Fire Research Note No. 918

THE EFFECT OF THE VELOCITY OF FOAM JETS ON THE CONTROL AND EXTINCTION OF LABORATORY FIRES

by

D. M. TUCKER, D. J. GRIFFITHS and J. G. CORRIE

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FIRE RESEARCH STATION

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The effect of the velocity of application of foam to the surface of flammable liquid fires has been assessed, using control and extinction times as the performance criteria.

Four different types of foam liquid were used on one hundred and thirty 0.28 m^2 fires in petrol and AVTUR fuels.

Extinction times were markedly affected by application velocity; control times to a lesser extent. Large differences in behaviour were found between the different types of foam liquids, and between different batches of protein foam liquid. These differences were found to depend on the type of fuel. High application velocity was not found to cause breakdown of the foam, but to produce mixing of the fuel and foam, thus preventing extinction.

The higher expansions and shear stresses favoured effective extinction at the higher application velocities.

The implication of the results to the design of laboratory test equipment and methods is discussed.

KEY WORDS: Foam; jets; velocity; extinguishing; fuel; liquid.

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INTRODUCTION

Hird, D., Rodriguez, A and Smith, D.[1] in 1969 drew attention to the difficulty of extinguishing petrol fires when foam was applied to the fuel surface as a jet, as opposed to gentle surface application. With fires of regular grade motor spirit of area 37 m^2 (400 ft^2) and depth 50 mm (2 in), neither of two protein foam liquids applied as a jet to the centre of the fire produced any substantial reduction in the intensity of the fire after 4-6 min application, while a fluoroprotein foam gave fire control in 45 s and extinction in 90 seconds. A conventional self-induction branchpipe was used and all the foams were applied at 0.082 $l/m^2/s$ (0.1 $gal/ft^2/min$). Since this is a recommended design rate, these findings of the inadequacy of the foam applied in this way give rise to considerable concern.

Using smaller fires of area 1.675 m^2 (18 ft^2) and .0725 m^2 (0.78 ft^2) they showed that the length of the preburn and the depth of the resulting hot zone affected the critical application rate, to different degrees for different foams. On 1.675 m^2 fires they obtained control in 1-2 mins and extinction in 5 min using fluoroprotein or Light Water; but again obtained no control with either of two protein foams.

In all these tests, the jet velocity was 8.2 m/s of foam, which is similar to that obtained in conventional 3.8 l/s (50 gal/min) branchpipes.

In 1964, Fittes, D.W., Coasby, R and Nash, P[2], noted that the difference in control time between gentle surface and forceful application varied markedly for different protein foam liquids.

In 1957 Hird, D., French, R.J and Nash, P[3], used protein foam as a jet on shallow petrol fires and on petrol-soaked sand. They found no difficulty in obtaining 90 per cent control in both circumstances.

Interest in this problem has also arisen from a different aspect. Foam liquid supplies for official use in the United Kingdom are generally purchased in compliance with Defence Standard 42-3[4]. This standard is based on a 0.28 m^2 (3 ft^2) petrol fire, using gentle surface application. It has proved to be of great practical value for many years in controlling the quality of protein foam compounds. Recent tests[5] using the newer foam liquids show that the petrol test fire of DEF 42-3 may not reflect the comparative performance of these foam liquids on larger fires of AVTUR fuel. Table 1 gives the comparative data for five foam liquids when used on 0.28 m^2 petrol fires according to DEF 42-3 and on 81 m^2 (875 ft^2) AVTUR fires.

Table 1 - Control and extinction of two test fires with various foam liquids

Foam liquid	0.28 m^2 fires Gentle surface application .04 $l/m^2/s$ - N.B.P. fuel		81 m^2 fires Branchpipe application .04 $l/m^2/s$ - AVTUR fuel	
	90 per cent control time s	Extinction time s	90 per cent control time s	Extinction time s
Protein	75	142	50	118
Fluoro-Protein A	95	187	25	56
Fluoro-Protein B	54	84	23	40
Fluoro-Chemical	43	45	25	33
Synthetic A	43	51	39	69

It may be seen that the small test fires do not place the foam liquids in the same order of merit as the large test fires and it was thought that the method of application may be the cause of this.

EXPERIMENTAL PROCEDURE

The effect of varying the application velocity of various types of foam applied to petrol fires was first assessed by a series of 0.28 m^2 test fires. The apparatus used was that described in Defence Standard 42-3[4], except that the foams were applied to the centre of the fire from a jet fixed 60 cm radially from the centre of the tank and 40 cm above the fuel surface, slight adjustments in these measurements being required to ensure that the foam stream always entered the centre of the fire regardless of the foam velocity used. The application rate was kept constant and the velocity was adjusted by changing the diameter of the jet. The 18 mm (i.e. $\frac{1}{2}$ inch BSP female) Tee-piece inlet at the side of the tank, specified in the Defence Standard test was also used and regarded as giving zero application velocity. The preburn time was 30 s for petrol fires, and was extended to 1 min for AVTUR fires which required this longer period to reach full intensity.

The test fire was in a circular tank 60 cm diameter with vertical sides 10 cm high. Its base was a cone sloping to the centre at 45°. The fuel level was $7\frac{1}{2}$ cm below the rim, so that the fuel depth was 2.5 cm at the circumference increasing to 32 cm at the centre. Attached to the apex of the cone was a graduated glass tube which enabled the liquid draining from the foam to be measured. The foam was produced in a laboratory generator into which liquid and air flows were metered and mixed in a column, in which the gauze packing could be varied to adjust the shear stress of the foam. The intensity of the radiation from the fire was measured by four symmetrically-placed radiometers, connected in series to an amplifier and recorder.

A second series of tests was conducted in a similar manner to investigate the effect of varying the shear stress and expansion with different foam velocities. In these tests only synthetic foam was used.

A third series of tests was conducted in a flat bottom tray, 60 cm dia and 10 cm high, using approx 5 cm depth of fuel. The foam was applied through a hand manipulated nozzle of 7.15 mm diameter. Attack was commenced from a distance of approx 2 m from the centre of the fire and approx 1 m above the fuel surface. When control was established, the fire was approached and circled and the foam was directed onto the vertical sides to obtain the quickest extinction possible. No radiation measurements were made and only the time for complete extinction was noted. In one test, the foam jet was replaced by a rose with 6 x 1.6 mm dia holes. This discharged the foam in an ellipse, approximately 1 m length x 0.5 m width, the foam falling as separate cylindrical flakes approx 25 mm long x 2.5 mm diameter. In this series of tests the jet size was constant, and several different foam liquids were used and the expansion and shear stress were varied.

In all the three series of tests, the fuel was a narrow boiling range (62-68°C) petroleum spirit, referred to as 'N.B.P.fuel'. The preburn time was always 30 s and the application rate was 0.04 $l/m^2/s$ (0.05 $gal/ft^2/min$).

A fourth series of tests examined the flammability of various foams to which a specific quantity of petrol had been added. A sample of foam was prepared by a standard procedure in an 800 ml stirred jar. Five per cent of N.B.P. fuel, (based on the liquid content of the foam) was then added, and mixed with the foam by stirring for 30 seconds. A portion of the petrol-containing foam was placed in a 7.5 cm diameter dish and tested for flammability by applying a small gas flame to the surface.

A fifth series of tests was similar to the first series, using varying application velocities from fixed nozzles, and various foam compounds, but in these tests the fuel was AVTUR.

The following foam liquids were used:

Protein A Protein B1 Protein B2 Protein B3 Protein B4	Protein foam liquids conforming to Defence Standard 42-3 Protein A from one manufacturer. Protein B1-4, different batches from a second manufacturer - B4 being a different grade.
Fluoroprotein A Fluoroprotein B	Commercially available liquids from different U.K. manufacturers.
Fluorochemical A	Commercial sample
Fluorochemical B	Commercial sample of a grade now discontinued
Synthetic A	Detergent based liquid normally used for high expansion foam.

EXPERIMENTAL RESULTS

The observations made in the experiments are recorded in Tables 2-6 and selected data are shown in Figs 1-15 which are referred to in the next section.

Table 2

0.28 m^2 fires - application ratio .04 $l/m^2/s$

Fixed jet, varying velocity, NBP fuel

Foam liquid	Test No.	Expansion	25% drainage time min	Shear stress N/m^2	Jet diameter mm	Nominal foam velocity m/s	75% control time s	90% control time s	Extinction time	5 min fire drainage %
4% protein A	1	8.0	3.3	34.5	2 x 18 side	0	96	123	209	33
	2	8.4	3.0	39.7	7.15	2.3	102	135	180	37
	3	7.9	2.9	35.0	7.15	2.3	103	122	160	34.5
	4	8.0	3.0	25.8	6.35	2.9	N.A.	N.A.	N.A.	-
	5	8.3	3.5	39.0	4.76	5.1	N.A.	N.A.	N.A.	-
4% protein B1	6	8.5	3.25	19.3	2 x 18 side	0	60	75	142	39
	7	8.0	-	15.4	7.15	2.3	55	69	90	42
	8	8.0	2.6	19.2	7.15	2.3	55	73	105	37.5
	9	8.2	2.6	14.7	6.35	2.9	53	71	138	39
	10	8.2	2.6	14.7	6.35	2.9	50	70	125	35
	11	8.1	3.0	20.5	4.76	5.1	50	65	301	42.5
	12	8.1	3.0	20.5	4.76	5.1	59	83	219	48
	13	7.9	2.75	17.6	3.97	7.3	73	120	N.A.	48
	14	7.9	2.75	17.6	3.97	7.3	69	105	N.A.	47

Table 2 (cont'd)

$0.28\ m^2$ fires - application ratio .04 $l/m^2/s$

Fixed jet, varying velocity, NBP fuel

Foam liquid	Test No.	Expansion	25% drainage time min	Shear stress N/m^2	Jet diameter mm	Nominal foam velocity m/s	75% control time s	90% control time s	Extinction time	5 min fire drainage %
4% protein B2	15	8.3	3.0	17.9	2 x 18 side	0	75	87	117	37
	15A	8.2	3.5	15.4	7.15	2.3	50	65	80	35
	16	7.9	3.3	15.4	6.35	2.9	46	59	90	35
	17	8.3	3.2	17.9	4.76	5.1	47	60	184	36
	18	8.5	3.6	16.8	3.97	7.3	55	73	280	38
	19	8.3	2.5	14.1	3.17	11.5	111	150	N.A.	40
4% fluoro-protein A	20	8.0	3.0	21.8	2 x 18 side	0	80	97	187	28
	21	7.9	3.0	22.4	7.15	2.3	65	92.5	177	30.5
	22	7.9	3.0	22.4	7.15	2.3	52	73	193	25
	23	7.9	3.25	24.4	7.15	2.3	56	82	112	29
	24	8.1	3.6	28.2	3.97	7.3	59	87	240	27
	25	8.1	3.6	28.2	3.97	7.3	70	90	240	29
	26	7.9	2.75	25.6	3.17	11.5	110	136	285	32
	27	7.8	2.75	22.7	3.17	11.5	108	155	282	27.5
	28	"8"	-	6.0	2.38	20.5	-	-	-	-

Table 2 (cont'd)

$0.28\ m^2$ fires - application ratio .04 $l/m^2/s$

Fixed jet, varying velocity, NBP fuel

Foam liquid	Test No.	Expansion	25% drainage time min	Shear stress N/m^2	Jet diameter mm	Nominal foam velocity m/s	75% control time s	90% control time s	Extinction time s	5 min fire drainage %
4% fluoro-protein B	29	8.1	2.7	7.7	2 x 18 side	0	42	54	84	35
	30	8.4	2.6	7.3	7.15	2.3	36	45	59	34.5
	31	8.5	2.6	7.4	7.15	2.3	38	48	57	36
	32	8.6	2.75	7.35	4.76	5.1	37	60	129	34
	33	8.6	2.75	7.35	4.76	5.1	39	57	125	35
	34	8.2	2.75	7.35	3.97	7.3	45	75	N.A.	34.5
	35	8.2	2.75	7.35	3.97	7.3	46	90	N.A.	34
	36	8.0	2.4	9.6	3.17	11.5	100	Almost	N.A.	37
	37	7.7	3.1	9.0	3.17	11.5	95	Almost	N.A.	-
2% Synthetic A	38	11.2	6.3	10.2	2 x 18 side	0	37	43	51	20
	39	11.7	6.0	12.1	7.15	3.4	34	48	N.A.	-
	40	12.0	6.3	12.8	6.35	4.3	36	53	N.A.	-
	41	12.7	6.3	11.5	4.76	7.6	38	90	N.A.	-
	42	12.0	-	-	4.76	7.6	32	96	N.A.	-
	43	11.0	5.25	11.5	3.97	11.0	63	109	N.A.	-
	44	"12"	-	-	3.17	17.0	Foam broke down through jet			

