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PRELIMINARY EXPERIMENTS ON THE USE OF WATER ADDITIVES FOR FRICTION REDUCTION IN FIRE HOSE

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P F THORNE and K JORDAN

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SUMMARY

Measurements have been made of the Fanning friction factor (f) for 19 mm hose-reel hose and 70 mm non-percolating fire hose for plain water and dilute (10 to 50 ppm) solutions of Polyethylene Oxide Polymer (PEO). Friction factors were reduced by about 50 per cent by the addition of PEO to the water. Passage of the dilute solutions through a small transportable fire pump destroyed the friction-reducing phenomenon. The presence of PEO in the water enhanced the coherence of water jets, contributing to increased 'throw'. The scope for the application of PEO in practical fire fighting operations is discussed.

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* The measurements described in this note were made by Mr K Jordan during a period (March to August 1970) of industrial training, spent at the Fire Research Station, which formed part of a degree course in Chemical Engineering at Bradford University.

KEY WORDS: Hose, Friction factor, Drag reduction.

DEPARTMENT OF THE ENVIRONMENT AND FIRE OFFICES COMMITTEE
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LIST OF SYMBOLS USED

d	internal diameter of pipe (hose)
e	roughness height $= \frac{e u_* \rho}{\mu} = Re\sqrt{f}.\frac{e}{d}$
e^*	dimensionless roughness height
$^e/d$	dimensionless roughness factor, "roughness"
f	Fanning's friction factor $= \frac{2\tau}{\rho \bar{u}^2}$
F_N	roughness function for Newtonian flow
F	" " " non-Newtonian flow
l	length of pipe (hose)
Re	Reynolds number $= \frac{\rho . d . \bar{u}}{\mu}$
t_1	characteristic relaxation time for polymer molecule
u	local velocity
$\bar{u}$	average velocity
u_{max}	velocity at pipe (hose) axis
u_*	shear velocity $= \sqrt{\frac{\tau}{\rho}}$. $\left((u_*)_o = \sqrt{\frac{\tau_o}{\rho}}\right)$
y	radial distance from pipe wall
Q	gross volumetric flow rate
Δ	function describing modification to wall velocity profile, defined by equation (25)
ΔP	pressure drop due to friction
δ_b	thickness of laminar or viscous sub-layer
ρ	fluid density
τ	shear stress (τ_o shear stress at onset of drag reduction)
μ	fluid viscosity
$\alpha', \alpha_1, \alpha_2, \alpha_3$.	are numerical constants, the values of which are specific to particular drag reducing additives

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1. INTRODUCTION

Drag reduction by dilute polymer solutions was first reported in 1948 by Toms[1], and is consequently often known as the "Toms phenomenon".

Frictional drag occurring during the turbulent flow of liquids can be significantly reduced by the addition to the liquid of relatively small quantities of both soluble and insoluble substances. Suitable soluble substances include long chain, high molecular weight polymers such as polyethylene oxide, polyacrylamide, polyisobutylene and polymethyl methacrylate, guar gum (a natural material) and certain soaps. Calf thymus DNA[2], a coiled long chain material and certain fish slimes[24] also exhibit the effect. Insoluble materials capable of reducing frictional drag include asbestos fibres[3] and certain algae[4].

Current practical applications are mainly limited to oil-well drilling operations. Further applications have been proposed and are being investigated, e.g. sewer systems, long crude petroleum pipelines, sprinkler irrigation and ship drag. One of the more obvious and valuable applications is in fire fighting operations, and trials have been made by the New York Fire Department[5,6].

Laboratory experiments reported in the technical literature have been mainly concerned with the Toms phenomenon in hydrodynamically smooth pipes. Since many practical applications are concerned with pipes of finite roughness, it is essential to know how the Toms phenomenon is modified by the presence of roughness on the pipe wall. Only a few workers have reported investigations (summarised in section 2.6) into drag reduction in rough pipes and these have been exclusively concerned with artificially roughened pipes, either by internal threading or lining with sandpaper.

In the preliminary experiments reported in this note, friction factors for 70 mm and 19 mm fire hose have been calculated from measurements made of pressure drop and flow rate for plain water and water treated with polyethylene oxide. The grade of polyethylene oxide (PEO)≠ used was chosen since it was the nearest equivalent available in the U.K. to that used by the New York Fire Department and it is also one of the polymers found by many workers to give the highest levels of drag reduction at low concentrations. The fact that PEO was used in these experiments does not imply that it is exclusively the only drag-reducing additive suitable for this particular application.

2. THEORETICAL CONSIDERATIONS

Symbols used have the meaning given to them on page ii.

2.1 Pressure losses in pipes due to friction

For the flow of an incompressible fluid in a hydrodynamically smooth pipe of constant circular cross-section, a balance can be made of the frictional forces ($\tau . \pi . d . \ell$) and the pressure losses ($-\Delta P \, \pi d^2/4$)

i.e. $\Delta P = 4 \tau \ell / d$

This can be written

$$\Delta P = 4\left(\frac{\tau}{\rho \bar{u}^2}\right)\frac{\ell}{d} \cdot \rho \bar{u}^2 \qquad \text{..... (1)}$$

The quantity ($2\tau/\rho \bar{u}^2$) is a dimensionless friction factor (f), known as the Fanning or D'arcy friction factor≠.

Hence

$$\Delta P = \frac{2 . f . \ell . \rho . \bar{u}^2}{d}$$

But

$$Q = \pi d^2 \bar{u}/4$$

Therefore

$$\Delta P = \frac{32}{\pi^2}\,\frac{f . \ell . \rho . Q^2}{d^5} \qquad \text{..... (2)}$$

≠ In this report PEO refers to polyethylene oxide of approximate molecular weight 4×10^6 supplied by Union Carbide (UK) Ltd, Rickmansworth, Herts., under the trade name "Polyox WSR301".

≠ Alternative forms of friction factors are often used, e.g. $\tau/\rho \bar{u}^2$ and $8\tau/\rho \bar{u}^2$ the latter being known as the Blasius friction factor.

For water, using imperial units, this can be written,

$$P_f = 0.08 f . l . G^2 / d^5 \qquad ..... (3)$$

P_f = pressure drop lb/in^2

l = length, feet

G = flow rate, gal/min

d = diameter, inches

This form of correlation is given in the Home Office Manual of Firemanship[7] for the calculation of pressure losses in fire hose, which is hydraulically rough, rather than "smooth". The value of 'f' taken for the calculation must be appropriate to the "roughness" of the hose. Over the range of flow rates of interest in fire fighting[7], it is assumed, for convenience, that 'f' is constant, e.g. for non-percolating hose 'f' is taken to be 0.005 and for unlined hose 'f' is taken to be 0.01. The value of 'f' for a hydrodynamically smooth pipe under similar conditions is of the order of 0.004. In fact, as discussed later, 'f' is not constant but is a function of the flow rate (Reynolds number) as well as the "roughness".

2.2 Boundary layer structure

When a fluid flows over a smooth solid surface, the fluid in contact with the surface is retarded and a velocity gradient is set up between this retarded layer of fluid and the bulk fluid flowing over the surface. This velicity gradient can be regarded as occurring within a thin layer of fluid adjacent to the surface, known as the boundary layer. When the flow of the bulk fluid is laminar, the boundary layer is itself homogeneously laminar and relatively thin. However, when the flow of the bulk fluid is turbulent, the boundary layer is much thicker and consists of two portions. Adjacent to the wall is a thin laminar region, known as the laminar or viscous sub-layer. The thickness of this important layer is given by the expression

$$\frac{\delta_b}{\delta} \simeq 62 \, R_e^{-7/8} \qquad ..... (4)$$

For example for a 70 mm diameter smooth pipe containing water flowing at a Reynolds number (Re) = 2 x 10^5 (190 gal/min) the thickness of the laminar sub-layer is about 0.5 mm. The remainder of the boundary layer in turbulent flow is itself turbulent. It is separated from the laminar sub-layer by a thin transition region often known as the "buffer layer". In pipe flow, the turbulent portion of the boundary layer is assumed to extend to the centre line of the pipe, i.e. the total boundary layer thickness is equal to the pipe radius.

The thickness of the laminar sub-layer is approximately inversely proportional to the Reynolds number. Therefore the laminar sub-layer thins as the flow rate is increased. For smooth pipes, frictional drag consists only of skin friction and the thinning of the laminar sub-layer at high flow rates does not alter the nature of this drag. Rough pipes have elements of roughness, or protrusions, situated on the interior walls. At low flow rates in pipes of low roughness, the thickness of the laminar sub-layer is much greater than the height of these protrusions and the pipe behaves as if it were smooth. As the flow rate is increased, the laminar sub-layer thins and becomes comparable with the height of the protrusions and an additional drag, known as form drag, resulting from eddy currents caused by impact of the fluid on the protrusions, comes into play. The friction factor for the rough pipe is consequently greater than that for a smooth pipe. As the flow rate is further increased, form drag predominates and the friction factor assumes a constant value. In this regime the flow is called "fully rough". If a pipe is very rough, form drag becomes important as soon as turbulent flow is established and the flow becomes "fully rough" at an early stage.

Flow in smooth pipes is often correlated by the well known Prandtl-Karman law and a modification of this is used for rough pipes. The form of these correlations is shown in Appendix 1.

2.3 Effect of friction reducing additives

A detailed account of the theories of drag reduction will not be given here since good accounts are available in the literature (e.g. Ref. 9A). Some salient features are outlined below.

