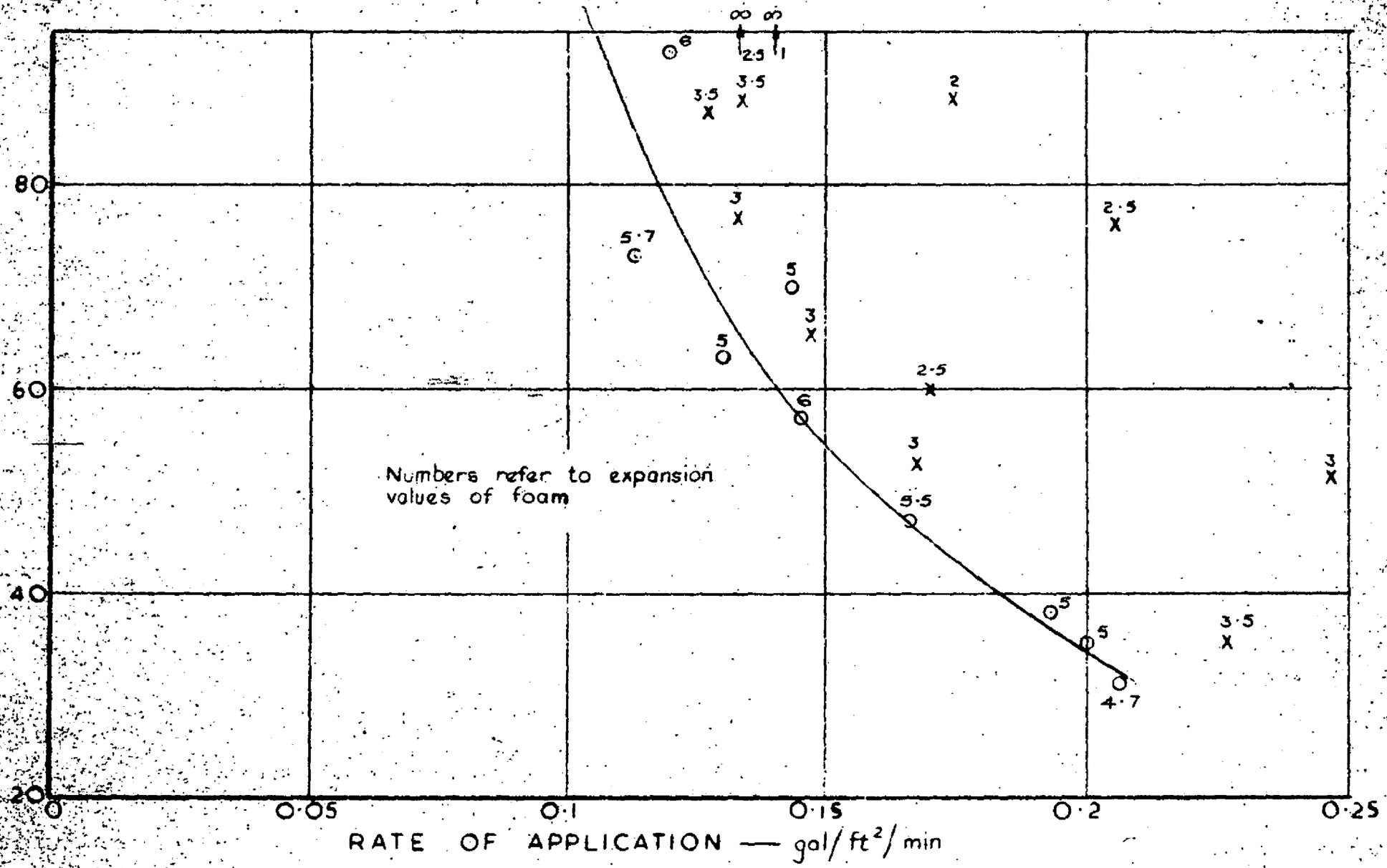

FIG 1. RESULTS OF "FOG-FOAM" TESTS ON 1250 FT² FIRE (rates of application calculated from nozzle delivery)