Table 2 (cont'd)

0.28 m^2 fires - application ratio .04 $l/m^2/s$

Fixed jet, varying velocity, NBP fuel

Foam liquid	Test No.	Expansion	25% drainage time min	Shear stress N/m^2	Jet diameter mm	Nominal foam velocity m/s	75% control time s	90% control time s	Extinction time s	5 min fire drainage %
6% Fluoro-chemical A	46	12.4	2.3	5.75	2 x 18 side	0	33	43	46	35
	47	11.9	2.6	6.4	7.15	3.4	25	31	N.A.	-
	48	11.9	2.6	6.4	7.15	3.4	24	32	N.A.	-
	49	12.5	2.3	5.4	6.35	4.3	25	35	N.A.	-
	50	12.5	2.3	5.4	6.35	4.3	26	35	N.A.	-
	51	12.1	2.25	5.1	4.76	7.6	30	45	N.A.	-
	52	13.0	2.9	7.0	3.97	11.0	50	N.A.	N.A.	-

Table 3

$0.28\ m^2$ NBP fires; application rate .04 $l/m^2/s$

Fixed jet varying shear stress, expansion and velocity

Foam liquid	Test No.	Expansion	25% drainage time min	Shear Stress N/m^2	Jet diameter mm	Nominal foam velocity m/s	75% control time s	90% control time s	Extinction time s	5 min fire drainage %
Synthetic A	53	8.7	-	18.9	2 x 18 side	0	64	73	80	21
	54	8.5	-	17.6	7.15	2.3	45	57	68	-
	55	8.8	-	16.7	6.35	2.9	40	50	68	-
	56	8.65	-	17.8	4.76	5.1	45	137	NA	-
	57	11.4	-	23.3	2 x 18 side	0	80	93	134	15
	58	12.0	-	23.4	7.15	3.4	58	72	82	-
	59	11.8	31.0	22.8	7.15	3.4	52	62	82	8.2
	60	11.8	-	23.9	6.35	4.3	46	58	210	8.2
	61	13.65	-	22.2	4.76	7.6	100	NA	NA	-
	62	16.5	-	30.0	2 x 18 side	0	72	91	115	-
	63	17.5	-	14.5	7.15	4.95	42	110	180	-
	64	17.5	-	32.2	7.15	4.95	67	78	94	-
	65	17.0	-	30.0	6.35	6.1	47.5	92	NA	-

Table 4

0.28 m^2 fires - application rate 0.04 $l/m^2/s$

Hand manipulated jet - NBP fires

Test No	Foam liquid	Expansion	Shear stress N/m^2	Jet diam. mm	Nominal foam velocity m/s	Extinction time s	Remarks
66	2% Synthetic A	12	23.3	7.15	3.4	79	
67	2% Synthetic A	12	23.3	7.15	3.4	75	
68	2% Synthetic A	13	22.7	Spray	11.3	73	)Delay on last)flickers around)edge
69	2% Synthetic A	13	22.7	Spray	11.3	74	
70	2% Synthetic A	10.5	13.9	7.15	3.4	66	
71	2% Synthetic A	10.5	13.9	7.15	3.4	75	
72	2% Synthetic A	17.5	29.0	7.15	5.0	57	
73	2% Synthetic A	17.5	29.0	7.15	5.0	87	
74	2% Synthetic A	22.5	30.5	7.15	6.4	55	) Fuel temp. 44°C
75	2% Synthetic A	22.5	30.5	7.15	6.4	58	)
76	4% Synthetic A	10.6	26.4	7.15	3.4	116	)
77	6% Fluoro-chemical A	12.25	3.9	7.15	3.4	81	Centre continued flickering
	"	12.25	3.9	7.15	3.4	41	No flickering
	"	12.25	3.9	7.15	3.4	52	Slight flickering
78	4% Protein B1	8.2	12.2	7.15	2.3	214	
79	4% Protein B1	8.2	12.2	7.15	2.3	170	
80	4% Fluoro-protein A	8.2	21.1	7.15	2.3	68	
81	4% Fluoro-protein A	8.2	21.1	7.15	2.3	105	Premixed 1.5 hours
83	4% Fluoro-protein B	8	8.3	7.15	2.3	50	
84	4% Fluoro-protein B	8	8.3	7.15	2.3	56	

Table 5

Ignition tests on foam containing 5 per cent of NBP fuel (based on liquid content) in 7.5 cm dish

Foam liquid	Observations
2% Synthetic A Expansion 8	Ignited and burned for 25 s. Relit and burned for 10 s. Would not continue burning without ignition source - some foam breakdown.
6% Fluorochemical A Expansion 8	No ignition at all. No foam breakdown
5% Fluoroprotein A Expansion 8	Burnt for 2-3 s - no foam breakdown - no sign of fire spreading.
5% Fluoroprotein B Expansion 8	Burnt for 2-3 s - no foam breakdown - no sign of fire spreading.
4% Protein B1 Expansion 8	Ignited instantly, burned for $1\frac{1}{4}$ min, $\frac{2}{3}$ of foam destroyed Very little petrol remaining and would only burn for 2-3 s.
4% Protein B3 Expansion 8	Ignited instantly, all foam destroyed in 40 s and fire burned for further 10 s.

Table 6

0.28 m^2 fires - application rate .04 l/m^2/s

Fixed jet, varying velocity, Avtur fires

Foam liquid	Test No.	Expansion	25% drainage time min	Shear stress N/m^2	Jet diameter mm	Nominal foam velocity m/s	75% control time s	90% control time s	Extinction time s	Notes
2% synthetic A	85	12.4	6.25	10.0	2 x 18 side	0	32	42	58	Rapid breakdown at edges. Rapid drainage from older portions of foam.
	86	11.8	4.0	10.0	Side	0	28	38	57	
(4 min preburn)	87	12.4	6.25	10.0	Side	0	34	46	64	Some breakdown on hot fuel.
	88	12.1	5.5	10.0	7.15	3.4	30	38	N.A.	Fire persisted through outer ring of foam.
	89	12.4	-	20.0	7.15	3.4	33	40	153	Foam piled at centre.
	90	12.4	5.0	10.5	3.97	11.0	29	~~57~~	N.A.	Foam picked up hot fuel - over 50%. Flammable foam temperature 65-70°C.
4% protein A	91	8.2	1.6	24.4	Side	0	35	48	72	
	92	8.0	2.2	22.2	7.15	2.3	64	73	92	
	93	8.1	3.1	35.0	6.35	2.9	58	72	98	Foam appears to boil on contact.

Table 6 (cont'd)

0.28 m^2 fires - application rate .04 $l/m^2/s$

Fixed jet, varying velocity, Avtur fires

Foam liquid	Test No.	Expansion	25% drainage time min	Shear stress N/m^2	Jet diameter mm	Nominal foam velocity m/s	75% control time s	90% control time s	Extinction time s	Notes
(4 min preburn)	94	8.0	2.9	29.0	6.35	2.9	62	84	110	Steam assisted extinction.
	95	8.2	2.3	34.4	4.76	5.1	53	66	110	
	96	8.3	3.7	29.0	3.97	7.3	41	53	103	Velocity assisted cooling of fuel by stirring.
	97	6.9	2.4	22.2	3.17	11.5	65	83	158	Burning at point of impact prolonged fire.
4% protein B2	98	8.1	1.4	16.6	Side	0	28	34	73	
	99	8.4	1.8	13.3	7.15	2.3	40	50	83	
	100	8.4	1.5	15.5	6.35	2.9	37.5	44	81	
	101	8.4	1.8	15.0	4.76	5.1	32	40	87	
	102	8.4	1.8	13.9	3.97	7.3	30	36	229	
4% protein B4	103	8.2	1.75	12.8	Side	0	28	33	52	
	104	8.2	1.7	17.8	7.15	2.3	29	37	62	
	105	8.2	1.9	11.1	6.35	2.9	28	36	60	
	106	8.3	1.8	18.9	4.76	5.1	30	41	59	Low fire drainage despite low 25% D.T.
	107	8.2	2.3	12.8	3.97	7.3	28	50	95	
	108	8.2	1.7	12.8	3.17	11.5	42.5	110	154	

Table 6 (cont'd)

0.28 m^2 fires - application rate .04 $l/m^2/s$

Fixed jet, varying velocity, Avtur fires

Foam liquid	Test No.	Expansion	25% drainage time min	Shear stress N/m^2	Jet diameter mm	Nominal foam velocity m/s	75% control time s	90% control time s	Extinction time s	Notes
Fluoro-protein A	109	8.4	1.8	15.5	Side	0	33	40	55	
	110	8.2	1.7	15.5	7.15	2.3	42.5	57	65	
	111	8.2	1.7	8.9	6.35	2.9	52.5	59	86	
	112	8.4	1.8	16.6	4.76	5.1	40	50	63	
	113	8.6	2.1	16.6	3.97	7.3	37.5	42	66	
	114	8.3	1.9	12.4	3.17	11.5	39	57	107	
4% fluoro-protein B	115	8.4	1.3	4.4	Side	0	24	29	40	
	116	8.4	1.4	5.5	7.15	2.3	31	37.5	46	
	117	8.4	1.3	4.4	6.35	2.9	29	35	43	
	118	8.4	1.5	5.5	4.76	5.1	31	36	56	
	119	8.4	1.4	4.4	3.97	7.3	35	39	64	
	120	7.7	1.25	4.4	3.17	11.5	34	44	N.A.	Small stable flame at edge, 6" x 3" when foam ran out.

Table 6 (cont'd)

0.28 m^2 fires - application rate .04 $l/m^2/s$

Fixed jet, varying velocity, Avtur fires

Foam liquid	Test No.	Expansion	25% drainage time min	Shear stress N/m^2	Jet diameter mm	Nominal foam velocity m/s	75% control time s	90% control time s	Extinction time s	Notes
6% fluoro-chemical B	121	12.7	2.7	3.9	6.35	4.3	27	37	N.A.)	These two tests with NBP fuel to check fluoro-chemical B behaves as fluorochemical A.
	122	11.7	4.0	5.5	3.97	11.0	55	N.A.	N.A.)	
	123	12.0	2.6	4.4	7.15	3.4	22	25	31	Rapid control despite hot fuel mixed with foam.
	124	12.0	2.3	4.4	6.35	4.3	23	26	49	Extinction prolonged 10 sec by flickers at edge.
	125	12.4	2.75	4.4	6.35	4.3	21	24	33	Hot foam at 59°C.
	126	13.2	2.8	5.0	4.76	7.6	19	22.5	33	Hot foam at 58°C.
	127	12.5	2.7	5.0	4.76	7.6	16	19	36	Area at jet impact clear of foam but not burning.
	128	12.1	2.75	5.5	3.97	11.0	22	26	48	Virtual extinction at 28 secs - flickers at tray side. Velocity forces foam to far side of tray.
	129	8.2	2.5	4.4	3.17	17.0	21	28	61	Large area of uncovered fuel where jet impacts.)
	130	4.8	<1	1.1	2.38	30.5	24	28	54	Large area uncovered at extinction.) (Note change of expansion - air input unchanged - velocity breakdown).

DISCUSSION

General

Caution is necessary in drawing conclusions from the numerical results of the experiments. The extinction of the fires did not always follow the same pattern. In some cases, a substantial proportion of the time was attributable to extinguishing persistent small flames around the tray edge, in other cases no edge fire would persist but a central pool of fuel-contaminated foam would delay extinction. Using the fixed jet, and particularly with high shear stress/high expansion foams, a 'mountain' of foam could accumulate at the point of impact which reduced the effective impact velocity on the fuel surface. In spite of such limitations, certain deductions can be made and some useful indications to assist future work have emerged.

NBP fuel fires with fixed jets

Fig 1 shows the typical correlation between jet velocity and control times. The curves in Fig 1 are for protein B1; similar curves pertain to all the other foams, with substantial differences in their numerical values. Increasing the velocity first affects the extinction time, without any marked change in the 90 per cent or 75 per cent control time; further increase results in the 90 per cent control time being increased and finally the 75 per cent control time. In some cases the extinction time and the control times at zero velocity are higher than that for 2.3 m/s. This is because the zero velocity was determined using the side inlet and not the central application of the other observations: It is a distribution effect and not an application effect.

From Fig 1 it can be seen that there is a range of jet velocities over which the fire can be readily controlled but cannot be extinguished - in this case between 5.1 and 7.3 m/s. This effect varies substantially for different foam liquids. For the fluorochemical foam on NBP fires, the control-without-extinction range was 3-8 m/s, for synthetic A 3-11 m/s, while fluoroprotein A would both control and extinguish up to 12 m/s.