The precise mechanism by which low concentrations of certain polymers reduce drag in turbulent pipe flow is still a matter for discussion between fluid dynamicists. Early hypotheses linked drag-reduction with visco-elasticity since the drag reducing solutions investigated were comparatively concentrated (typically 0.1 to 0.5 per cent) and possessed marked visco-elastic properties. Solutions of some polymers currently available (e.g. PEO) do not possess visco-elastic properties at the very low concentrations (e.g. 10 ppm to 50 ppm) at which they are effective. They do, however, still possess a characteristic molecular relaxation time (t_1), and this is used in a hypothesis which proposes that the coiled macromolecules interact, possibly by stretching, with turbulent eddies over the whole pipe cross-section. An extension of this hypothesis is focussed in the wall region; this proposes that interference with the generation and dissipation of eddies occurs near the edge of the laminar (viscous) sub-layer. This is thought of either as a thickening of the laminar sub-layer itself, as in the correlations of Elata[10] and Mayer[11], used later, or as a modification and extension of the buffer layer, the laminar sub-layer remaining unchanged, as proposed by Virk[18,19]. Virk renamed the modified buffer layer the "elastic sub-layer". Byron et al[20] present evidence that absorption of PEO occurs on pipe walls leading to a thickening of the laminar sub-layer. In all these hypotheses concerned with the wall region, the thickening of the viscous and/or buffer (elastic) layer is a consequence of the interaction between macromolecules and turbulent eddies, and is not itself the primary cause of drag reduction in smooth pipe flow. No explanation has been published for the effect of pipe roughness on Toms phenomenon, but the following type of explanation seems likely. Following the onset of drag reduction the turbulent flow of drag-reducing solutions in rough pipes enters a regime in which behaviour is identical to that of the same solution flowing in a smooth pipe of the same internal diameter. This behaviour is analagous to the "smooth" behaviour of a rough pipe with plain fluids below a certain value of Reynolds number (as discussed previously). Since a thickened laminar/buffer layer is present due to the drag reducing processes occurring in both smooth and rough pipes, the "smooth" behaviour of rough pipes is prolonged since the combined laminar/buffer layer will not become thin enough to become comparable to the height of the protrusions on the pipe walls until larger Reynolds numbers are reached. When this condition is reached, form drag begins to compete with the normal drag reducing processes and ultimately predominates. The effect of dilute drag-reducing solutions on form drag has not been extensively studied, although White[16] records the observation that 30 ppm PEO increased the drag of a falling sphere at Reynolds numbers greater than 2 x 10^5 and James and Gupta[28] measured increased drag on cylinders at Reynolds numbers less than 300. The role of form drag in the flow of drag-reducing solutions through rough pipes is a topic which requires further investigation. It can be visualised that at high enough Reynolds numbers all the drag-reducing effect is lost and this could be an important limitation on the use of drag reducing additives in practical applications.

Modifications to the Prandtl-Karman law taking into account the effect of drag reducing additives and pipe roughness have been suggested by Meyer[11], Elata[10] and Spangler[14]. These are discussed and further developed in Appendix 1 where it is shown that the suggested modifications are substantially identical and of the form:

$$\frac{1}{\sqrt{f}} = 4 \log Re\sqrt{f} - 0.4 - \frac{F}{\sqrt{2}} - \frac{\alpha'}{\sqrt{2}} \log\left(\frac{\tau}{\tau_o}\right) \qquad \ldots\ldots (5)$$

where the symbols have the meanings given them on page ii.

2.4 Previous work with rough pipes

The New York Fire Department[5] reported the following effects of 50 ppm (0.005 per cent) polyethylene oxide in water (calling the solution "slippery water").

Reach and nozzle pressure	–	100 per cent increase
Nozzle reaction	–	75–100 per cent increase
Discharge rate (gpm)	–	50–60 per cent increase
Pump pressure	–	20 per cent decrease

Unfortunately, further details about the conditions under which these results were obtained are not given and the information is therefore of limited value. The particular grade of polyethylene oxide used is not stated but it is thought to be "Friction Reducing Agent" (FRA) grade which has a molecular weight $> 6 \times 10^6$. Further trials have recently been reported[6] using a modified polyethylene oxide additive in slurry form (renamed "rapid water"). This is in the form of a concentrated suspension or slurry of powdered PEO in a viscous water miscible carrier in which PEO is not soluble.(cf. method for preparing aqueous solution, Appendix 3). Again insufficient data has yet been published to enable a full assessment of the system to be made. However, Rubin[31], using a similar type of system has reported friction reduction of up to 60 per cent for a 2 inch diameter rubber lined hose.

There are three papers available in the literature to date in which drag reduction in rough tubes has been investigated in some detail[14,16,17]. The conditions obtained in these experiments are summarised in Table 1. A common feature found by each investigator is the the tendency with increasing Reynolds number (flow rate) for friction factor initially to be reduced to a minimum value then for it to increase towards the value of friction factor for the pure solvent. The drag reducing effect, after reaching a maximum, tended to disappear at very high flow rates. Spangler[14] demonstrated that this decrease in drag reduction was not due, in the test rig used, to degradation of the polymer and was therefore due to some other modification of the Toms phenomenon by the tube roughness at high flow rates. White[16] showed that guar gum had no drag reducing effect in rough pipes although PEO had. He also experimented with jets of PEO solution discharing into tanks of the same solution and noted a damping of small scale, high frequency turbulence by PEO but not by guar gum. Virk[17] used small bore (d = 8.6 mm) pipes which yielded results with the polymers used at or near the maximum drag reduction asymptote. White[16] has pointed out that for PEO, a minimum tube diameter of about 10 mm is necessary if reliable data for scale-up purposes is required.

The results of these three workers are summarised in Figs 6 and 7 in which friction factor (f) is plotted against Reynolds number (Re) on the usual friction factor diagram.

3. EXPERIMENTAL

The equipment used in the present experiments is shown diagrammatically in Figs 1 and 2. Water from a 27,300 dm^3 (6000 gal) overhead storage tank, (a) was pumped by a 37 kW (50 H.P.) centrifugal pump (B) to a valved hydrant (C) into which was plugged one inlet arm of a collecting breech. Concentrated 'Polyox' solution was fed from the polyox dispenser (D) into the mixing length of hose (E) through a perforated copper tube (6.4 mm (0.25 inch) diameter) introduced into the hose via the other inlet arm of the collecting breech and held concentric with the outlet arm. The arrangement is shown in more detail in the inset in Fig. 1. The pressure drop across the test length of hose (F) was measured by two pressure gauges (G). The flow rate could be controlled either by the hydrant valve (C) or a valve (H) situated at the end of the test length of hose. A nozzle (I) could be attached to the end of the 70 mm hose for observing the effect of Polyox on water jets.

Flow rate was measured for the 70 mm hose by the fall in level of water in the overhead tank. It was determined experimentally that 10 mm = 8.92 dm^3 (1 inch = 49.8 gal). For the 19 mm hose, flow rates were measured by collection in a 227 dm^3 (50 gal) tank. For this tank 10 mm = 3.65 dm^3 (1 inch = 2.04 gal).

The pressure drop across the test length of 70 mm hose was measured by means of two 0–1380 kN/m^2 (0–200 psi) pressure gauges (G) connected to pressure tappings made in special hose couplings. The couplings consisted of a 200 mm (8 inch) length of 70 mm I.D. brass pipe to the ends of which were welded standard hose couplings. The gauges were throttled to reduce needle vibration. The pressure drop across the test length of 19 mm hose was measured on two 0–413 kN/m^2 (0–60 psi) gauges connected to "Tee" connections at each end of the hose.

The mixing length of 70 mm hose was 2.43 m (8 ft)long, equivalent to 35 pipe diameters. The 19 mm hose test length was 16.5 m (54 feet) 870 diameters and the 70 mm hose test length was 75.3 m (247 feet), 1008 diameters.

Concentrated PEO solutions were made up according to the method described in Appendix 2 and held in the dispenser D. The concentration for experiments with 19 mm hose was 0.02 per cent by weight and with 70 mm hose was 0.2 per cent by weight. Compressed air was introduced at a constant pressure into the dispenser via the valve (J) and the pressure was measured on the gauge (K). The level of concentrated PEO solution could be measured by means of the external level gauge (L). The flow rate of PEO was measured by level difference. For the dispenser 10 mm = 0.365 dm^3 (1 inch = 0.204 gal). The flow rate was controlled by the valve (M). The water temperature was 10°C.

Sone experiments were made in which a premixed solution of PEO in water (at 30 ppm) was pumped through the test length of 70 mm hose using a small transportable fire pump. A 1 per cent solution was made up as described in Appendix 2 and this was diluted to 30 ppm in a 900 l (200 gal) tank with gentle stirring. The diluted solution was fed to the pump from this tank via suction hose.

4. RESULTS AND OBSERVATIONS

4.1 Results

The pressure drop and flow rate measurements are tabulated in Tables 2 to 6 and are plotted on log scales in Figs 3 and 4. The results have been correlated by non-linear regression analysis using a "least squares parabola" of the form

$$\log Q = a_0 + a_1 \log \Delta P + a_2 (\log \Delta P)^2$$

The following values of a_0, a_1 and a_2 were obtained, for Q expressed in gpm and Δ P in lbf/in^2.

	a_0	a_1	a_2
70 mm hose - plain water	1.553	0.560	- 0.011
19 mm hose - plain water	0.601	0.280	0.088
70 mm hose - injected PEO	1.566	0.792	- 0.125
19 mm hose - injected PEO	0.708	0.434	- 0.053

The average concentration of PEO during each run was calculated from the measured flow rates of plain water and concentrated PEO solution.

Values of Q and Δ P given by the above correlation have been used to calculate Reynolds number (Re) and friction factor (f) i.e.

$$Re = \rho \frac{d \bar{u}}{\mu} = \frac{4 \rho Q}{\pi \mu d} = 3.9 \times 10^3 Q \text{ for 19 mm hose}$$

$$= 1.06 \times 10^3 Q \text{ for 70 mm hose}$$

Q expressed in gpm

and $$f = \frac{\pi^2}{32} \frac{\Delta P . d^5}{Q^2 \ell \rho} = \frac{12.9 \, \Delta P d^5}{Q^2 \, \ell \, d.}$$

$$f = 0.055 \quad P/Q^2 \quad \text{for the 19 mm hose}$$

$$f = 7.96 \quad P/Q^2 \quad \text{for the 70 mm hose}$$

Q expressed in gpm , P in lbf/in^2

Friction factor (f) is plotted against Reynolds number (Re) in the conventional friction-factor chart form in Fig. 5. Also included for comparison are cufves for hydraulically smooth pipes and for pipes of roughness $^{e}/d$ = 0.0006 taken from a Moody friction factor chart.

4.2 Observations

During this work some incidental observations were made of the effect of PEO on the appearance of the water jet discharging from a 19 mm ($\frac{3}{4}$ inch) nozzle attached to the end of the 70 mm hose test section. With plain water the jet had a white, opaque appearance and produced a loud "hissing" noise. Break-up of the jet commenced between 0.5 and 1.0 m from the nozzle. When PEO was added to the water at the same flow rate, the jet became translucent (semi-transparent) enabling objects held close to the jet to be distinguished on looking through the jet. The noise level was much reduced and jet break-up was delayed by several metres.