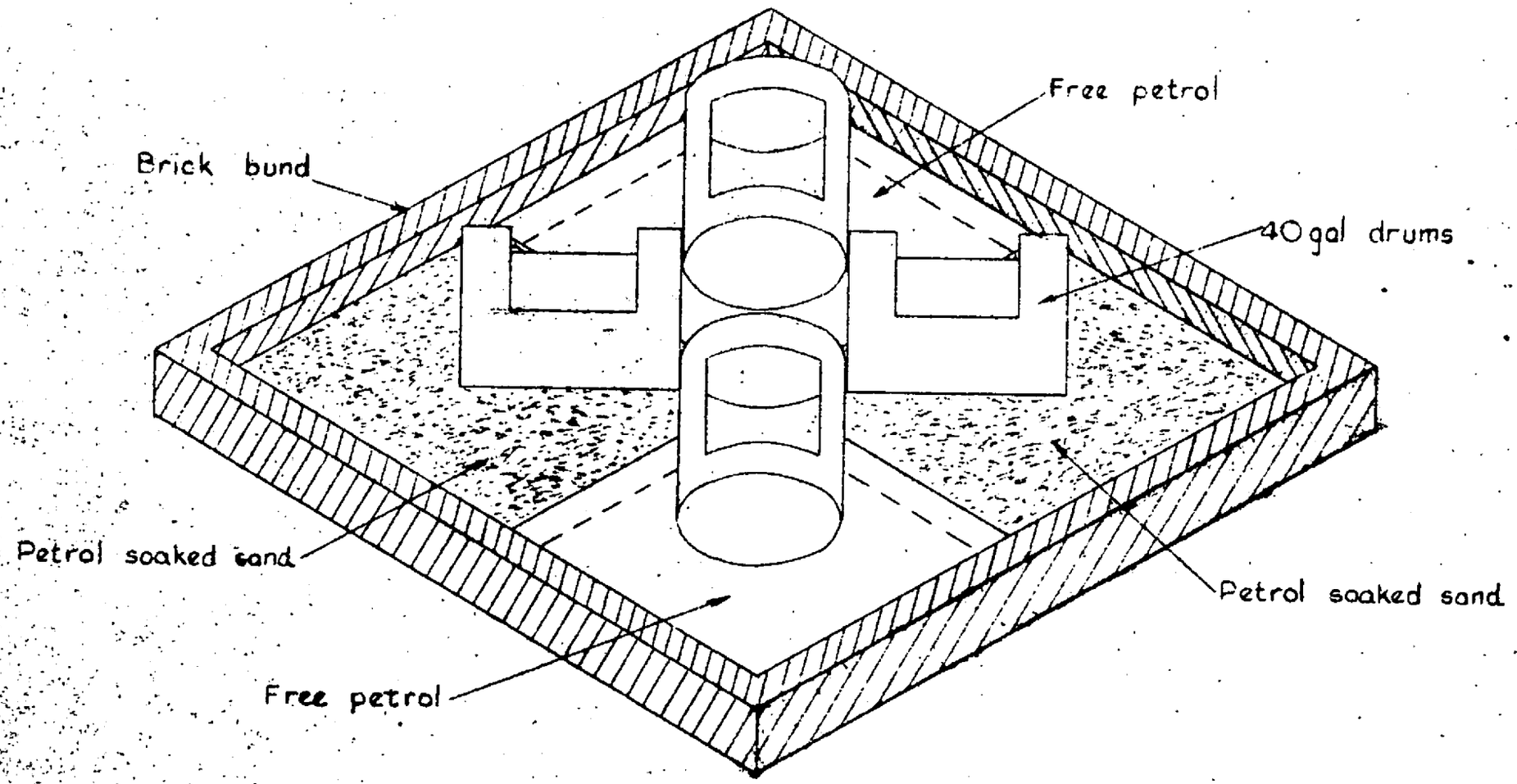

FIG 2 DIAGRAMMATIC ARRANGEMENT OF TEST FIRE

FIG. 3.