Figures 2 and 3 show the relationship between jet velocity and control time (Fig 2) and extinction time (Fig.3) for the various foams on NBP fires. Increasing the velocity does not affect the 90 per cent control time until a very substantial velocity is attained. (8 m/s is a typical exit velocity from a 227 l/min (50 gal/min) branchpipe).

The effect on the extinction time of increasing the velocity is much more pronounced (Fig 3). A small increase in velocity to 3.4 m/s was sufficient to prevent extinction with the fluorochemical and synthetic foams; while fluoroprotein A was outstanding and extinguished at velocities up to 11.5 m/s.

Fig 4 shows the 90 per cent control time and jet velocity curves for three different batches of protein foams on NBP fires. Very large differences are evident - the worst batch (Protein A) reacting to application velocity as markedly as any other foam tested, while protein B2 was among the best tested. The extinction time curves show differences of a similar order, protein A failing to extinguish at 2.9 m/s, while protein B2 extinguished at 7.3 m/s. Why proteins differ to this extent is a subject which obviously merits some study as it would be a considerable advance if all protein foam liquids could have the superior properties of protein B2. This may be possible by some quite simple chemical adjustment e.g. of the pH, sodium chloride or iron content etc.

Figs 5 and 6 show the fire drainage for the various foams when applied to NBP fires at different velocities. In no case is there a substantial breakdown of the foam as the velocity of application is increased, and therefore breakdown of the foam is not the explanation of the failures to extinguish.

Observation of the fires suggested that failure to extinguish was because sufficient fuel became mixed with the foam to enable it to keep burning in spasmodic flickers until the foam was destroyed.

It was surprising that fluorochemical A failed to extinguish the petrol fire at a very low velocity (3.4 m/s) since fluorochemical foam usually gives a notably good extinction on experimental spill fires.

Laboratory ignition tests

The behaviour of fluorochemical A prompted the laboratory ignition tests recorded in Table 5. Fluorochemical foam containing 5 per cent of petrol would not ignite, while protein B1 foam containing 5 per cent of petrol ignited readily. These observations indicate that the effect of application velocity depends on the readiness with which the fuel will mix with the foam, and on the amount of fuel the foam can tolerate before becoming flammable, and that these two factors are of varying relative importance for different foams. Fluorochemical foam has a high tolerance to petrol before becoming flammable, but also has a high propensity to mix with NBP petrol.

Low drainage rate of synthetic A foam on petrol fires

In test 59, which used synthetic foam at expansion 11.8 and shear stress 22.8 N/m^2, the 5 minute fire drainage was 8.2 per cent. This is a remarkably low figure. By comparison, the Defence Standard test calls for fire drainage not to exceed 48 per cent in 10 minutes, which is approximately equivalent to 28 per cent in 5 minutes. This stimulates interest in the use of synthetic foam at high shear stress.

Variation of shear stress and expansion of synthetic foam from a fixed jet

The tests recorded in Table 3 all used synthetic A foam and NBP petrol, and the shear stress and expansion were varied, as well as the jet velocity. A very lengthy test programme would have been required to assess fully the effect of these three variables for a single foam compound, and this could not be done; moreover the phenomenon of foam piling at the point of impact became apparent at high shear stresses and high expansions. Figs 7 and 8 attempt to depict the results obtained. Increasing the shear and the expansion both favour obtaining extinction at higher application velocities. At an expansion of 17.5 and a shear stress of 32 N/m^2, extinction was achieved at a velocity of 4.95 m/s as compared with being unable to achieve extinction at 3.4 m/s with expansion 12 and shear stress 12 N/m^2. Increasing the shear increased the control time substantially for surface application (zero velocity), as is already well known; the increase was less marked when the foam was applied forcibly.

An interesting observation was that at low shear stress the jet of foam would disintegrate on striking the fuel surface, the foam behaving as a liquid. At high shear stresses, the jet of foam would penetrate the fuel surface and re-appear some centimetres distant as a coherent cylinder of foam, behaving like a plastic solid. This suggests that there may be a critical application velocity determining whether or not the foam jet disintegrates on meeting the fuel, and this would be expected to influence the admixture of fuel and foam.

The improvement in extinction time at high expansion may be due to a greater loss of momentum by the more bulky foam jet before reaching the fuel surface. This is probably not the major reason because at the commencement of the tests using foam of expansion 17, the jet of foam could be observed to penetrate the fuel surface in a very definite manner, the surface not being obscured by foam.

Another observation from these tests is that the time to extinguish is influenced by the degree of fuel contamination of the foam occurring during the control period. If a layer of fuel-contaminated foam is formed in the control period, extinction will subsequently be difficult or impossible.

Variation of expansion and shear stress with a moving jet

The cushioning effect of foam piling at the point of jet impact led to the tests recorded in Table 4 using a similar size 60 cm tray and a hand-manipulated jet and petrol as fuel. All the tests were with a 7.15 mm jet so that velocity changes are directly related to the expansion. In these tests particularly, the extinction times are of limited value because the extinction time was prolonged in different fires for different reasons - sometimes it would be an area of contaminated fuel, sometimes small persistent flames around the tray edge.

Fig 9 shows the tests with synthetic foam and supports the indications from the fixed jet tests that high expansion and high shear stress reduce extinction time.

At expansion 22.5 and shear stress 30 N/m^2, the synthetic foam extinguished in 56 seconds, which is a good performance.

The three tests with fluorochemical are interesting; in the first test a central pool of foam was contaminated with fuel and delayed extinction, while in the second test contamination was not evident and a very quick extinction was achieved. In the fixed jet tests the fire could not be extinguished using this size of jet with fluorochemical. Success in the hand-manipulated tests was probably obtained because the foam was applied at a distance of 2 m instead of 0.6 m, loss of momentum by the jet before reaching the fire lowering its mixing capacity.

Tests 83 and 84 with fluoroprotein B were impressive. The foam was very fluid and the jet broke up on striking the fuel. It was expected that the foam would be contaminated with fuel and that this would extend the extinction time, but this did not occur.

The tests 80 and 81 with fluoroprotein A extinguished in 68 and 105 s as compared with 185 s using the same foam from a fixed jet (Fig 3) indicating the value of physical distribution of the foam in reducing the long coverage time resulting from a high shear stress.

Tests 68 and 69 using the spray are misleading. The spray pattern was very unsatisfactory and extinction time was extended by the inability to direct the spray, which was not a solid cone, on to small flames around the tray edge. Further tests with a solid cone spray matching the tray size are indicated.

Tests with AVTUR and fixed jets

The 45 tests using AVTUR are recorded in Table 6. Figures 10-15 compare the control and extinction times for each foam liquid with those obtained on the petrol fires. Major differences were found in the behaviour of the foams on the two fuels, but these did not show a consistent correlation for the different foams.

To enable a comparison to be made Figs 10-15 have been used to assign each foam a velocity range rating on the following basis to prepare Table 7.

Unable to control (or extinguish) at 5 m/s application velocity				= 0
Control (or extinguish)	$5-7\frac{1}{2}$ m/s	"	"	= 1
" (or extinguish)	$7\frac{1}{2}-12$ m/s	"	"	= 2
" (or extinguish)	above 12 m/s	"	"	= 3

Table 7

Velocity range rating for various foams on 0.28 m^2 Petrol and AVTUR fires

	Petrol rating		AVTUR Rating		Total Rating
	90% control	Extinction	90% control	Extinction	
Protein A	0	0	3	3	6
Protein B2	3	1	3	1	8
Fluoroprotein A	3	3	3	3	12
Fluoroprotein B	2	1	3	2	8
Fluorochemical A/B	2	0	3	3	8
Synthetic A	3	0	3	0	6

Fluorochemical A could not be tested on AVTUR fires because supplies ran out; but Tests 121 and 122 (Table 6) showed that Fluorochemical B behaved similarly to Fluorochemical A on NBP fires and results for A and B are grouped together in Table 7.

From Table 7 it can be seen that fluoroprotein A is superior to all the other foams when judged in this way, with fluoroprotein B and protein B2 and fluorochemical also obtaining high ratings.

Protein A, and fluorochemical, were excellent on AVTUR fires but failed to extinguish petrol fires at 5 m/s application velocity. The differences between the performance of protein A on the two fuels is remarkable - it obtained the bottom rating on petrol and the top rating on AVTUR. The synthetic foam was the only one which failed to extinguish both fuels at 5 m/s application velocity.

Control times

It should be noted that the above rating method does not include a 'rapidity of action' factor and provides quite a different assessment than the frequently used index of 90 per cent control time. Tables 8 and 9 give the 90 per cent control times, and extinction times, for gentle surface application and 5 m/s. These are discussed later.

Table 8

90 per cent control times – 0.28 m^2 fires – seconds

	NBP		AVTUR	
	Gentle surface	5 m/s	Gentle surface	5 m/s
Protein A	123	∞	48	70
Protein B2	87	60	34	43
Fluoroprotein A	97	75	40	51
Fluoroprotein B	54	58	29	38
Fluorochemical A/B	43	35	25	25
Synthetic A	43	55	40	42

Table 9

Extinction times – 0.28 m^2 fires – seconds

	NBP		AVTUR	
	Gentle surface	5 m/s	Gentle surface	5 m/s
Protein A	209	∞	72	107
Protein B2	117	165	73	85
Fluoroprotein A	187	203	55	64
Fluoroprotein B	84	120	40	50
Fluorochemical A/B	46	∞	30	30
Synthetic A	51	∞	58	∞

Behaviour of the AVTUR fires

Observation of the fires provided some information which is valuable but not readily quantified.

The synthetic foam was very prone to pick up the AVTUR fuel, and at the highest velocity of application, foam with over 50 per cent fuel admixed could be scooped from the surface. This mixture had a temperature of 65 - 70°C, and foam breakdown was appreciable. It seemed probable that foam breakdown was the result of the foam mixing with the heated fuel picked up, rather than the interfacial heat transfer between the foam layer and the hot fuel layer.

The fluorochemical also appeared to emulsify much fuel into the foam, but in spite of this, rapid extinction occurred, even when an area of fuel around the application point was free of foam cover. Presumably the film-forming properties of the fluorochemical contributed to its performance on AVTUR. In some cases noticeable 'boiling' of the foam was apparent in the initial stages and steam evolution appeared to assist fire control.

With protein foam, using the higher application velocities, the stirring of the fuel was probably assisting cooling of the surface layer by mixing it with the lower layers of fuel.

Forceful application assists spreading of the foam and the importance of the shear stress of the foam controlling coverage time is reduced, as compared with gentle surface application.

Significance of the results to laboratory test procedures

The rating method used in Table 7, based on performance at various application velocities, provides a different approach to foam liquid assessment. The evaluation obtained, however, does not indicate the relative performance of the various foam liquids when used on 81 m^2 AVTUR spill fires (Table 1) any more reasonably than do the Defence Standard 42-3 surface application tests using NBP fuel. If, however, we compare the 0.28 m^2 control and extinction times (from Tables 8 and 9), at application velocities of 0 and 5 m/s, using AVTUR fuel, with the 81 m^2 AVTUR spill fires, it can be seen in Table 10 that a much closer prediction of the large scale performance is obtained. The use of the same fuel in the laboratory and large scale tests is largely responsible for the improvement, and whether gentle or foreceful application is used is of lesser importance.

Table 10

Comparison of large AVTUR spill fires, laboratory petrol fires and laboratory AVTUR fires

<table>
<tr><th rowspan="2"></th><th colspan="2">81 m^2 AVTUR fires</th><th colspan="2">0.28 m^2 Petrol fires -DEF 42-3</th><th colspan="4">0.28 m^2 AVTUR fires</th></tr>
<tr><th colspan="2">Branchpipe</th><th colspan="2">Gentle surface</th><th colspan="2">5 m/s</th><th colspan="2">Gentle surface</th></tr>
<tr><th></th><th>90% control s</th><th>Extinction s</th><th>90% control s</th><th>Extinction s</th><th>90% control s</th><th>Extinction s</th><th>90% control s</th><th>Extinction s</th></tr>
<tr><td>Protein B2</td><td>50</td><td>118</td><td>87</td><td>117</td><td>43</td><td>85</td><td>34</td><td>73</td></tr>
<tr><td>Fluoro-protein A</td><td>25</td><td>56</td><td>97</td><td>187</td><td>53</td><td>67</td><td>40</td><td>55</td></tr>
<tr><td>Fluoro-protein B</td><td>23</td><td>40</td><td>54</td><td>84</td><td>38</td><td>50</td><td>29</td><td>40</td></tr>
<tr><td>Fluoro-chemical</td><td>25</td><td>33</td><td>43</td><td>46</td><td>25</td><td>30</td><td>25</td><td>30</td></tr>
<tr><td>SyntheticA</td><td>39</td><td>69</td><td>43</td><td>51</td><td>42</td><td>∞</td><td>40</td><td>58</td></tr>
</table>

Assessment at a single application velocity, eg 5 m/s used above, in place of gentle surface application will usually make very little difference to the results except in those cases where it reveals a complete inability to extinguish at the velocity selected. (Ref. Figs 1, 2, 3 and 4).