An observation was made similar to that reported by the Fire Department of New York[5]. When PEO was added to plain water being pumped through the 70 mm hose, the upstream pressure always fell and the pressure at the end of the hose increased. It was therefore possible to increase the upstream pressure to its original value, thus concentrating the benefit of drag reduction in the form of increased pressure at the end of the hose.

5. DISCUSSION

In these experiments the method used for injecting the "concentrated" (0.2 per cent) PEO solution into the water flowing through the hose did not allow exact adjustment of the final concentration. Although a final concentration of 30 ppm was aimed for, the range of concentrations measured in the experiments with 70 mm hose was approximately 10–50 ppm with an average value of 23 ppm, the range and average value for the 19 mm hose were 10–60 ppm and 33 ppm respectively. Within the ranges of concentration used, there appears to be no correlation between reduction in friction factor, PEO concentration and Reynolds number.

The readings of flow rate and pressure drop obtained are shown in Figs 3 and 4 together with the correlating curves obtained as described in Section 4. The results obtained in experiments where premixed PEO solution at a concentration of 10–50 ppm was pumped through the 70 mm hose are shown in

Fig. 3. It can be seen that these results fall on the correlation for the plain water results. It is clear from these results that under the conditions in these experiments, the pump degraded the PEO solution sufficiently that no subsequent friction reduction effect could be detected in 70 mm hose. Two types of degràdation are possible. Mechanical rupture of the long chain molecules is possible due to the high shearing forces in the pump, thus reducing the effective molecular weight of the polymer. It has also been suggested that degradation of the long chain molecule occurs by oxidation which is accelerated by high intensities of turbulence, and that such oxidative degradation can be countered by a suitable anti-oxidant additive. Whatever the cause of the degradation, it is clear that at the present tim e it presents serious operational limitations on the use of premixed PEO solutions. For example, it would be convenient for some applications to pump premixed PEO solutions from a 400 gal water tender. Due to degradation in the pump, this does not appear to be possible.

Figure 5 shows the correlated results for both hose sizes plotted as friction factor (f) against Reynolds number (Re), on logarithmic scales. It can be seen that friction factor is not constant, but varies with water flow rate. Over the range of flow rates used the friction factor for 70 mm hose with plain water varies between 0.0054 (at 75 gal/min) to 0.0045 (at 350 gal/min). The value given[7], for non-percolating hose with plain water is 0.005. The value of friction factor for 19 mm hose with plain water varied between 0.0062 and 0.0066. This higher level of friction factor is probably explained by the different method of wall construction of 19 mm hose-reel hose. The Prandtl-Karman correlation for hydrodynamically smooth pipes with Newtonian fluids, e.g. plain water, has been included in Fig. 5 for comparison.

The range of flow rates used in these tests was not wide enough to reveal the full extent of the variation of friction factor with Reynolds number for the dilute PEO solutions. There are a number of features of drag reduction, found by other workers, using both smooth and rough pipes, which have not been measured in this investigation. Some of these features hold important implications for the practical use of dilute PEO solutions in fire fighting. These are:

1) A minimum shear stress (τ_o) is required for the onset of drag reduction. Below τ_o, the behavior of the solution is identical to that of the solvent. In general the onset shear stress is inversely proportional to the concentration and is also a function of certain properties of the polymer, e.g. molecular weight. For a given polymer solution, the larger

the pipe diameter, the higher the Reynolds number at onset.

The results of White and Spangler for rough pipes are shown in Fig. 7, together with the results of the present investigation. White's results show onset occurring at a Reynolds number of 8×10^3. Spangler's results, for different experimental conditions, show onset at Re = 7×10^3. Some of Virk's results are summarised in Fig. 6. Virk's tube diameters were small enough for τ_o to be exceeded as soon as or soon after turbulent flow was established (Re > 2000). Curves A and B are for water, A' and B' for dilute PEO solutions and A" B" for other polymer systems which yielded results partly coincident with the maximum drag reduction asymptote (see below).

For dilute PEO solutions, Virk[18,19] gives τ_o as 7 dynes/cm^2 which corresponds to Re = 3.4×10^4 (Q = 32 gal/min) for 70 mm hose and Re = 7×10^3 (Q = 2 gal/min) for 19 mm hose. Practical flow rates used in hoses are such that it is almost certain that Reynolds number would be beyond onset conditions for both hose sizes.

2) The Maximum Drag Reduction Asymptote (MDRA) represents the minimum friction factor achievable under any conditions. Maximum drag reduction is achieved only by the most effective polymers in small diameter pipes of relatively short length. For smooth pipes the MDRA continues with a negative slope (as shown in Fig. 6) as far as experimentation has yet been taken. Virk shows that for rough pipes, the friction factor follows the MDRA for a while before flattening and departing from the MDRA, at a point dependent upon pipe roughness. It subsequently increases. (curves A", B" Fig. 6).

3) The existence of a minimum value of friction factor for the rough pipe flow of dilute polymer solutions is an important feature of drag reduction. A minimum value of friction factor for smooth pipe flow has been reported only by Paterson and Abernathy[25] who used relatively long (1700 diameters) pipes of 0.248 inches internal diameter. They showed that degradation of the polymer molecules occurred during turbulent flow in smooth pipes and that the extent of this degradation was a function of both the wall shear stress ( ) and the residence time in the wall region (distance along the pipe). Other reported measurements with smooth pipes have been made with much shorter pipes, e.g. Virk[27] (165 diameters) and Goren and Norbury[26] (420 diameters). In neither case was degradation observed, nor has degradation occurred in other smooth pipe experiments in which the pipe length has not been reported.

Reported experiments with "rough pipes" have all yielded a minimum value for friction factor and extrapolation of the curves shown in Figs. 6 and 7 suggest that at high enough Reynolds numbers, the drag reducing effect would no longer operate. For the 70 mm hose this would occur at a Reynolds number of about 5 or 6 x 10^5 (Q 500 gal/min), and about 7 or 8 x 10^4 for 19 mm hose (Q $\simeq$ 20 gal/min). This would present a limitation for 70 mm hose only at very high pumping rates. The maximum operational flow rate used with 19 mm hose-reel hose is of the order 25 gal/min. It can be seen, from Fig. 5, that the friction factor for PEO treated water, with 19 mm hose, increases with flow rate over the useful range and, if the results are extrapolated, becomes identical to that for plain water before the maximum rate is reached. Thus there appears to be a limitation to the usefulness of PEO when used with 19 mm hose-reel hose.

It is clear that two factors contribute to the increase in rough pipes of friction factor at high Reynolds numbers. The predominant factor is the pipe roughness itself and this mechanism has been discussed in Section 2.4. This factor operates in all rough pipes, but in addition in pipes of high length/diameter ratio, the possibility exists of polymer degradation. Paterson and Abernathy demonstrated that if the wall shear stress (τ) and residence time (length/ diameter ratio) are appropriate, polymer degradation can occur during turbulent flow, even in hydrodynamically smooth pipes. Since, for a given Reynolds number, the wall shear stress (τ) is higher in a rough pipe than in a smooth pipe, polymer degradation can be expected to be a feature of turbulent flow in rough pipes. The results of Paterson and Abernathy indicate that significant degradation did not occur below a wall shear stress of the order of 50 to 100 dynes/cm^2 for smooth pipes of l/d ratio 670 and 1700. In the 70 mm hose (l/d ratio 1008) a wall shear stress of 50 dyne/cm^2 corresponds to a Reynolds number of 1.3 x 10^5 and a value of 100 dyne/cm^2 to 1.9 x 10^5. Although no attempt was made in the experiments to measure the extent of any degradation, it can be expected that some degradation did occur during flow through the hose.

As indicated above in Section 2.3 a correlation has been established between the friction factor (f) and Reynolds number (Re) for the turbulent flow of drag reducing solutions in rough pipes which takes into account the roughness of the pipe and certain properties of the solute. The factors can be combined in a function delta (Δ) which represents the modification to the Prandtl-Karman correlation by pipe roughness and a drag-reducing solute.

The function Δ is derived in Appendix 1 and is defined by the following equations:

$$\frac{1}{\sqrt{f}} = 4 \log Re\sqrt{f} - 0.4 - \frac{\Delta}{\sqrt{2}} \qquad \text{..... (6)}$$

$$\Delta = F - \alpha' \log \left(\frac{\tau}{\tau_o}\right) \qquad \text{..... (7)}$$

where the symbols have the meaning given them on page ii.

The function Δ has been calculated and is shown plotted versus the dimensionless roughness height e* or roughness Reynolds number (Re(R)) (= $Re\sqrt{f}\,e/d$) in Fig. 8 .

Δ has also been calculated from the results given by Virk[17], White[16] and Spangler[14] and their results, expressed in this way, are also shown in Fig. 8. In this graph curves for plain water are seen to lie close together. If the physical nature of the different pipe roughnesses had been identical it is to be expected that the curves would have been coincidental. For plain water the function Δ is identical to the Newtonian roughness function, F_N (see Section 2.3.2). Departure from the plain water curves towards lower values of Δ indicate a decrease in drag. A value of $\Delta = 0$ corresponds to an hydraulically smooth pipe. Negative values of Δ indicate drag lower than that shown by an hydraulically smooth pipe. The range of conditions investigated was not wide enough to show the full range of variation of Δ with Re(R), but the graph underlines the features discussed above in connection with Figs. 6 and 7.

It is clear that further detailed study (see Section 7) over a wider range of conditions is necessary in order to explore fully the ranges of applicability and the limitations of PEO in practical fire-fighting. As well as further laboratory studies, similar to those described herein, experience needs to be gained in the use of PEO with operational fire fighting equipment. As explained above, the direct pumping of dilute premixed PEO solutions does not appear feasible at least under the conditions of these experiments. Some means is required for introducing concentrated PEO solutions or suspensions directly into fire hose downstream of a pump. This would involve a flow sensing device, contributing negligible pressure loss, situated in the hose and coupled to some means of injecting the concentrated PEO "pro rata" into the hose. The development of such equipment is a priority requirement if a meaningful operational assessment of PEO is to be made.