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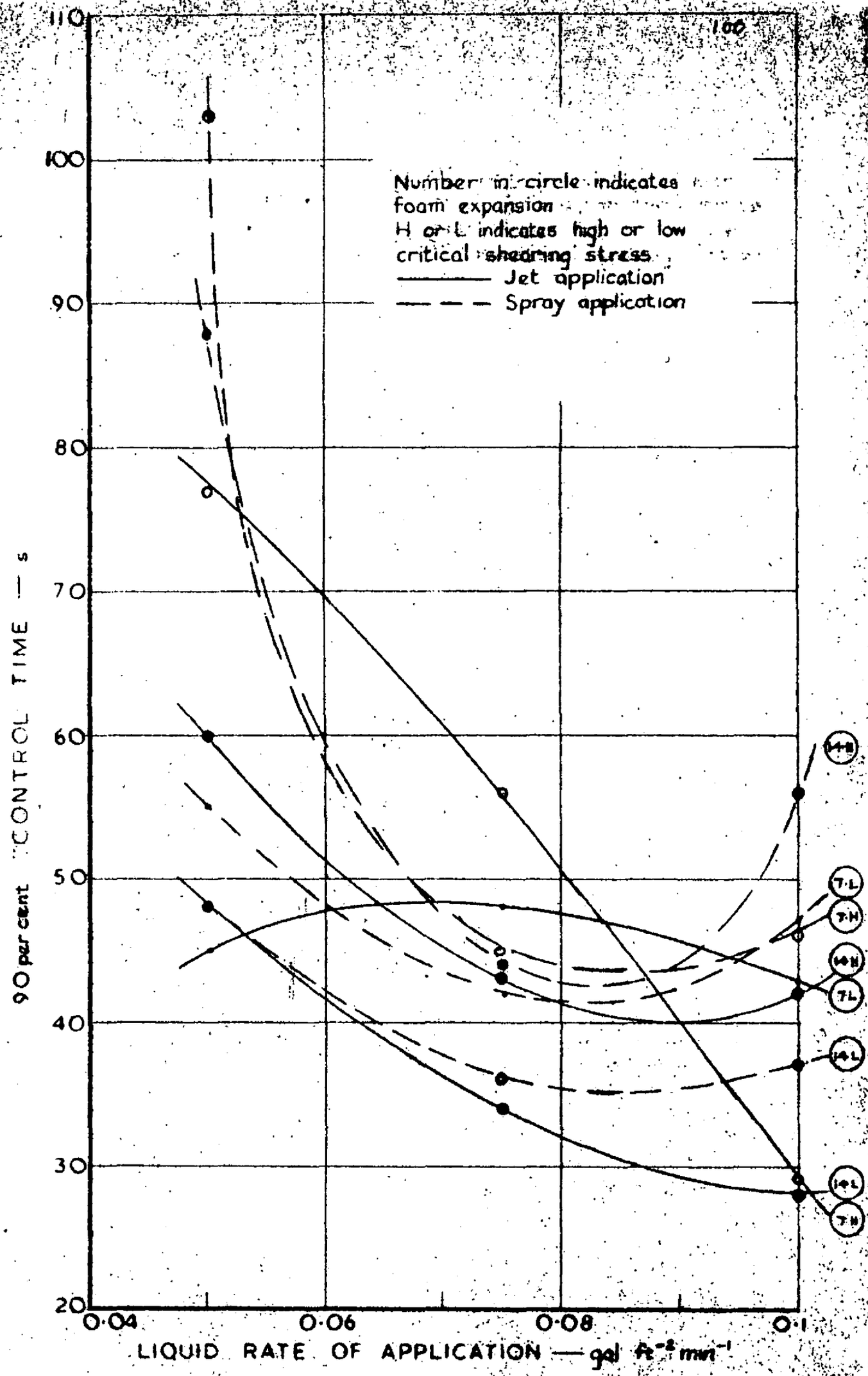