The extinction times of the laboratory test fires using AVTUR and gentle surface application place the five foams in the same order of merit as the 81 m^2 tests, and the 5 m/s extinction times show some agreement.

Ninety per cent control times are less well predicted, fluoroprotein A in particular tending to give higher control times in the laboratory than in the field tests. This is almost certainly related to the foam properties which could not be matched between laboratory and field trials because they varied for the different application rates in the field trials.

These experiments show that the type of fuel has a major effect on the difficulty of extinction when forceful application is used. Since in aircraft crash fires the fuel involved may well be aviation gasoline or a wide cut fuel (JP4/AVTAG), and not a narrow cut kerosine (JetA, JP5, AVTUR), the approval of foam liquids for airport use should take account of this and not be limited to one grade of kerosine. N.A.F.E.C[6] for instance found JP4 spill fires more difficult to extinguish with protein foam than Avgas or Jet A fires.

The mutual emulsification properties of fuel and foam appear to be the important factor in determining the extinction performance. We would not expect emulsification properties to depend primarily on the boiling range of the fuel, although it is probable that there is a general correlation that low boiling point fuels are more difficult to extinguish since a lower fuel content in the foam will suffice to make it flammable.

Different grades of motor spirit might well vary significantly in their emulsification properties with the same foam, according to the additives they contain. Similarly, the data for the performance of three different protein liquids on the same petrol (Fig 4) shows that differences in the foam properties, other than expansion, shear stress and drainage rate, can result in large differences in extinction performance. It may be possible to develop simple laboratory emulsification tests which will provide an indication of the fire extinction ability of a particular foam and a particular fuel.

Conclusions and recommendations

1. If a foam is applied forcibly to a burning fuel surface it may be possible to obtain a rapid 90 per cent control yet not be possible to extinguish the fire. Any evaluation of foam liquids whose use is not to be specifically restricted to gentle surface application should therefore include an assessment of control and extinction performance with both gentle and forceful application.

2. Difficulty in extinguishing petrol fires with foam which is forcibly applied is not because the foam breaks down on contact with the fuel, but because sufficient petrol becomes mixed with the foam to make it flammable. The same effect is also an important factor in extinguishing Avtur fires.

3. Different foam liquids vary substantially in the extent to which the application velocity to a petrol or Avtur fire affects their ability to extinguish it, and usually, to a much lesser extent, their ability to control the fire. Some foams would not extinguish petrol fires when applied at 3.4 m/s while one foam would extinguish when applied at 11.5 m/s. For Avtur fires, one foam forcibly applied would not extinguish at 3.4 m/s while another foam extinguished at 30.5 m/s.

4. Three protein foams were found to vary markedly in their ability to extinguish petrol fires when applied forcibly. This merits investigation to enable all protein foams to be manufactured with a superior performance when forcibly applied.

5. Synthetic A foam when forcibly applied would not extinguish Avtur fires.

6. Fluorochemical foam when forcibly applied would not extinguish NBP fires.

7. The fluoroprotein foams when forcibly applied gave a notably good extinction performance on both petrol and Avtur fires.

8. Small scale laboratory fires give a reasonable prediction of 81 m^2 fires, when Avtur is used as the fuel in both large and small tests. The prediction should be further improved if foam properties in the two tests are matched.

9. These experiments illustrate the complex nature of the control and extinction of hydrocarbon fires by foam and the study still required to define the process in detail, and to develop valid laboratory fire tests. The optimum large scale application, and the small scale laboratory tests, should take account of all the following principal factors:

(a) the character of the foam liquid
(b) the expansion and shear stress of the foam produced
(c) the method of application of the foam - its velocity and distribution
(d) the character of the fuel
(e) the depth of fuel and the length of time it has been burning
(f) the application rate of the foam.

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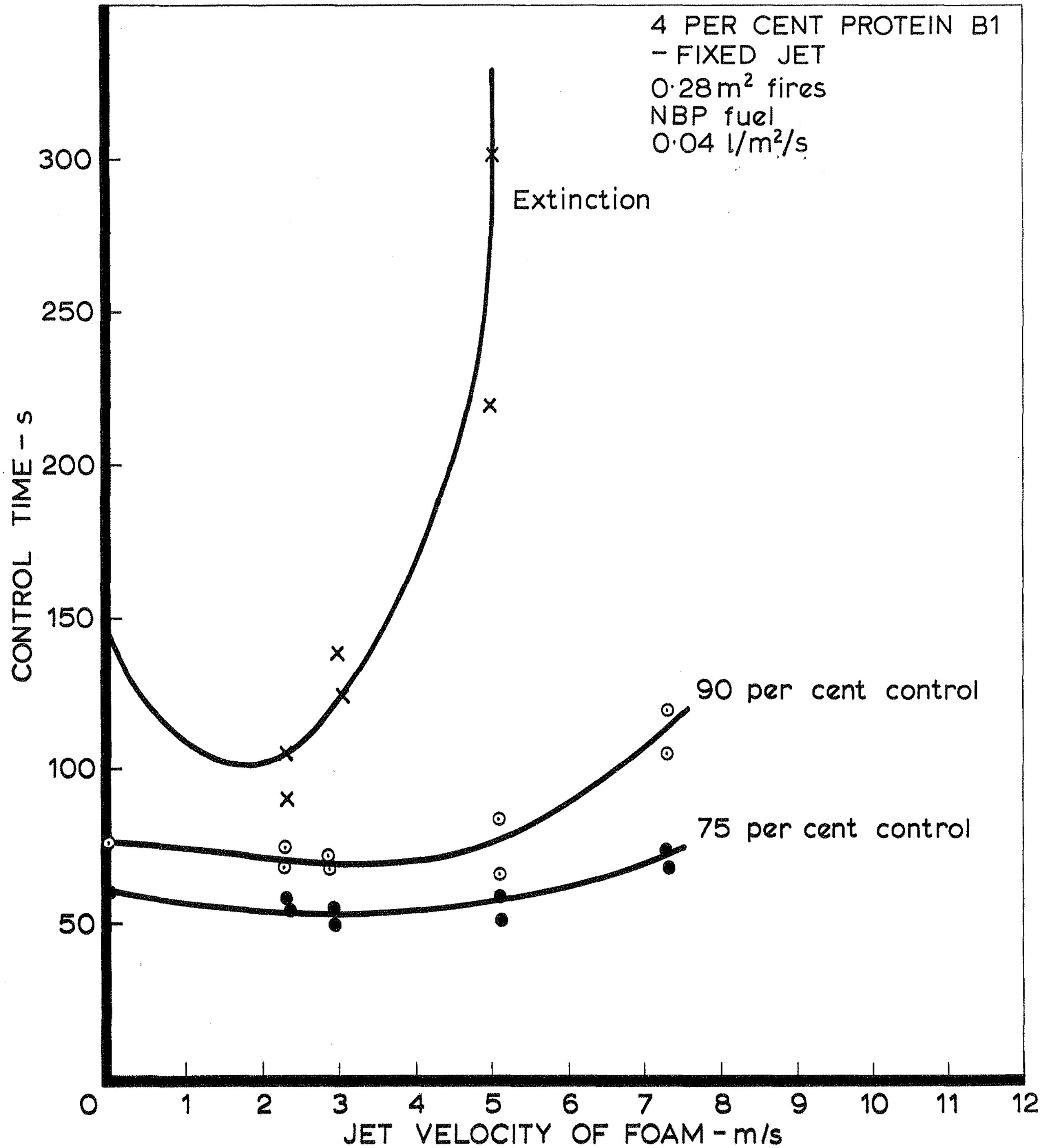