The observations made of the apparent reduction in turbulence in a water jet with PEO additive are in line with those of White[16] who used a 19 mm ($\frac{3}{4}$ inch)jet to demonstrate that certain polymers, including PEO, suppress small scale high frequency turbulence in jets. In water jets, it is clear that PEO tends to reduce turbulence, at least in the surface layers of the jet. The opaque appearance of the jet is due to the rippling and distortion of the surface of the jet by small fluid particles moving radially by turbulent diffusion. Indeed many of the fluid particles penetrate the surface to form a mist of fine droplets which can be observed surrounding the jet. As soon as a deformation appears in the jet surface, it will tend to be accentuated due to air resistance. This is an accelerating phenomenon and the jet will become unstable and break up. Clearly, a reduction in turbulence will attenuate the disturbance of the jet surface and enhance the coherence of the jet. This aspect of the use of friction reducing additives requires further investigation.

6. APPLICATIONS TO FIRE FIGHTING

Fabula[23] has discussed the benefits which might result from the use of friction reducing additives in fire fighting operations. His predictions are based upon Virk's[18] Maximum Drag Reduction Asymptote (MDRA). The present work has shown that friction factors for fire hose do not approach the low levels of the MDRA and therefore any predictions based on the MDRA will tend to overestimate the effects of friction reducing additives. Although little has so far been published on the Fire Department of New York trials, the implication of the data available is that friction factors for $1\frac{1}{2}$ inch rubber lined hose can be reduced to 0.002 or below.

The results reported in this note show that under the flow conditions reported, the friction factor of 70 mm non-percolating fire hose is reduced from 0.005 to 0.0027, a reduction of 46 per cent. Further tests are expected to show similar benefits for other hoses and improved injection techniques may well bring further improvement. Important limitations on the amount of benefit gained at very high flow rates have become apparent, but assuming that reductions of this order can be achieved with all hose and other types of pipe work used by Fire Brigades, some idea of the advantages of PEO, or similar substances, for practical fire-fighting use can be obtained.

Assuming that further friction reduction will be possible by the use of improved techniques, the following estimations are conservative.

In general, PEO will be of use in situations where the desired effect, usually the "throw" of a water jet or flow rate of water pumped, is limited by large pressure losses due to friction in the hose or pipe. Particular examples are the pumping of water through open ended hose or large bore monitor operation. Particular examples can now be given.

6.1 Water relaying

The Manual of Firemanship[7] gives values of the optimum distance over level ground for a pump working at a pressure of 100 lbf/in^2 and discharging 350 gpm. The optimum distances for water treated with PEO have been calculated and are shown for comparison below.

Hose arrangement	Pumping distance (ft)		Per cent increase in distance
	Plain water	PEO treated water	
Single $2\frac{3}{4}$ in non-percolating	350	650	86
Twin " " " "	1,400	2,600	86

It is therefore possible to pump PEO-treated water a given distance using only one pump where it would be necessary to use two pumps with plain water. Alternatively, it would have required a higher pump pressure of 185 lbf/in^2. Since pumping PEO solutions destroys the friction-reducing effect, it is not possible to use two pumps in relay with PEO-treated water unless more PEO is added after the second pump.

6.2 The Glasgow "Scoosher"

This appliance uses 2 inch copper pipe, 45 ft on the chassis and 37 ft on the boom, a total of 82 ft. The pump pressure is 100 lbf/in^2 and the water flow rate approximately 200 gpm. Copper pipe of plumbing quality is almost hydraulically "smooth" and therefore has a friction factor (f) of 0.0037 at this flow rate (see Fig. 3).

Using equation (3) the pressure drop due to friction is 32 lbf/in^2. If the boom is in the vertical position, there will be an additional pressure loss due to static head equal to 16 lbf/in^2. The total pressure drop is 48 lbf/in^2 and the nozzle pressure is therefore 52 lbf/in^2. If PEO were added to the water, the friction factor may be expected to fall at least to 0.002 and probably lower, resulting in a frictional pressure loss of 17 lbf/in^2, making a total loss of 33 lbf/in^2. The nozzle pressure, if pump pressure is maintained at 100 psig, would be 67 lbf/in^2 which is an increase of about 30 per cent.

6.3 Ejector pumps

The effect of PEO on the friction factor of 4 inch suction hose has not yet been determined. It is difficult, therefore, at this stage, to predict the effect of PEO or ejector pump performance when added either to the water to be removed and/or to the water supply from the primary pump.

If the suction lift is 20 ft and the barrier height is 5 ft then the total pressure drop to be overcome is about 9 lbf/in^2 over the suction height and 2 lbf/in^2 over the barrier[24]. If the pump is removing water at a rate of 100 gpm then assuming a friction factor of 0.02 for 4 inch suction hose with plain water, the pressure drop due to friction is about 0.3 lbf/in^2. This is not significant when compared with the pressure loss due to the head of water and no significant advantage could be gained by adding PEO to the water to be removed. The addition of PEO to the water supplied to the ejector pump by the primary pump may be advantageous if the primary pump has to be positioned some considerable distance from the ejector pump, in that a higher pressure and hence suction may be attained.

6.4 Fire nozzle performance

The vertical height reached by the main body of a fire fighting water jet was first measured by Freeman[29]. He expressed his results as

$$H = K\left[2.3\,P_N - 0.0072\,\frac{P_N^{\,2}}{d_N}\right] \qquad \ldots\ldots (8)$$

where H is the height of the jet in feet

P_N is the nozzle pressure in lb/in^2

d_N is the nozzle diameter in inches

K is a factor in the range 0.65 to 1.0 depending upon P_N

The formula given in the Manual of Firemanship[7] for calculating the height of fire fighting jets is identical to Freeman's but with a value of 0.67 for K. However, the data used in the following illustrations of the effects of friction reducing additives on nozzle and pump pressures, height and range of jets is based on the work of Blair[30]. Blair measured both the height and range of jets and his results are shown in graphical form. This data has been used because it appears to be the only relatively recent measurements of both height and range using nozzles similar to those in current use in the Fire Service. Blair's results for a one inch diameter nozzle correspond to a value of 0.85 for K in Freeman's formula. The illustrative data is shown in Figs 9, 10 and 11, for 1, 1½ and 2 inch diameter nozzles respectively. The effect is shown of 70 mm non-percolating hose in lengths of between 200 and 1000 ft at pump pressures up to 200 lbf/in^2 on nozzle pressure, discharge rate, height and range of jets, for both plain water and water treated with 30 ppm of PEO. Constant value for friction factor for the hose of 0.005 and 0.0027 for plain and treated water respectively have been used in the calculations. Superimposed on the figures is a discharge rate v. outlet pressure operating line for a typical centrifugal fire pump at full throttle setting.

For example, in Fig. 9 , it is seen that a pump operating at 150 lbf/in^2 can pump 190 gal/min of plain water through 1000 ft of 70 mm hose ending in a one inch nozzle. The nozzle pressure would be 58 lb/in^2. The height of a vertical jet would be 92 feet and the maximum range 112 feet. With 30 ppm PEO in the water the flow rate would rise to 218 gal/min, the nozzle pressure would increase to 75 lb/in^2. The height of a vertical jet would increase by 20 feet to 112 feet (equivalent to increase in reach of two storeys). The maximum range of a jet would increase by 16 feet to 138 feet. The pump pressure would decrease by 10 lb/in^2 to 140 lb/in^2. If the pump had not been operating at full throttle, this could have been increased to restore the pump pressure to 150 lb/in^2; the discharge rate, nozzle pressure, jet height and maximum range would have then increased further. Further examples can be worked out in a similar manner using Figs 9, 10 and 11.

7. RECOMMENDATIONS

In view of the results obtained in these preliminary experiments, the following items need further investigation.

1) Measurement of friction factor for 70 mm non-percolating fire hose beyond the range of Reynolds numbers so far encountered, i.e. down to 10^4 and up to 10^6.
2) Further measurements of friction factor with 19 mm hose-reel hose.
3) Measurement of friction factor for other types of hose, e.g. unlined hose, suction hose, 45 mm ($1\frac{3}{4}$ inch) and 85 mm ($3\frac{1}{2}$ inch) hose.
4) The effect of method of introduction of the concentrated PEO solution into fire hose, i.e. whether at hose axis or at the walls and the determination of the length of hose required for complete mixing of the PEO solution with the water.
5) The effect of PEO on the production of sprays and fogs from jet/spray branches and fog nozzles.
6) The effect of PEO on the coherence of water jets.
7) The effectof hose length on the performance of PEO, i.e. polymer degradation during turbulent flow in the hose.
8) The development of a system for introducing PEO into fire hose on the fire ground.
9) Alternative friction-reducing additives.

8. ACKNOWLEDGMENT

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APPENDIX 1

FRICTION FACTOR CORRELATIONS

A1.1 Correlations for plain fluids

A1.1.1 Smooth pipes

The turbulent portion of the velocity profile in smooth pipe flow is described by part of the Universal Velocity Profile:

$$\frac{u}{u_*} = 5.75 \log \frac{y u_* \rho}{\mu} + 5.5 \qquad \ldots\ldots (9)$$

For fully developed turbulent flow, it is known[8] that

$$u_{max} = \bar{u} + 4.07\, u_* \qquad \ldots\ldots (10)$$

Therefore evaluating the universal velocity profile at the centre line where $y = {}^{d}/2$, $u = u_{max}$, yields the well known Prandtl-Karman law

$$\frac{1}{\sqrt{f}} = 4 \log Re\sqrt{f} - 0.4 \qquad \ldots\ldots (11)$$

A1.1.2 Rough pipes

For flow in rough pipes the right hand side of equation (9) above is abated by a roughness function F_N , i.e.

$$\frac{u}{u_*} = 5.75 \log \frac{y . u_* \rho}{\mu} + 5.5 - F_N \qquad \ldots\ldots (12)$$

so that the Prandtl-Karman law becomes

$$\frac{1}{\sqrt{f}} = 4 \log Re\sqrt{f} - 0.4 - \frac{F_N}{\sqrt{2}} \qquad \ldots\ldots (13)$$

It is known[8] that F_N is a function of the dimensionless roughness height (e^*) where

$$e^* = \frac{e u_* \rho}{\mu} = Re\sqrt{f} . {}^{e}/_{d} \qquad \ldots\ldots (14)$$