FIG. 4. CONTROL TIME v RATE OF APPLICATION FOR TESTS ON 100 SQ FT MOCK AIRCRAFT FIRE

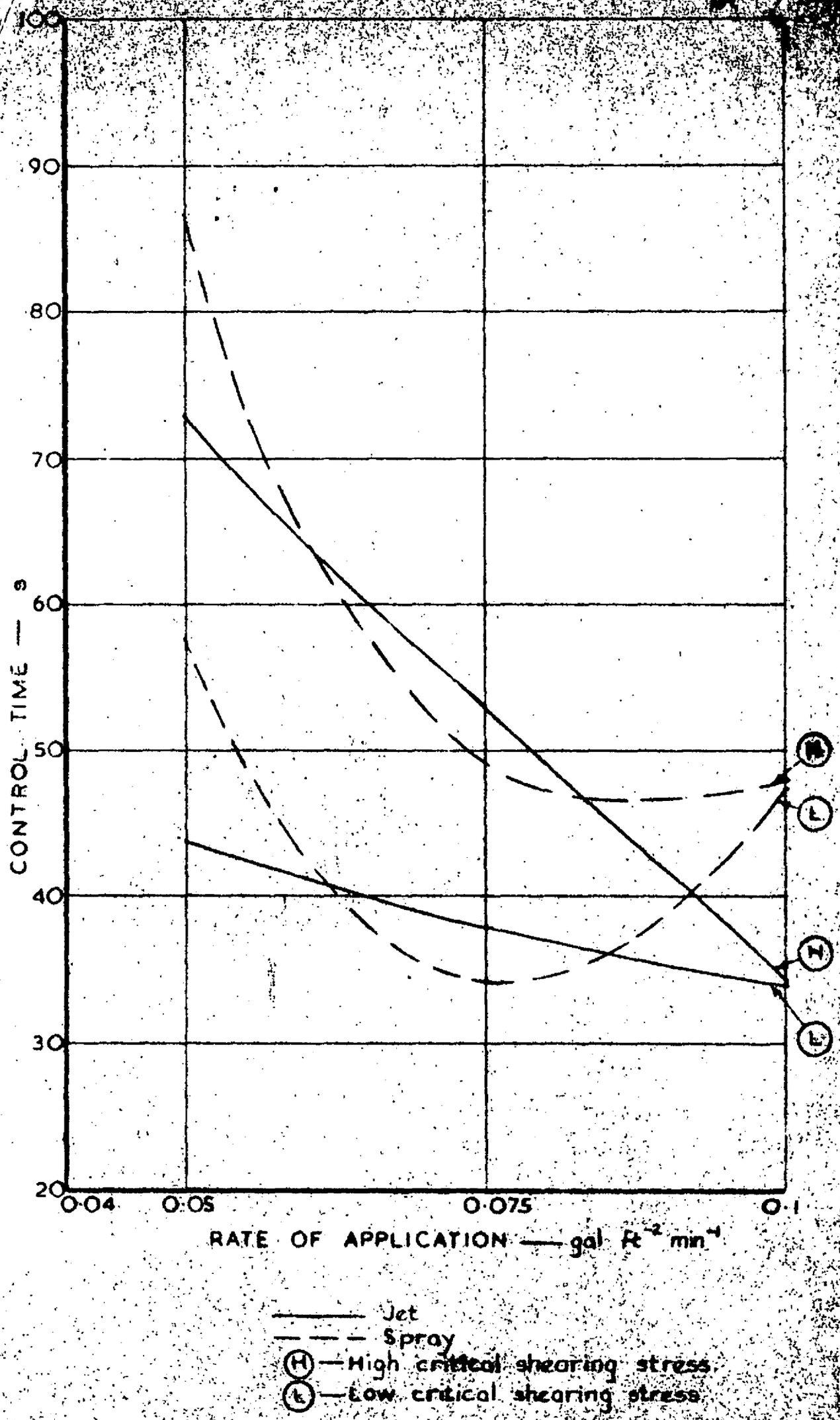