FIG. 1 THE EFFECT OF THE JET VELOCITY OF PROTEIN FOAM ON CONTROL AND EXTINCTION TIMES OF LABORATORY PETROL FIRES

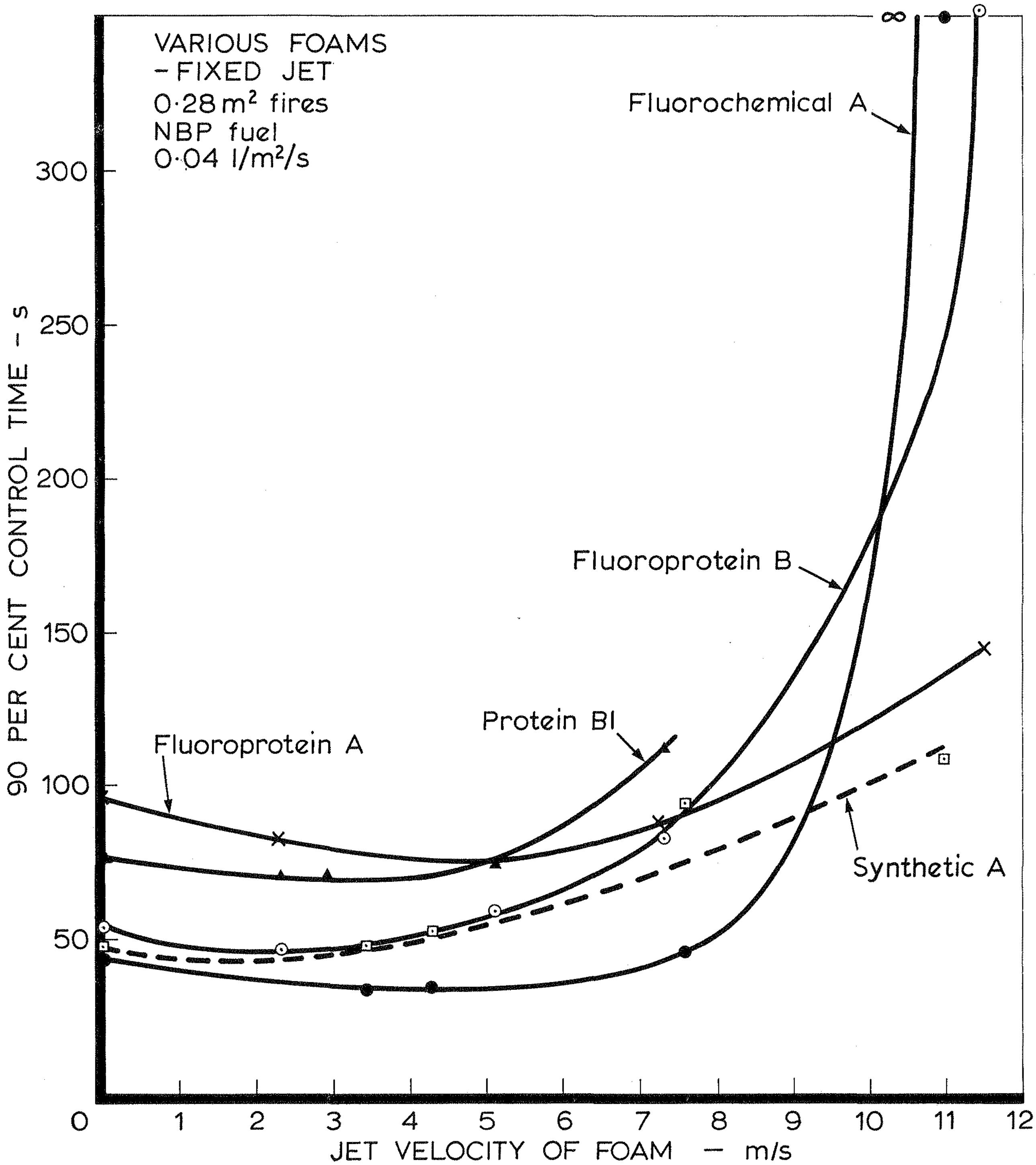

FIG. 2 THE EFFECT OF THE JET VELOCITY OF VARIOUS FOAMS ON THE CONTROL TIME OF LABORATORY PETROL FIRES

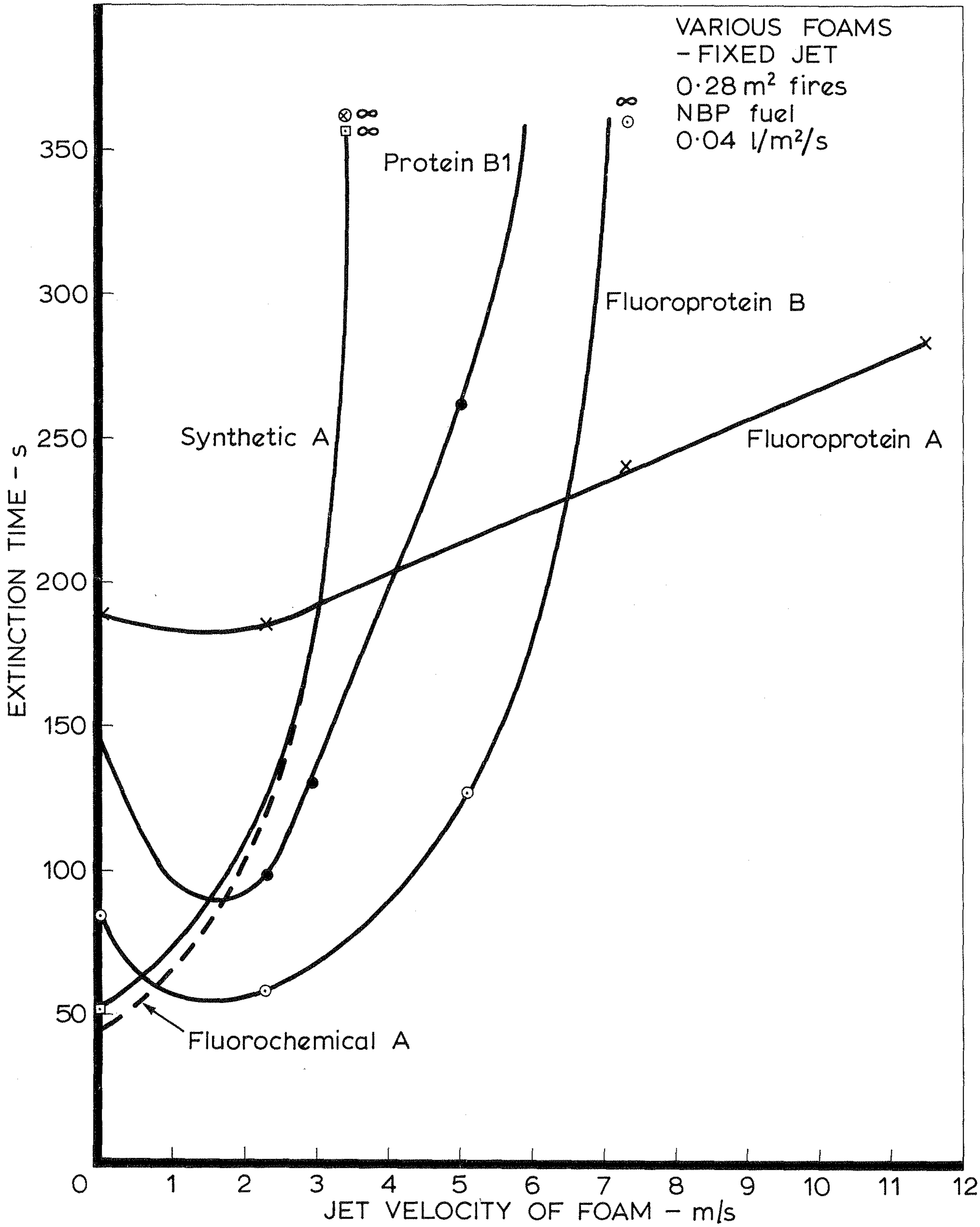

FIG. 3 THE EFFECT OF THE JET VELOCITY OF VARIOUS FOAMS ON THE EXTINCTION TIME OF LABORATORY PETROL FIRES

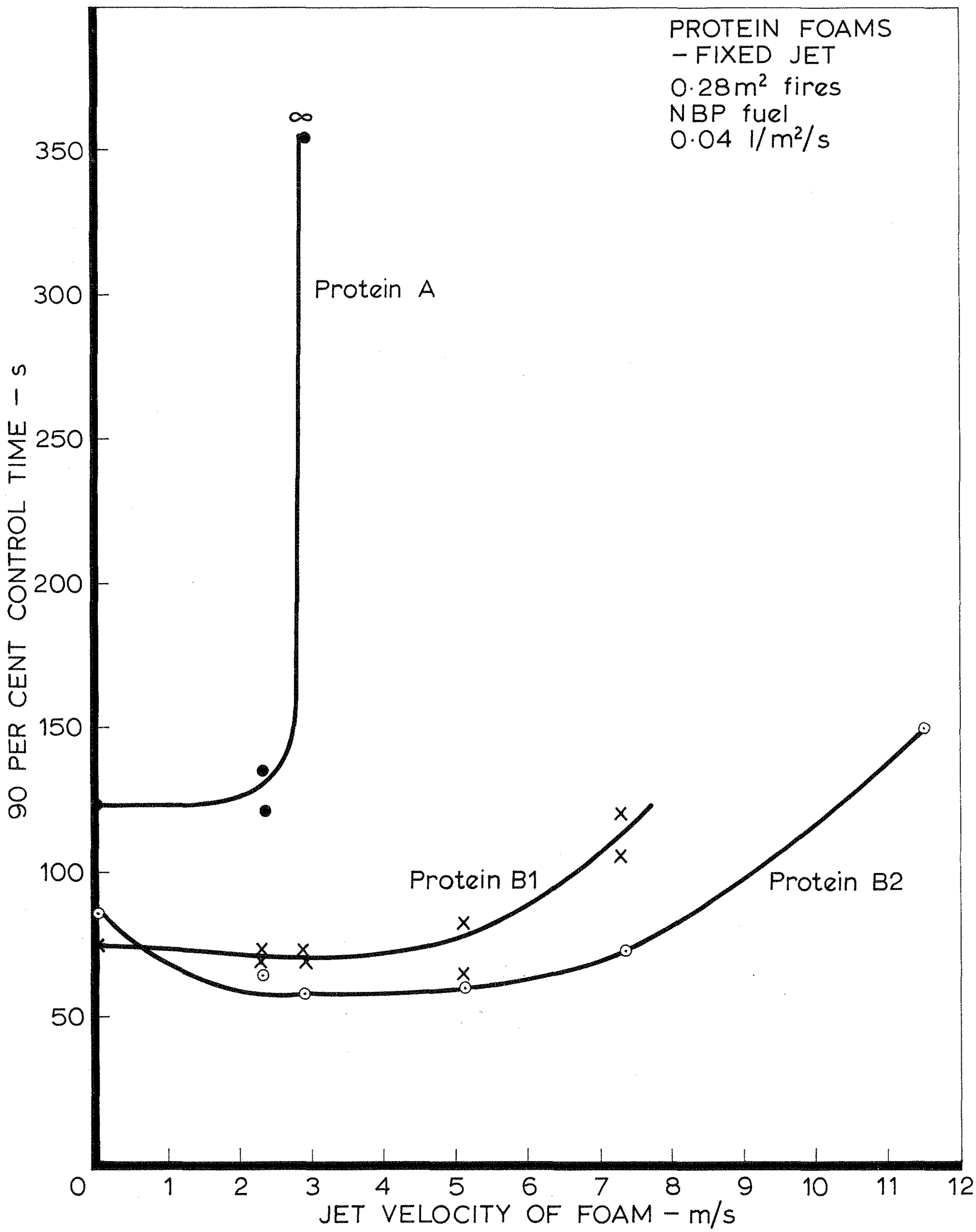

FIG. 4 THE EFFECT OF THE JET VELOCITY OF THREE PROTEIN FOAMS ON THE CONTROL TIME OF LABORATORY FIRES

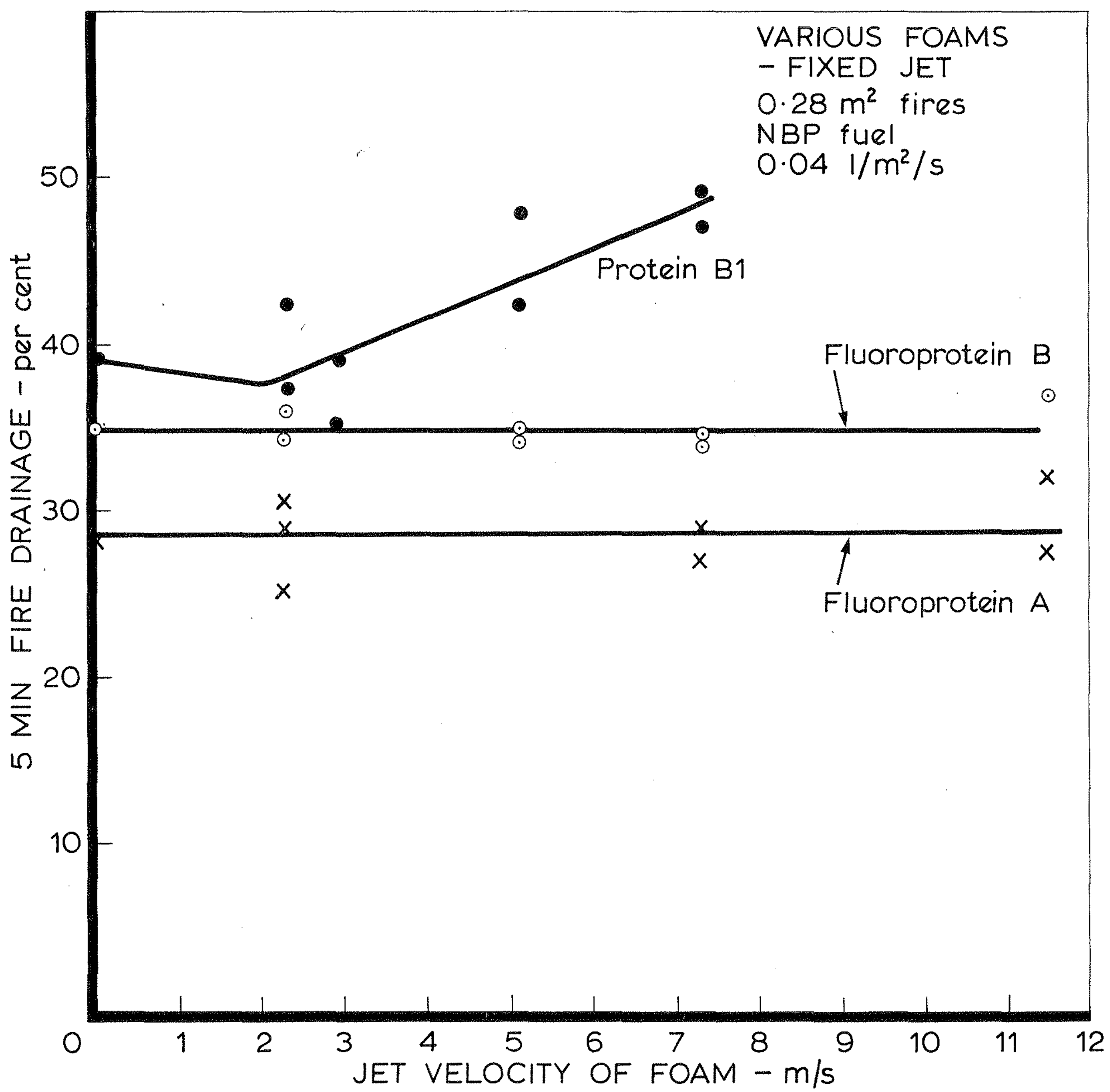