A1.2 Correlations for drag reducing solutions

A1.2.1 Smooth pipes

Modifications to the smooth pipe universal velocity profile for the turbulent flow of dilute solutions of drag reducing substances have been made by Elata et al[10] and Meyer[11]. Elata's correlation, using the visco-elasticity hypothesis is

$$\frac{u}{u_*} = 5.75 \log \frac{y . u_* \rho}{\mu} + 5.5 + \alpha_1 \log \left(\frac{u_*^2 t_1 \rho}{\mu} \right) \quad \ldots\ldots (15)$$

The group $\left(\frac{u_*^2 t_1 \rho}{\mu} \right)$ is called the Deborah number (De) (relaxation time/flow time ratio). Other forms of this Deborah number have been proposed, i.e. Rodriguez et al[12] $De = u t_1 d^{-0.2}$ and Sayer and Metzner[13] $De = u . t \, Re^{0.75}/d$. The various forms of the Deborah number have been discussed by Gordon[13A] who points out that the best form of De is not yet at all clear. Meyer's modification of the universal velocity profile based on velocity profiles measurements, which indicate a thickening of the laminar sub-layer, is

$$\frac{u}{u_*} = 5.75 \log \frac{y . u_* \rho}{\mu} + 5.5 + \alpha_2 \log \frac{u_*}{(u_*)_0} \quad \ldots\ldots (16)$$

A1.2.2 Rough pipes

Spangler[14], using Meyer's velocity distribution, gives the following correlation

$$\frac{u}{u_*} = 5.75 \log . \frac{y . u_* \rho}{\mu} + 5.5 + \alpha_2 \log \frac{u_*}{(u_*)_0} - F \quad \ldots\ldots (17)$$

where F is an abatement due to roughness of the pipe. The magnitude of F was found by Spangler to be greater than F_N, the Newtonian roughness factor.

The above expression gives

$$\frac{1}{\sqrt{f}} = \left(4 + \frac{\alpha_2}{\sqrt{2}} \right) \log Re \sqrt{f} - 0.4 - \frac{\alpha_2}{\sqrt{2}} \log \left(\frac{\sqrt{2} . d . (u_*)_0 \rho}{\mu} \right) \quad \ldots\ldots (18)$$

This can be written more simply

$$\frac{1}{\sqrt{f}} = 4 \log Re\sqrt{f} - 0.4 - \frac{\Delta_M}{\sqrt{2}} \qquad \text{..... (19)}$$

where Δm is the combined effect, according to Meyer's velocity profile, of the pipe roughness and the drag reducing additive,

i.e. $$\Delta m = F - \alpha_2 \log \frac{u_*}{(u_*)_o} \qquad \text{..... (20)}$$

A similar treatment of Elata's wall profile correlation can be made, in which case

$$\frac{u}{u_*} = 5.75 \log \frac{y u_* \rho}{\mu} + 5.5 + \alpha_1 \log De - F \qquad \text{..... (21)}$$

$$\therefore \frac{1}{\sqrt{f}} = 4 \log Re\sqrt{f} - 0.4 - \frac{\Delta_E}{\sqrt{2}} \qquad \text{..... (22)}$$

where $$\Delta_E = F - \alpha_1 \log De \qquad \text{..... (23)}$$

The following approximate expression for relaxation time has been given[15]

$$t_1 \simeq \frac{\mu}{\tau_o} \qquad \text{..... (24)}$$

Therefore Elata's Deborah number can be written

$$D = \frac{u_*^2 \rho}{\tau}$$ but by definition $$u_* = \sqrt{\frac{\tau}{\rho}}$$

Therefore $$De = \frac{\tau}{\tau_o}$$

Mayer's quantity $\frac{u_*}{(u_*)_o}$ can also be written $\sqrt{\frac{\tau}{\tau_o}}$

Δm and Δ_E can now be written

$$\Delta m = F - \frac{\alpha_2}{\sqrt{2}} \log \left(\frac{\tau}{\tau_o}\right) \qquad \text{..... (25)}$$

$$\Delta_E = F - \alpha_1 \log \left(\frac{\tau}{\tau_o}\right) \qquad \text{..... (26)}$$

and the two correlations, (a) Spangler via Meyer and (b) a modification of Elata, are therefore substantially identical and can be written

$$\frac{1}{\sqrt{f}} = 4 \log Re\sqrt{f} - 0.4 - \frac{\Delta}{\sqrt{2}} \qquad \text{..... (27)}$$

where

$$\Delta = F - \alpha' \log\left(\frac{\tau}{\tau_0}\right) \qquad \text{..... (28)}$$

APPENDIX 2

<u>To make up 5 gal of 0.2 per cent w/w PEO solution</u>

1) Weigh out 45.5 gms PEO powder

2) Place in 500 ml beaker, add 300 ml iso-propyl alcohol* and stir for approx. 1 minute, or until a homogeneous suspension is obtained.

3) Pour the suspension into a suitable vessel containing 6 pints of tap water, while stirring vigorously.

4) Make up to 1 gal with tap water to form a 1.0 per cent solution.

5) Leave 24 hours before making up to 5 gal with tap water to form a 0.2 per cent solution.

*Other water miscible solvents may be used, e.g. methyl alcohol, ethylene glycol and propylene glycol.

APPENDIX 3

Estimate of annual usage of PEO

The annual consumption of water for fire fighting operations (excluding sprinkler systems and portable fire extinguishers) is unknown. An order of magnitude figure can, however, be obtained. Fry and Lustig[22] give percentage frequencies of usage of different quantities of water on all fires (other than chimneys, grassland, heath and railway embankments) based on data from eleven brigades. Taken in conjunction with a total number of such fires of the order of 2×10^5 (1969 figures) this yields a total consumption of 160×10^6 gal. Allowing for practice and the activities of industrial and airport brigades, the annual consumption is likely to be of the order of 250×10^6 gal/year. At a concentration of 30 ppm this would require about 40 tons/year of PEO plus suitable dispersant chemicals. Since PEO would not be used at all fires, this would appear to be the maximum quantity required, even allowing for some wastage.

Table 1

Summary of previous work with rough pipes
(for graphical summary of results - see Figs 6 and 7)

Worker	Ref.	Tube diameter (mm)	Polymers	Tube roughness details
White	(16)	19	PEO*	Threaded : $\frac{5}{8}$ in. Whitworth form $^e/d$ = 0.09 nominal = 0.04 "equivalent tube roughness"
Spangler	(14)	12.5	Acrylamide/Acrylic acid co-polymer	Threaded $^e/d$ = 0.01 "equivalent tube roughness"
Virk	(17)	8.6	PEO* Other polyethylene oxides Polyacrylamide	Lined with waterproof abrasive paper $^e/d$ = 0.0143, 0.0219, 0.0342 "equivalent sand roughness"

* Note: PEO is WSR 301 grade

Table 2

Results for 75.3 m (247 ft) length of 70 mm ($2\frac{3}{4}$ in) non-percolating hose using plain water

Run No.	Pressure drop Δ P		Flow rate Q	
	lbf/in^2	kN/m^2	gal/min	dm^3/min
1	11	75.8	144	656.2
2	30	206.8	212	964.5
3	38	262	274	1,247
4	28	193.1	222	1,010
5	53	365.4	288	1,310
6	58	399.9	349	1,588
7	48	331	313	1,424
8	33	227.5	225	1,023
9	18	124.1	174	791.6
10	48	331	284	1,292
11	60	413.7	324	1,474
12	73	503.3	338	1,538
13	15	103.4	169	769
14	14	96.5	149	677.9
15	20	137.9	179	814.5
16	16	110.3	179	814.5
17	14	96.5	139	632.4
18	10	69	129	586.9
19	9	62.1	124	564.1
20	8	55.2	104	473.2
21	7	48.3	104	473.2
22	6.5	44.8	99.6	453.2
23	5.5	37.9	89.6	407.7
24	3	20.7	69.6	316.6
25	10	69	125	568.7
26	9	62.1	114	518.7
27	6	41.4	89.5	407.1
28	5	34.5	92.4	420.5
29	5	34.5	84.8	385.9
30	4	27.6	74.8	340.3

Table 3

Results for 16.5 m (54 ft) length of 19 mm ($\frac{3}{4}$ in) hose-reel hose using plain water

Run No.	Pressure drop Δ P		Flow rate	
	lbf/in^2	kN/m^2	gal/min	dm^3/min
1	45	310.3	20.6	93.7
2	33	227.5	16.9	76.9
3	28	193.1	14.6	66.4
4	39	268.9	18.9	86
5	27	186.2	15.4	70.1
6	25	172.4	13.7	62.3
7	27	186.2	14.3	65.1
8	10.5	72.4	9.6	43.7
9	9	62.1	8.7	39.6
10	20.5	141.3	13.1	59.6
11	24.5	163.9	14.5	66
12	16.5	113.8	12.1	55.1
13	24.0	165.5	14.9	67.8
14	21.0	144.8	13.5	61.4
15	17.5	120.7	11.8	53.7
16	23.0	158.6	14.5	66
17	19.5	134.5	13.7	62.3
18	17.0	117.2	12.0	54.6

Table 4

Results for 75.3 m (247 ft) length of 70 mm ($2\frac{3}{4}$ in) non-percolating hose using solution of PEO and injection technique

Run No.	PEO concentration (ppm)	Pressure drop Δ P		Flow rate	
		lbf/in^2	kN/m^2	gal/min	dm^3/min
1	10.4	36	248.2	339	1,543
2	19.4	24	165.5	269	1,224
3	17.6	36	248.2	295	1,342
4	23.7	31	213.7	284	1,292
5	10.7	49	337.8	354	1,611
6	23.4	36	248.2	314	1,429
7	12.4	30	206.8	280	1,275
8	20.0	21	144.8	264	1,201
9	12.8	39	268.9	314	1,429
10	11.4	28	193.1	280	1,275
11	15.8	16	110.3	214	973.6
12	17.8	19	131	244	1,110
13	10.2	14	96.5	199	905.5
14	40.8	8	55.2	169	769
15	32.0	6	41.4	129	568.9
16	15.8	36	248.2	314	1,429
17	15.1	25	172.4	269	1,224
18	14.8	43	296.5	338	1,538
19	17.2	32	220.6	299	1,360
20	12.6	21	144.8	244	1,110
21	16.4	30	206.8	295	1,342
22	20.0	13	89.6	203	923.7
23	26.1	12	82.7	189	860
24	21.6	9	62.1	160	728
25	19.3	27	186.2	290	1,319
26	21.5	30	206.8	280	1,275
27	31.6	31	213.7	298	1,356
28	30.8	31	213.7	298	1,356
29	21.8	28	193.1	288	1,310
30	18.5	32	220.6	288	1,310
31	26.4	12	82.7	204	928.1
32	10.7	15.5	106.9	212	964.5
33	27.2	12	82.7	204	928.1
34	30.4	13.5	90.1	204	928.1
35	26.8	12.5	86.2	204	928.1
36	29.6	9.5	65.5	159	723.5
37	36.1	9.5	65.5	159	723.5
38	45.9	9.5	65.5	159	723.5
39	45.0	10	69	159	723.5
40	36.9	11.0	75.8	179	814.5
41	21.4	13.0	89.6	174	791.6
42	56.9	11.5	79.3	174	791.6