FIG 5 "MOST LIKELY" RESULTS OF TESTS

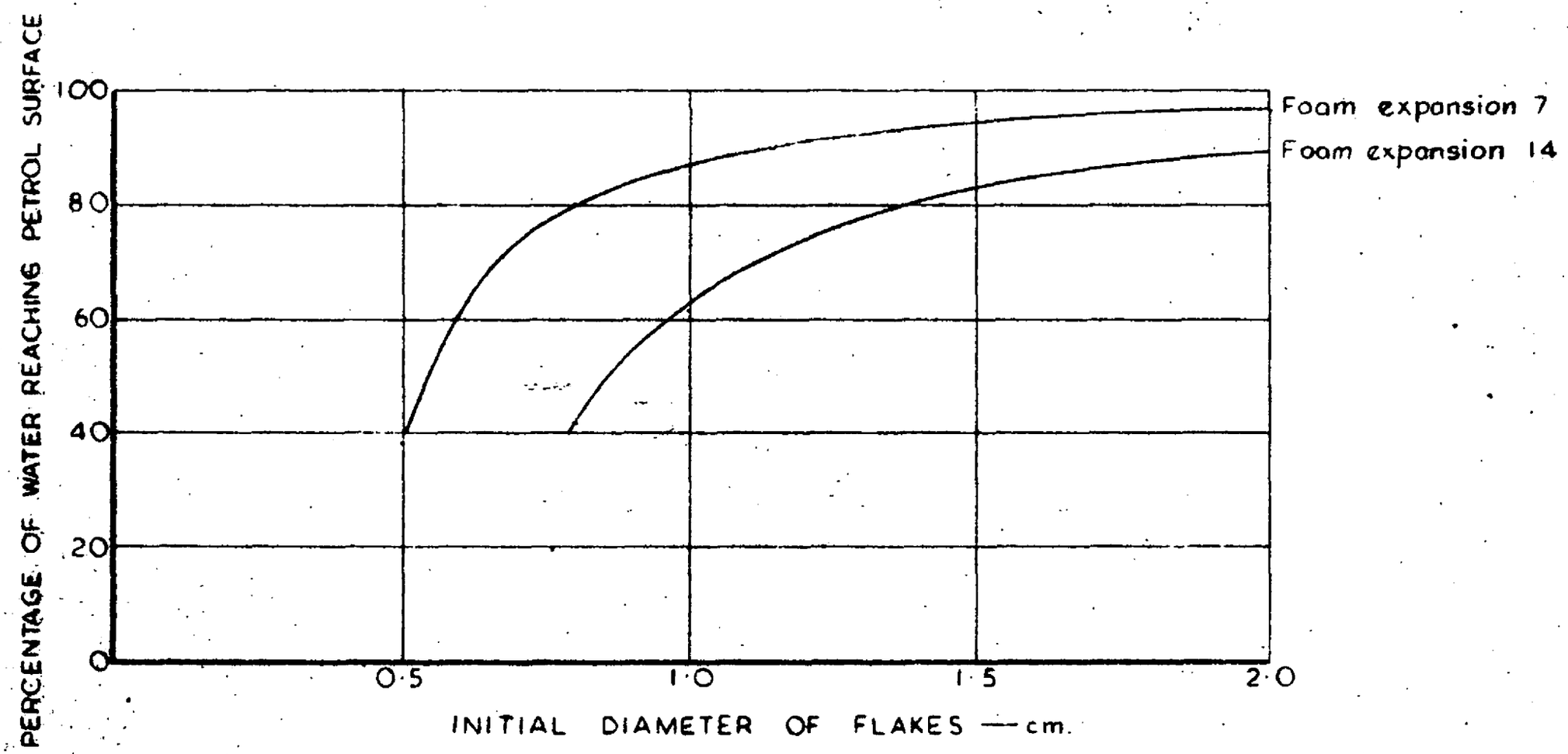

FIG. 6. CALCULATED EVAPORATION LOSSES FROM FOAM SPRAY