FIG. 5 THE EFFECT OF THE JET VELOCITY OF VARIOUS FOAMS ON THE DRAINAGE WHILE EXTINGUISHING LABORATORY PETROL FIRES

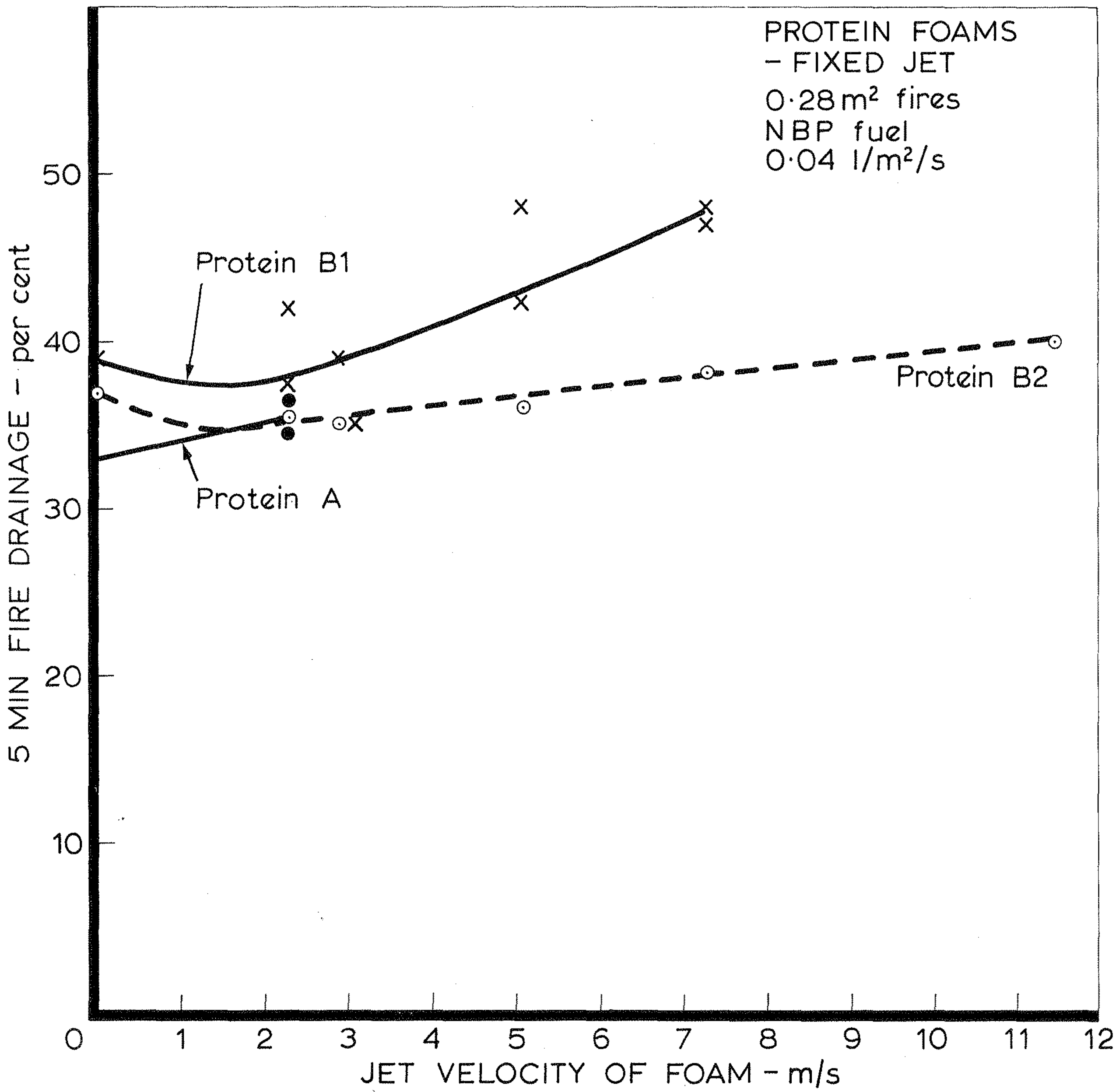

FIG. 6 THE EFFECT OF THE JET VELOCITY OF THREE PROTEIN FOAMS ON THE DRAINAGE WHILE EXTINGUISHING LABORATORY PETROL FIRES

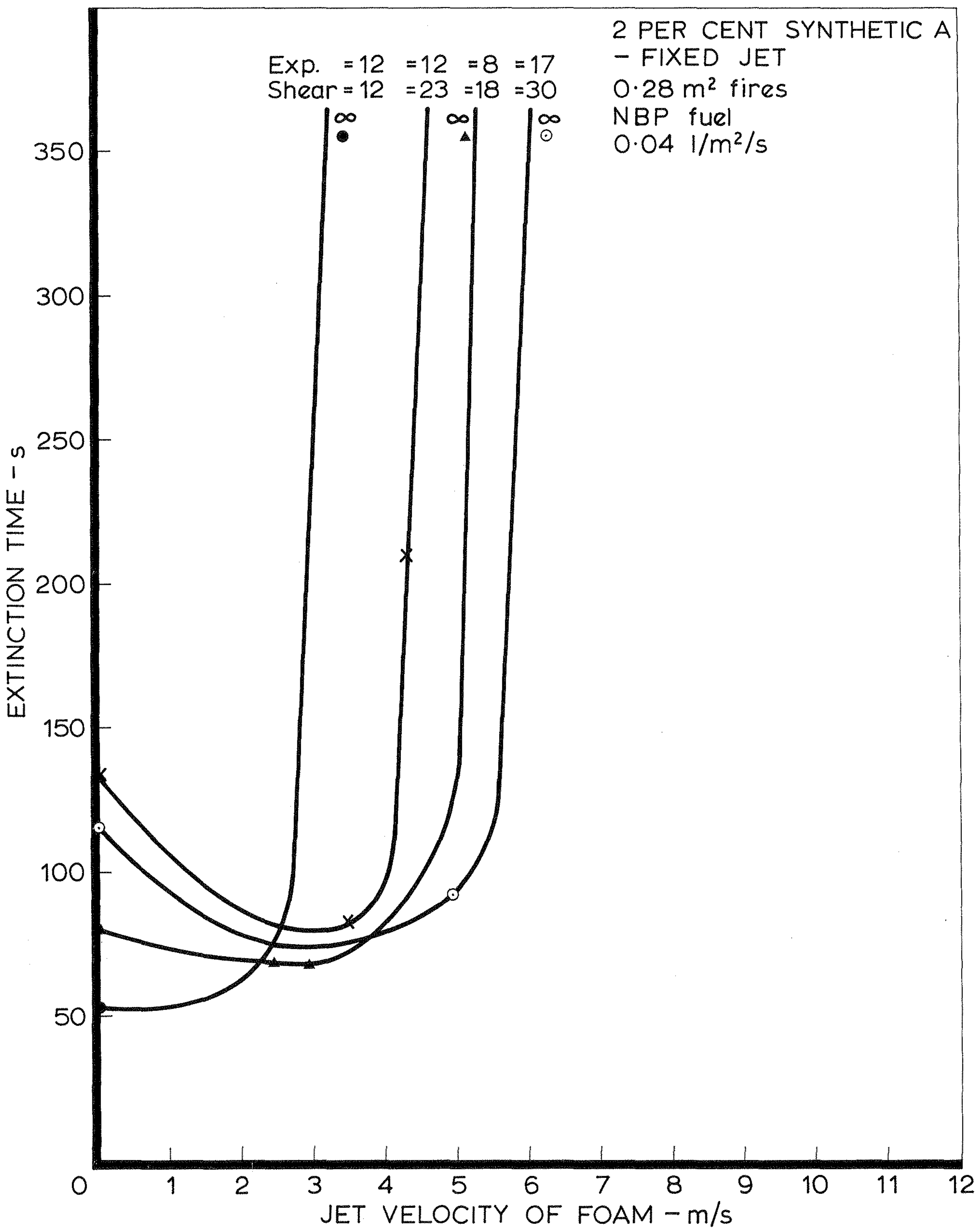

FIG. 7 THE EFFECT OF THE JET VELOCITY OF SYNTHETIC FOAM ON THE EXTINCTION TIME OF LABORATORY PETROL FIRES AT VARIOUS SHEAR STRESSES AND EXPANSIONS

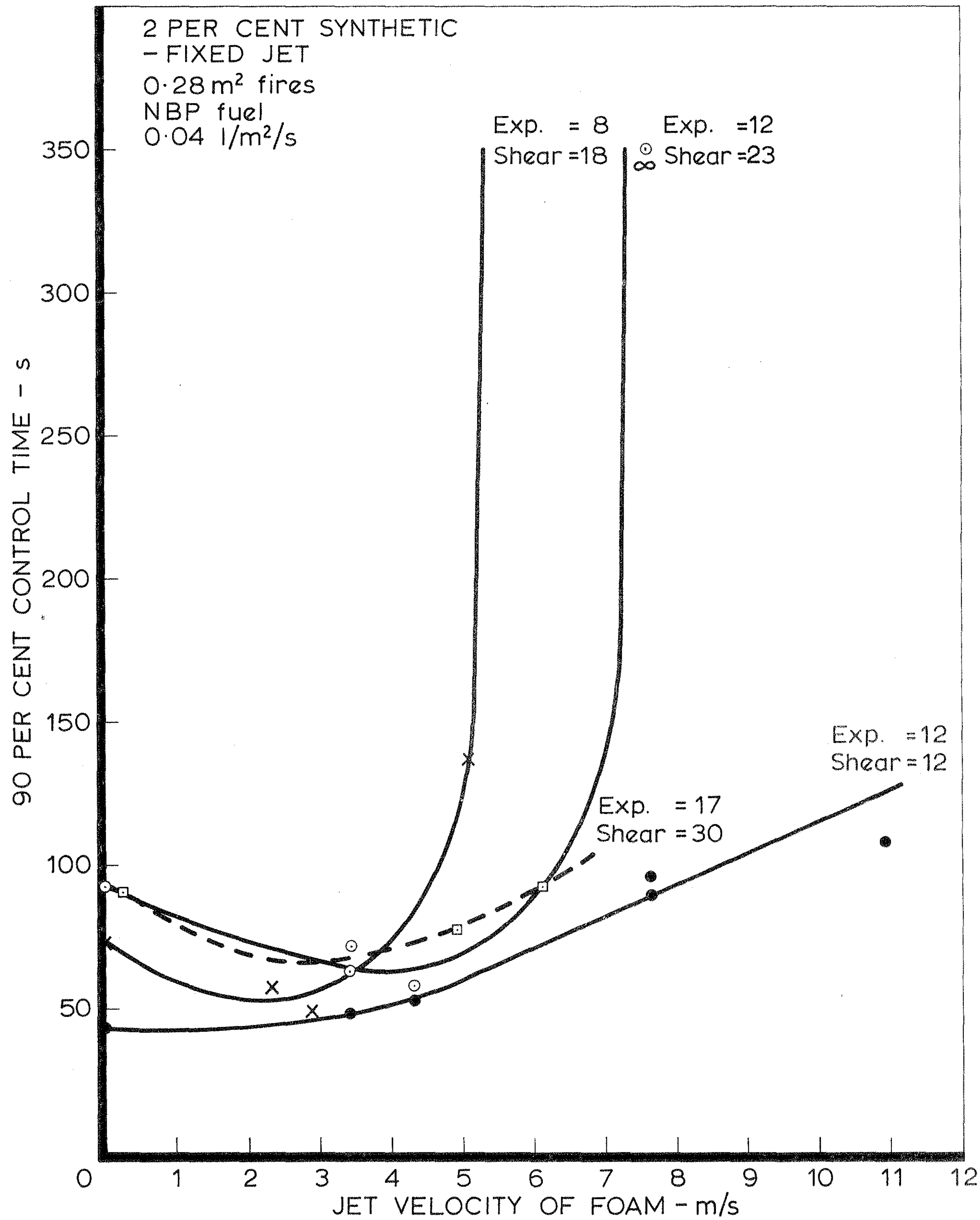

FIG. 8 THE EFFECT OF THE JET VELOCITY OF SYNTHETIC FOAM ON THE CONTROL TIME OF LABORATORY FIRES AT VARIOUS SHEAR STRESSES AND EXPANSIONS