Table 5

Results for 16.5 m (54 ft) length of 19 mm ($\frac{3}{4}$ in) hose-reel hose using solution of PEO and injection technique

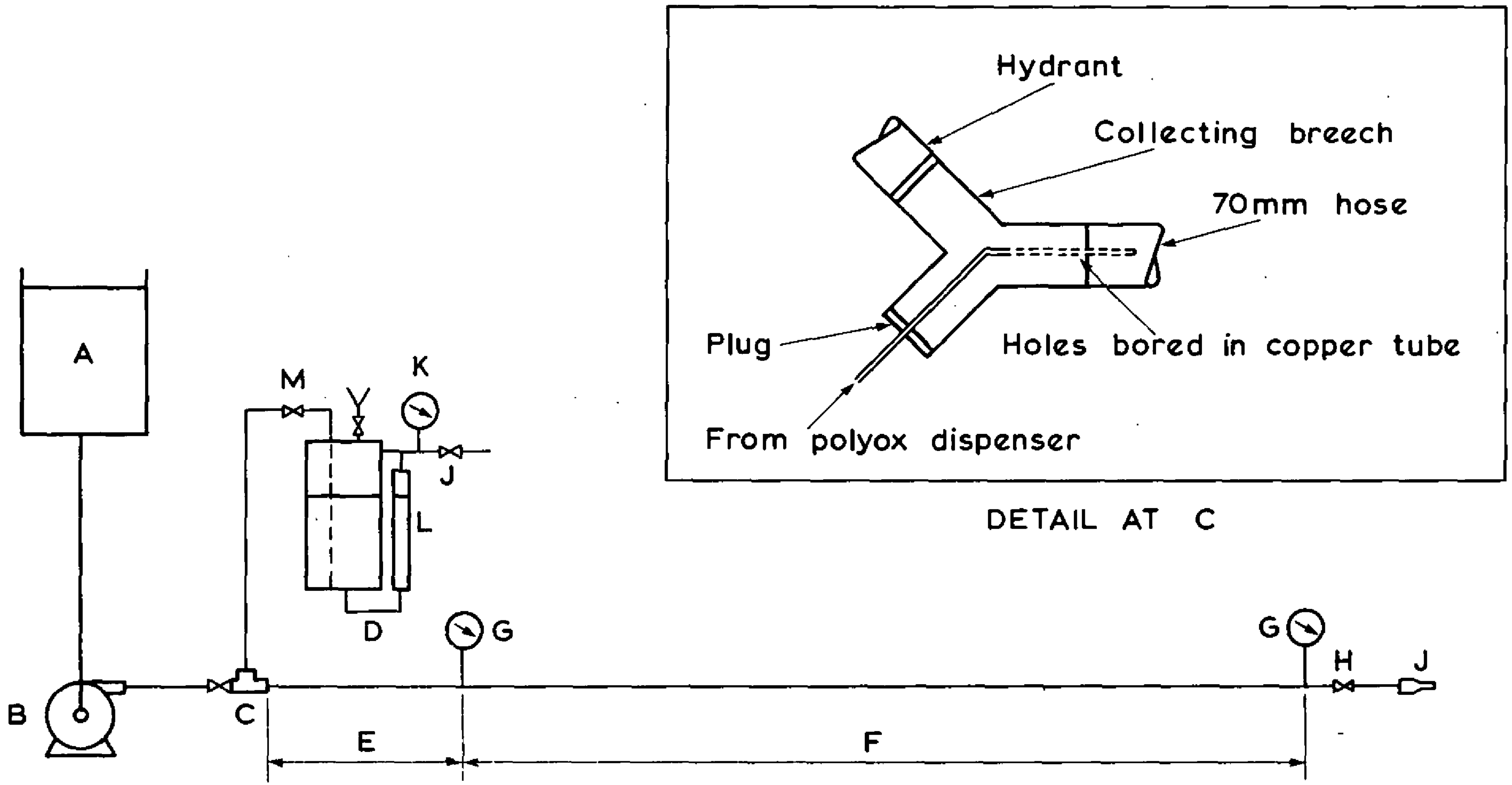
Run No.	PEO concentration (ppm)	Pressure drop Δ P		Flow rate Q	
		lbf/in^2	kN/m^2	gpm	dm^3/min
1	44.7	8	55.2	12.2	55.5
2	46.6	10	69	12.2	55.5
3	61.5	9.5	65.5	11.8	53.7
4	59.6	7.5	51.7	10.0	45.5
5	30.8	6.5	44.8	10.4	47.3
6	34.8	8.5	58.6	11.6	52.8
7	34.6	8.5	58.6	10.8	49.1
8	34	5.0	34.5	9.8	44.6
9	19.7	8.5	58.6	12.4	56.4
10	14.1	10	69	12	54.6
11	10.4	11	75.8	12.9	58.7
12	24.9	10.5	72.4	12.7	57.8
13	19.5	11	75.8	13.9	63.2
14	30.9	11	75.8	12.9	58.7
15	24.8	11.5	79.3	12.4	56.4
16	17.8	12	82.7	13.1	59.6
17	29.4	10	69	11.8	53.7
18	52.2	10.5	72.4	12.2	55.5
19	44	9.5	65.5	1.2	54.6
20	26	7.5	51.7	11.2	51
21	30.9	9.0	62.1	11.2	51

Table 6

Results for 75.3 m (247 ft) length of 70 mm ($2\frac{3}{4}$ in) non-percolating hose using solution of PEO and pumping technique

Run No.	PEO concentration (ppm)	Pressure drop Δ P		Flow rate Q	
		lbf/in^2	kN/m^2	gpm	dm^3/min
1	30	34	234.4	242	1,101
2	"	40	275.8	262	1,192
3	"	37	255.1	282	1,283
4	"	34	234.4	224	1,019
5	"	34	234.4	224	1,019
6	"	27	186.2	200	909.9
7	"	34	234.4	243	1,106
8	"	39	268.9	264	1,201
9	"	24	165.5	199	905.5
10	"	32	220.6	234	1,064
11*	"	10	69	113.5	516.4

*In run No-11, the premixed solution of Polyox was recirculated through the pump for 10 minutes before pumping through the hose.