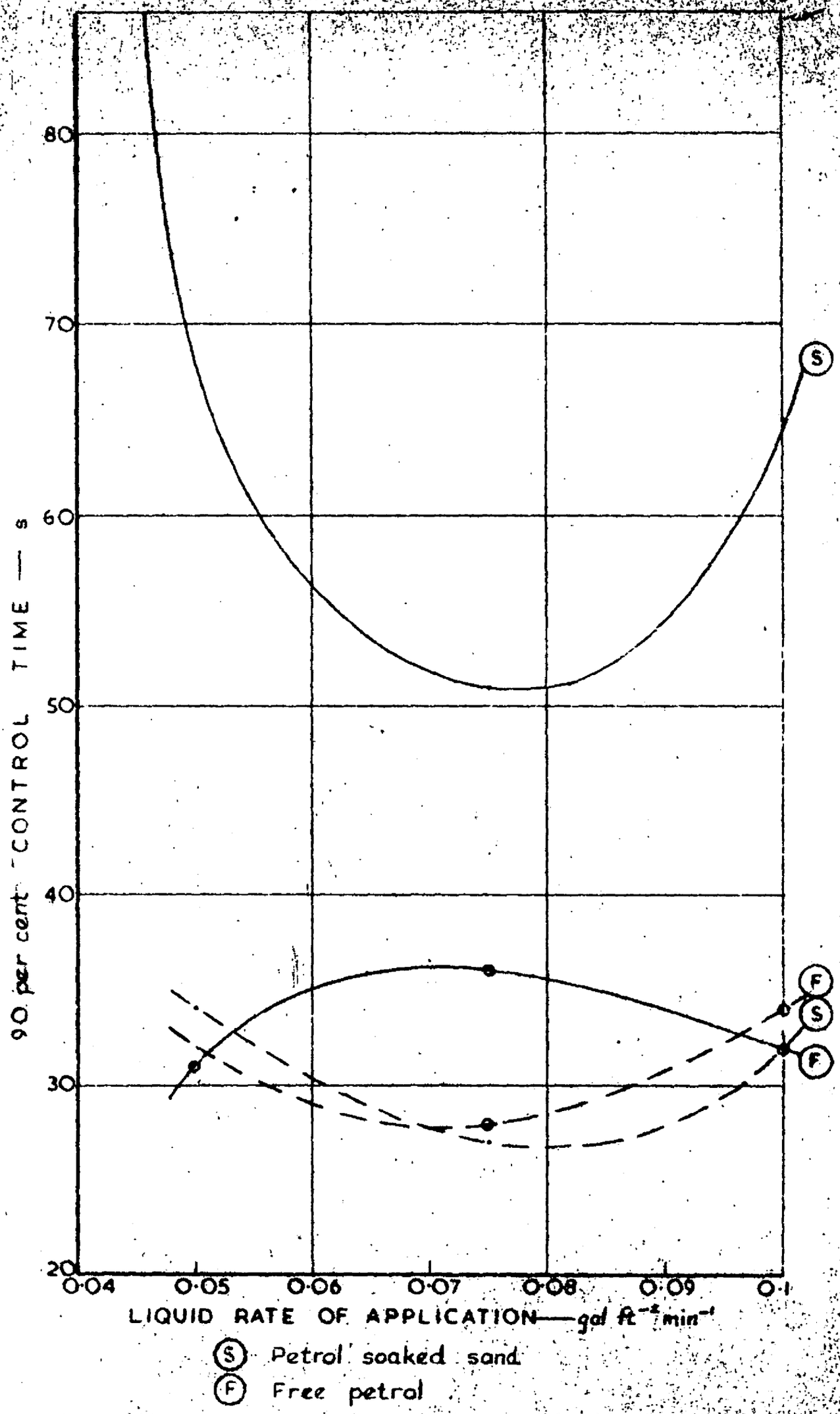

FIG. 7 CONTROL TIME v RATE OF APPLICATION FOR FREE PETROL AND PETROL SOAKED SAND