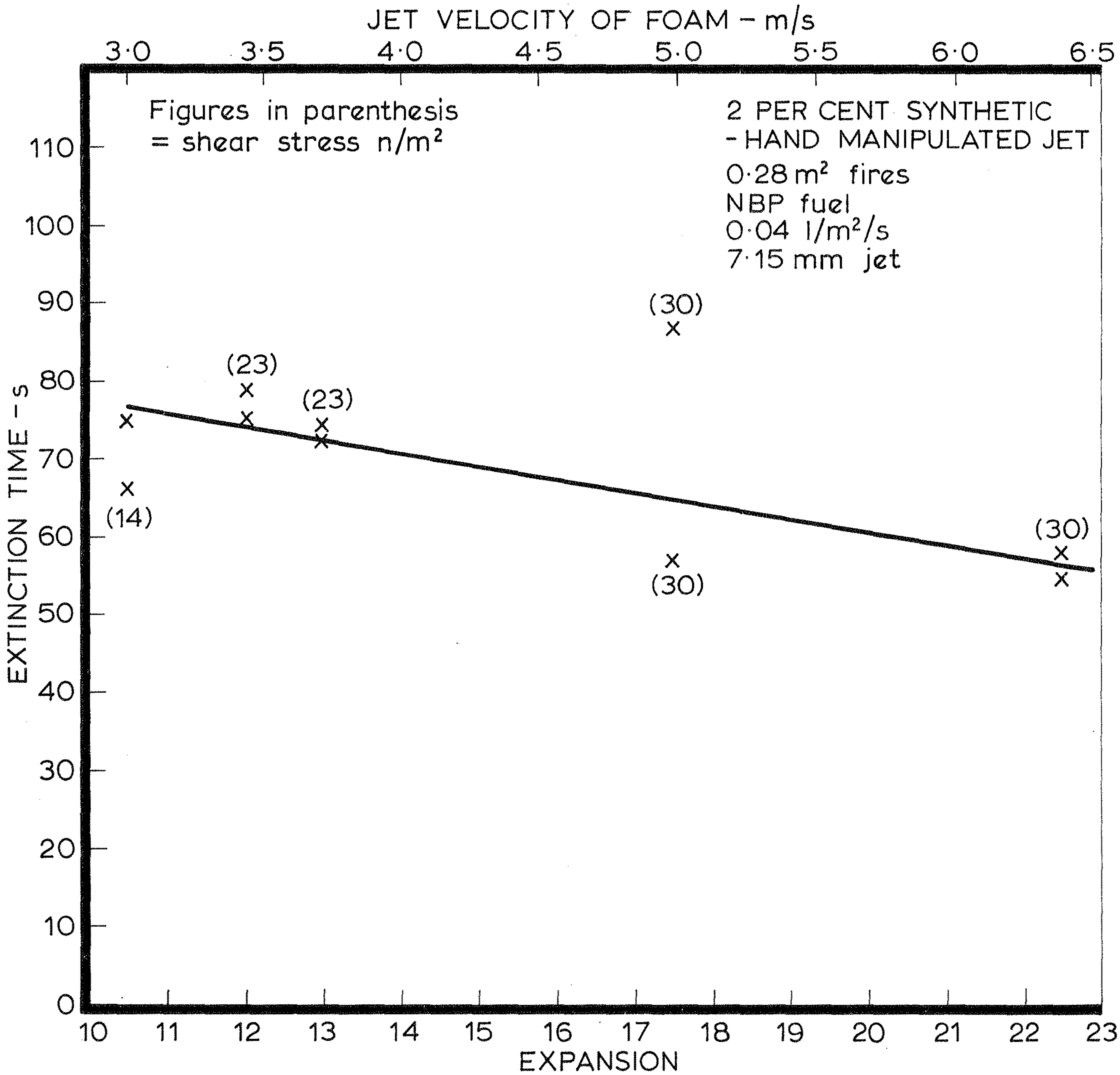

FIG. 9 THE EFFECT OF EXPANSION OF SYNTHETIC FOAM ON THE EXTINCTION TIME OF LABORATORY PETROL FIRES

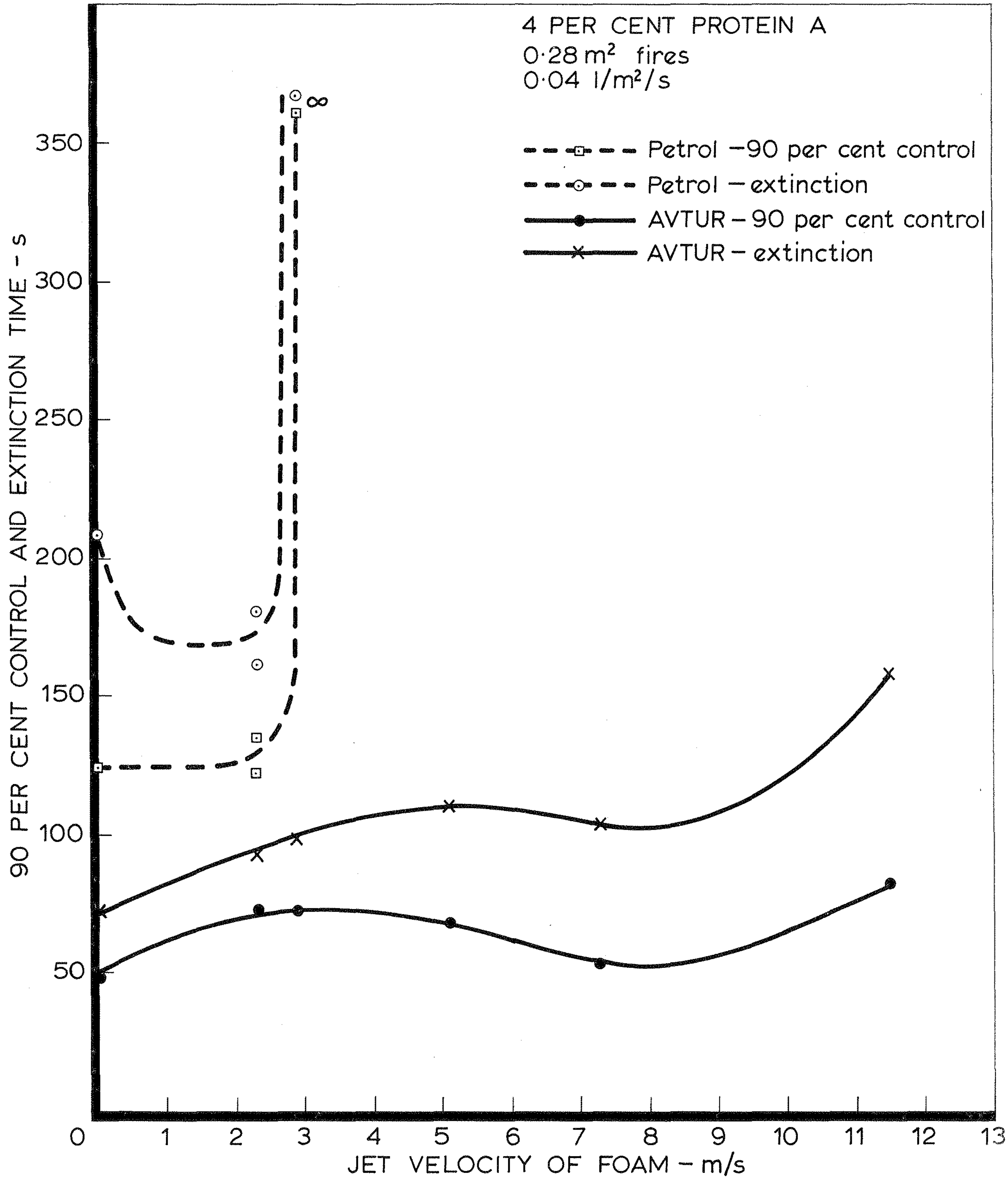

FIG. 10 COMPARISON OF PROTEIN A ON PETROL AND AVTUR FIRES

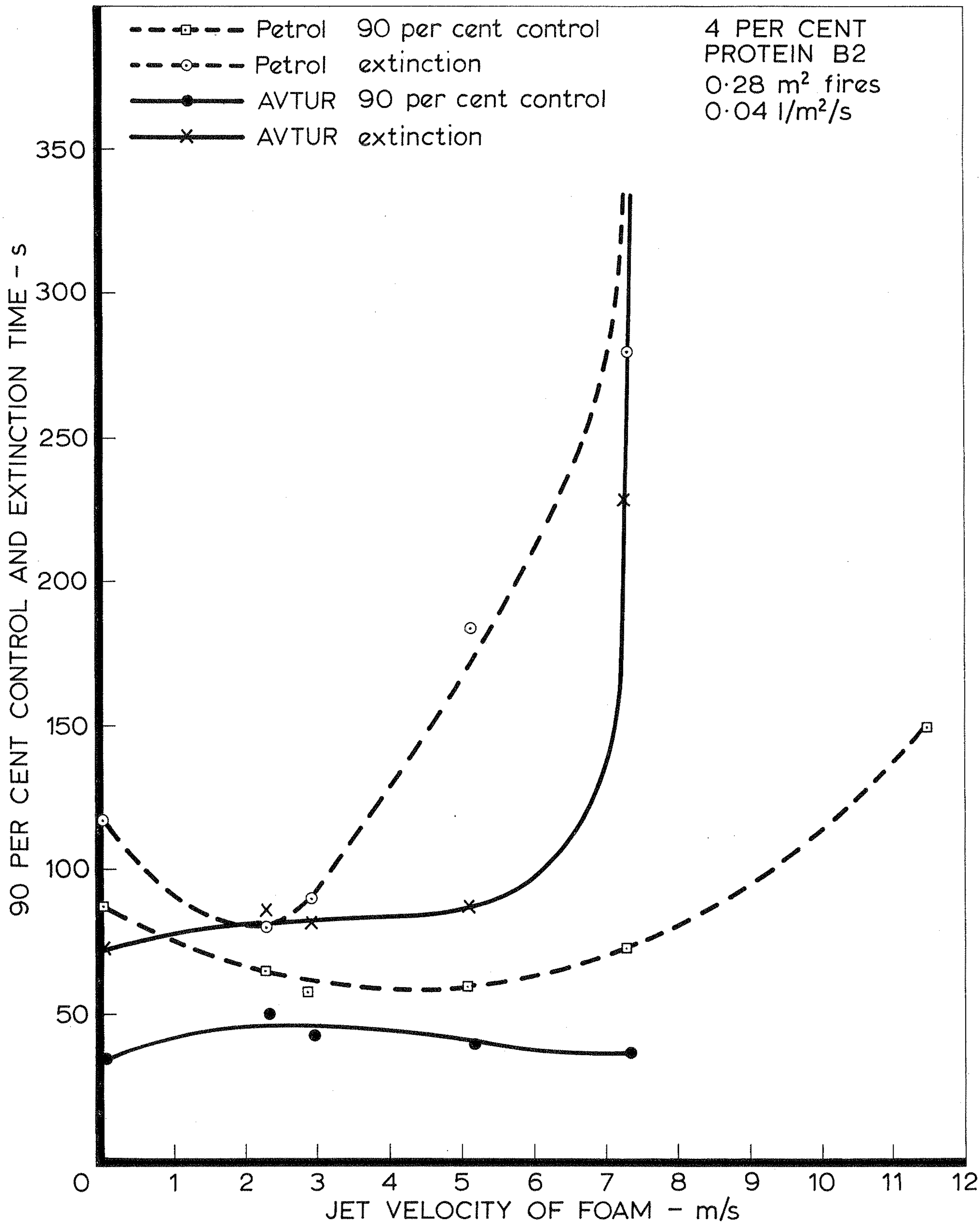

FIG. 11 COMPARISON OF PROTEIN B2 ON PETROL AND AVTUR FIRES

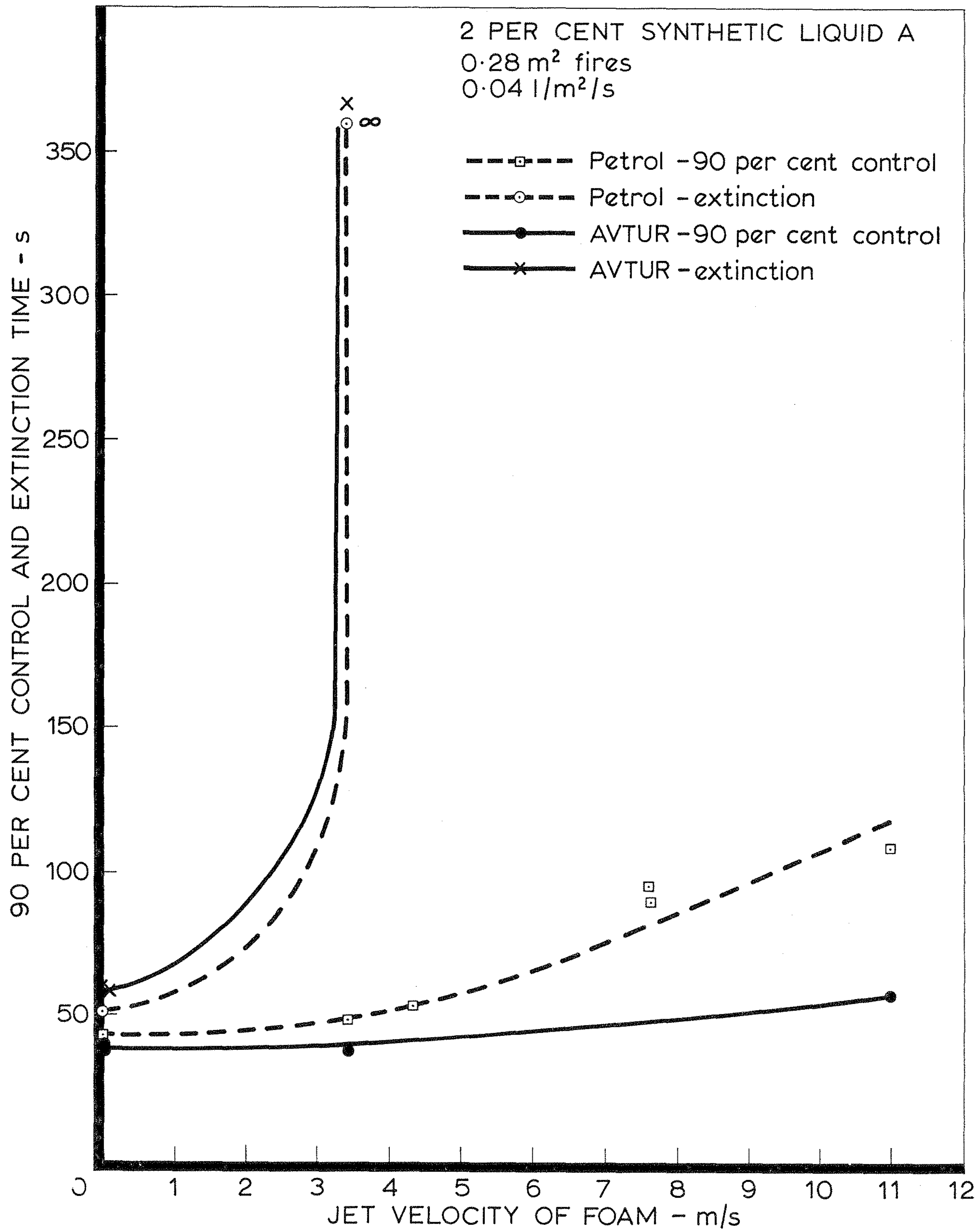

FIG. 12 COMPARISON OF SYNTHETIC LIQUID A ON PETROL AND AVTUR FIRES

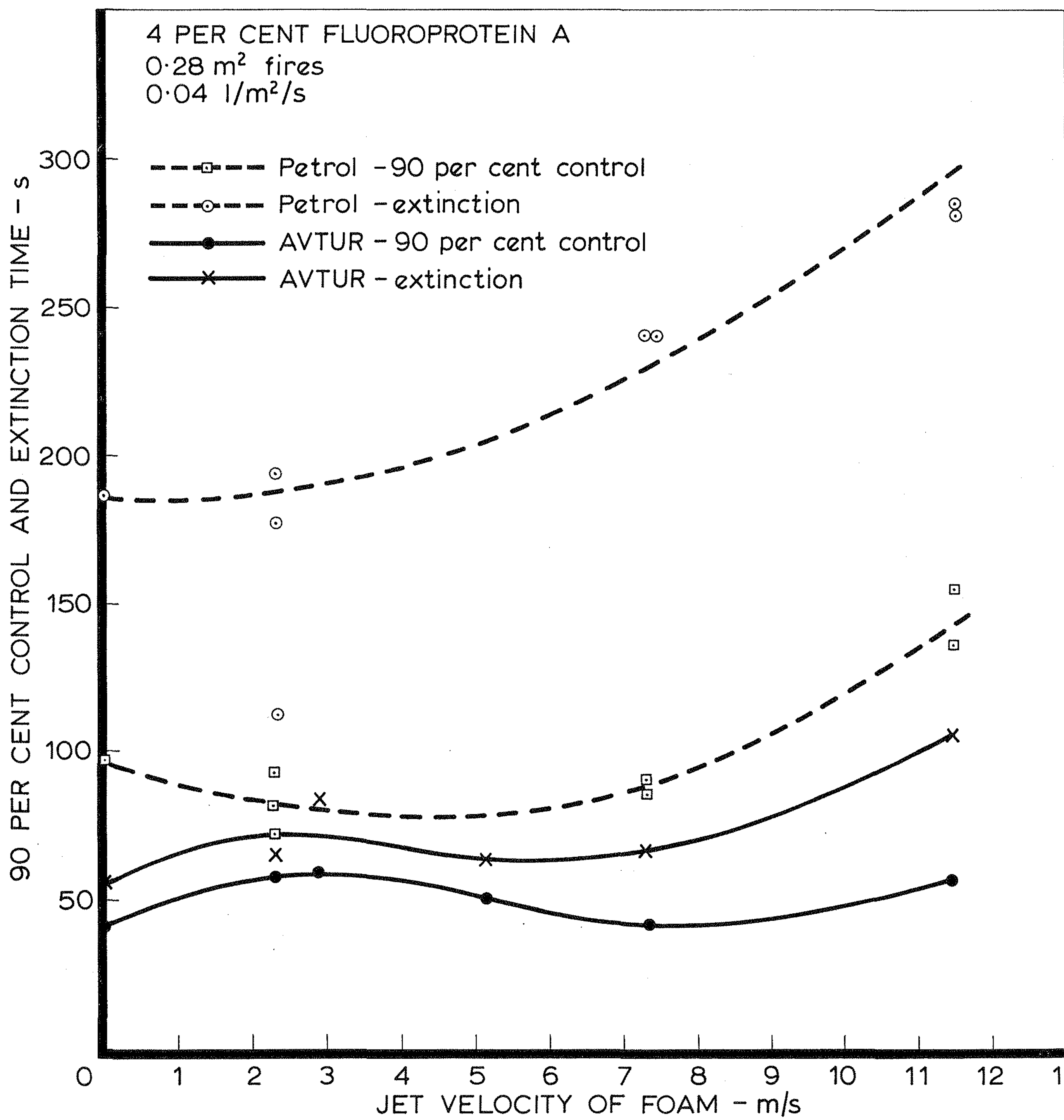

FIG. 13 COMPARISON OF FLUOROPROTEIN A ON PETROL AND AVTUR FIRES

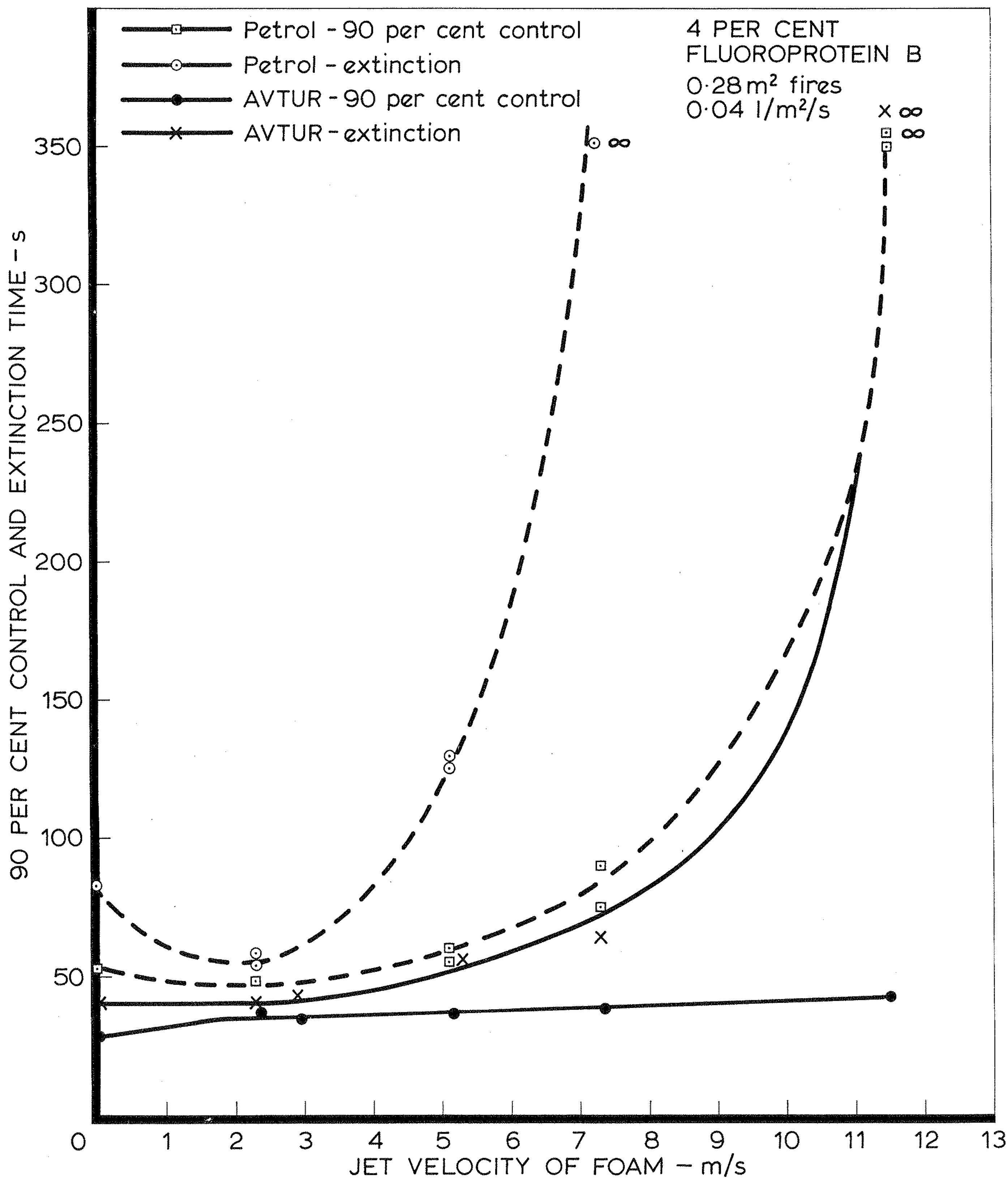

FIG. 14 COMPARISON OF FLUOROPROTEIN B ON PETROL AND AVTUR FIRES

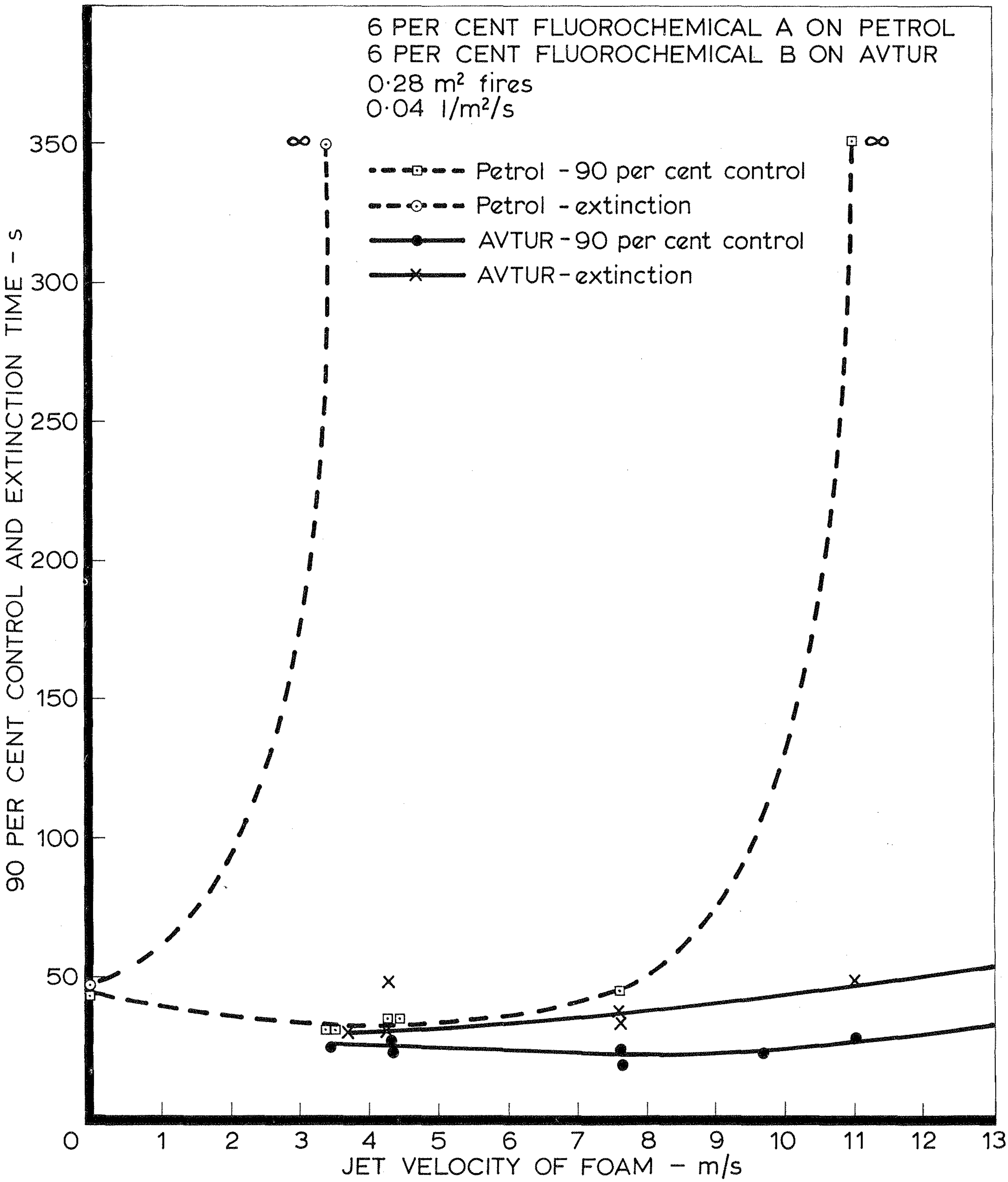

FIG. 15 COMPARISON OF FLUOROCHEMICAL A/B ON PETROL AND AVTUR FIRES