NOT TO SCALE

FIG. 1 DIAGRAM OF EXPERIMENTAL RIG

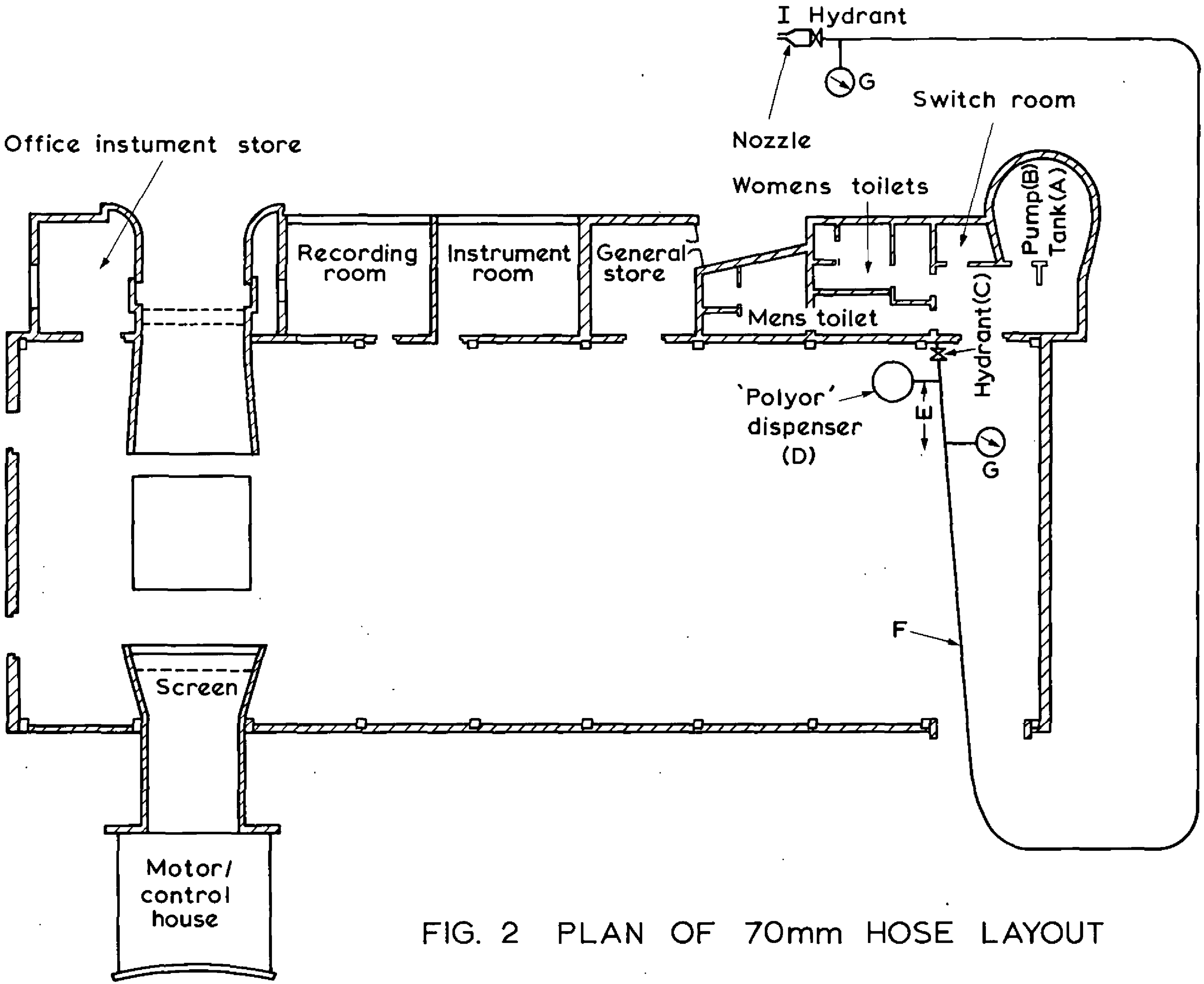


FIG. 2 PLAN OF 70mm HOSE LAYOUT

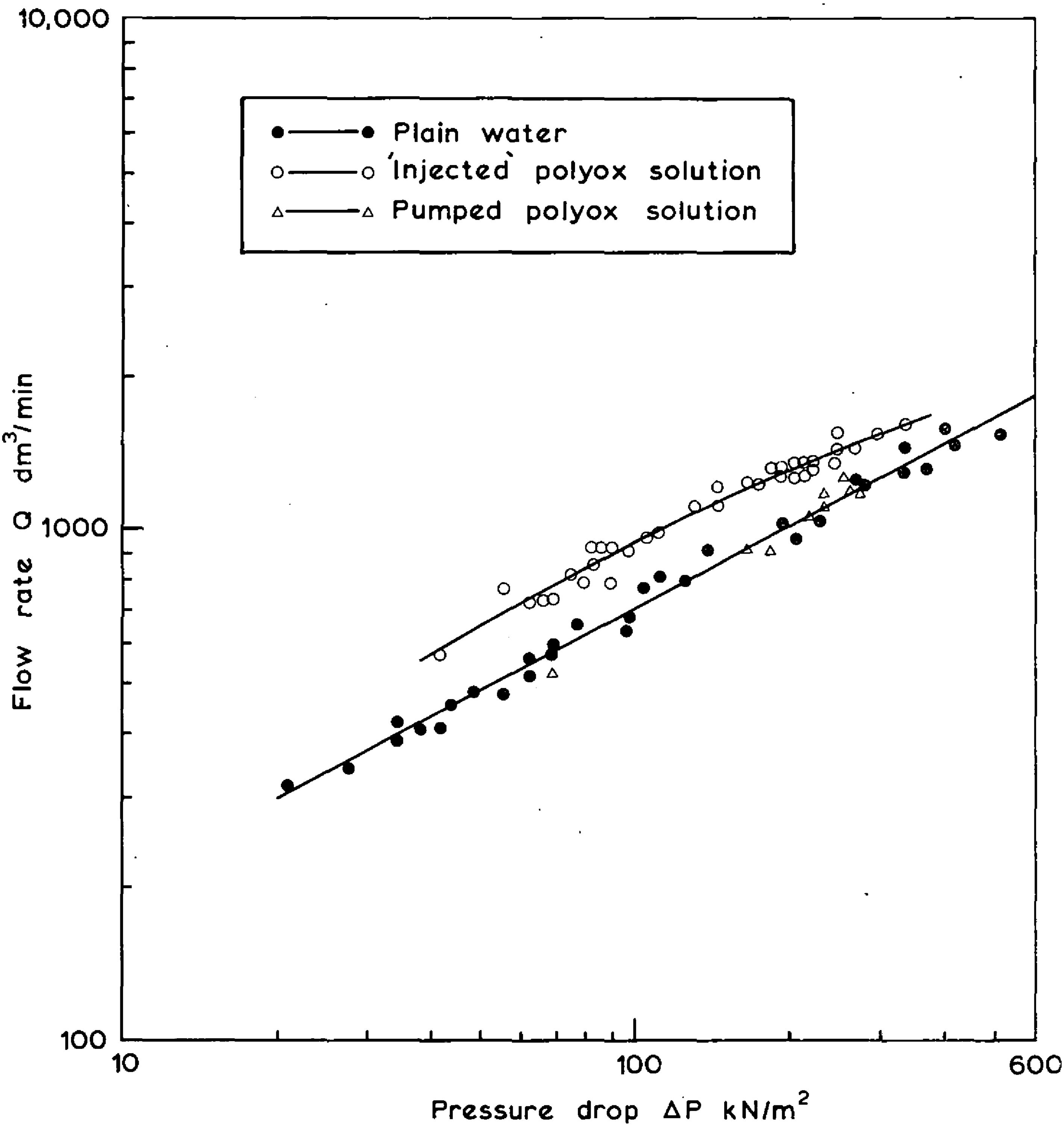


FIG. 3 RESULTS FOR 70mm (2 3/4") HOSE

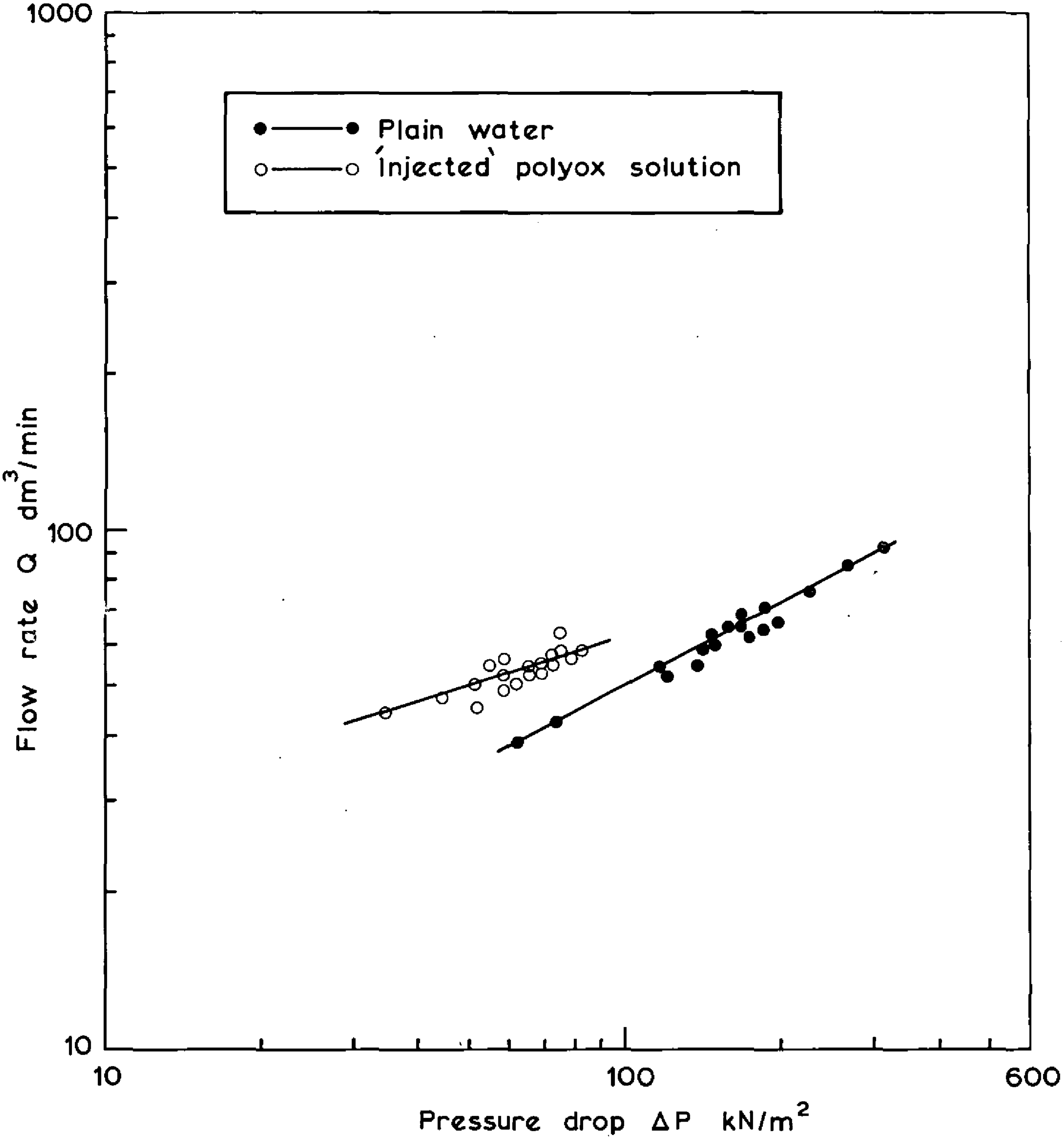


FIG. 4 RESULTS FOR 19mm ($^3/_4$") HOSE

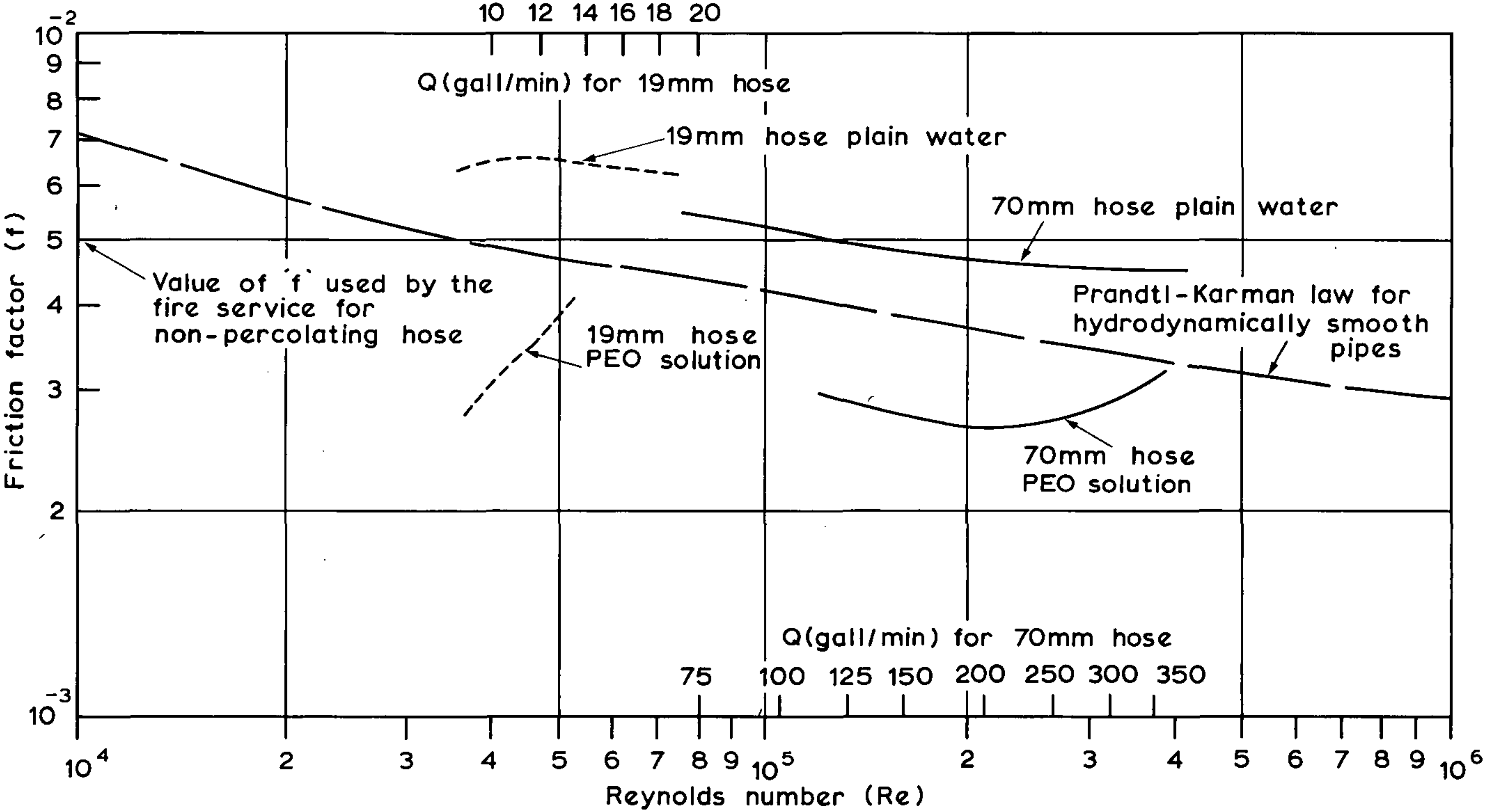
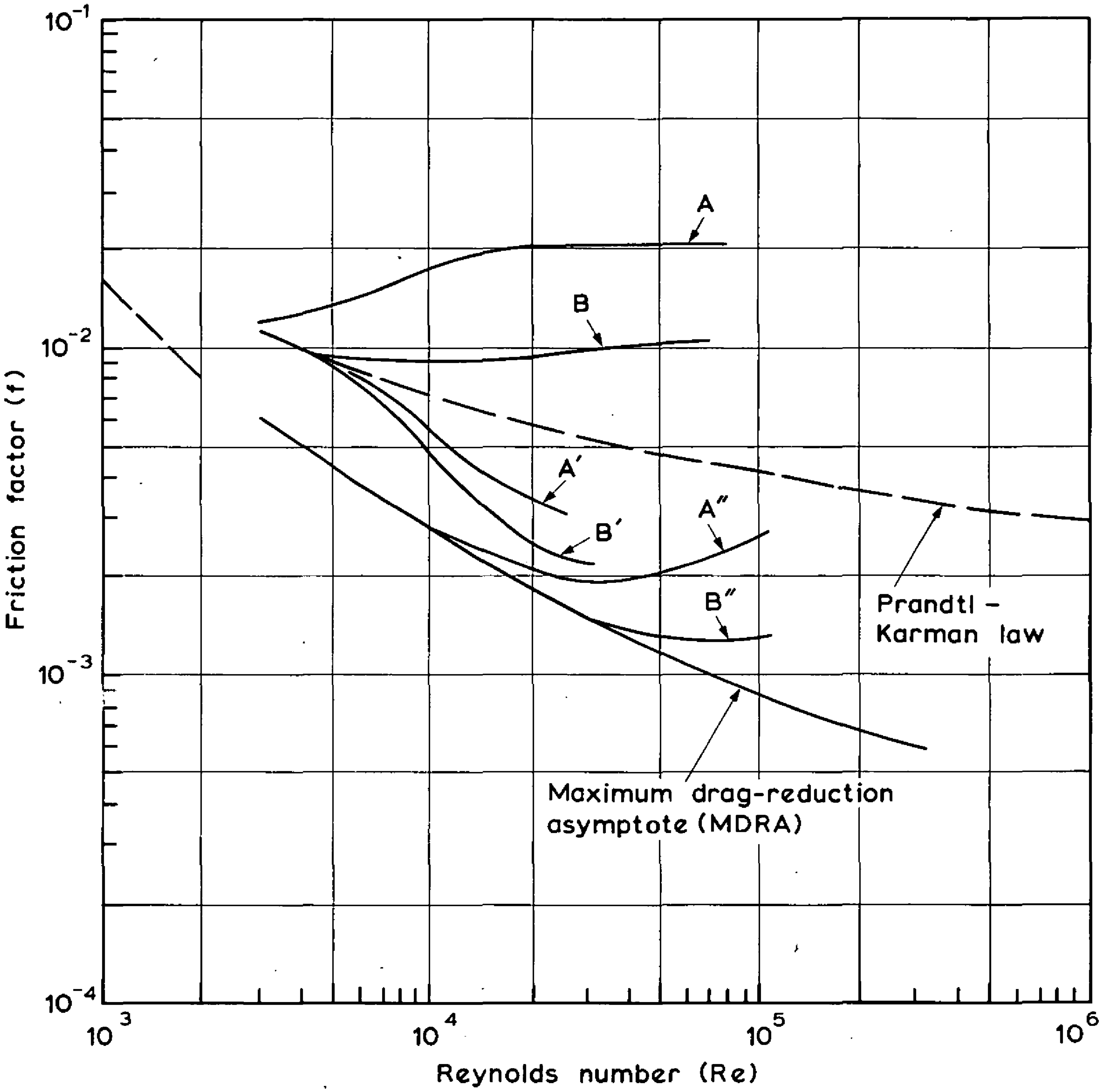
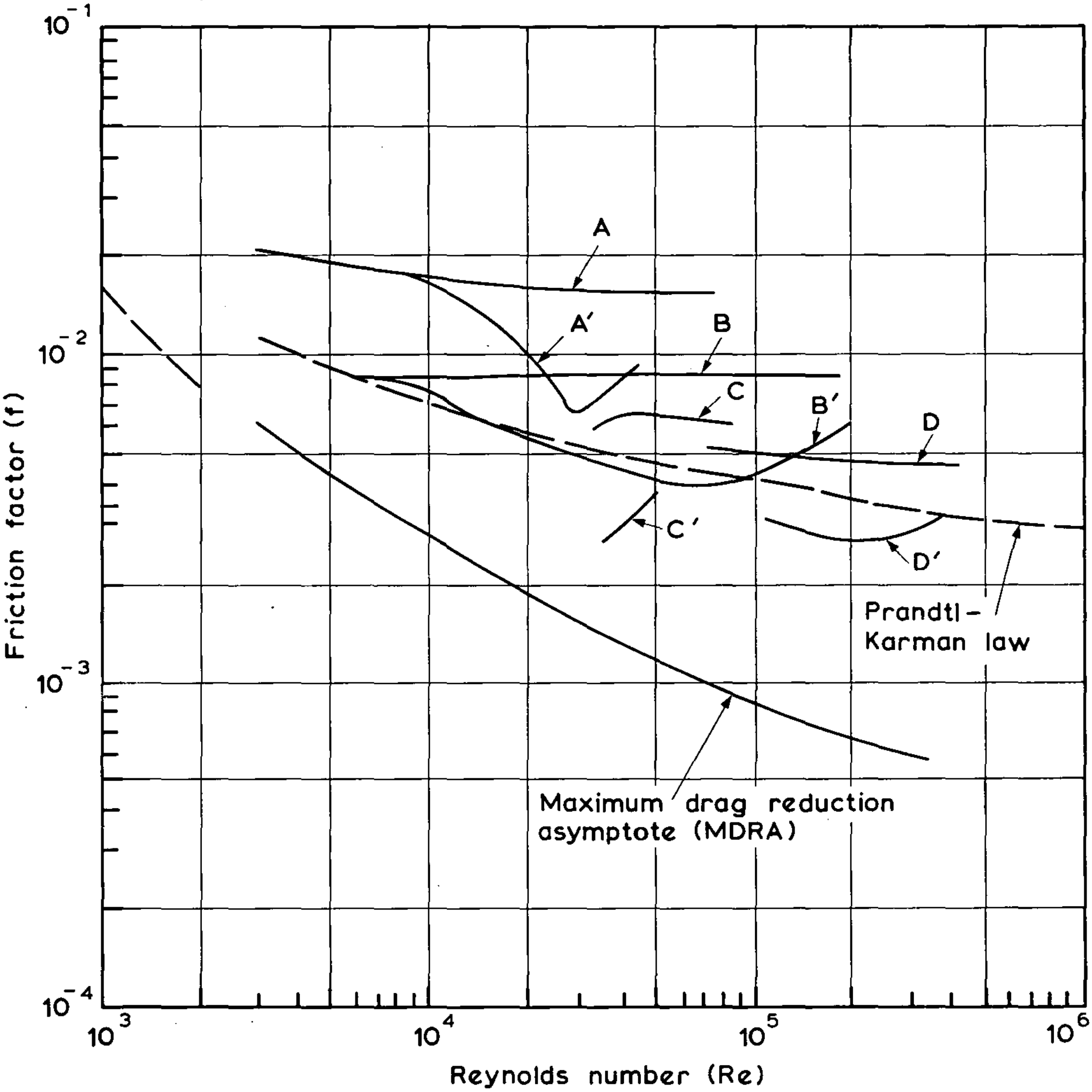


FIG. 5 FRICTION FACTOR (f) FOR 70mm (2¾") AND 19mm (¾") HOSE WITH PLAIN WATER AND 'INJECTED' PEO SOLUTIONS



Curve	e/d	Fluid
A	0·034	Water
B	0·014	
A′	0·034	Dilute PEO
B′	0·014	
A″	0·034	Other dilute polymers
B″	0·014	

FIG. 6 RESULTS OF VIRK (17) FOR ROUGH PIPES



A A′	Water Polymer	White
B B′	Water Polymer	Spangler
C C′	Water Peo	This work 19mm hose
D D′	Water Peo	This work 70mm hose

FIG. 7 RESULTS OF WHITE (16) AND SPANGLER (14) AND FROM PRESENT INVESTIGATION

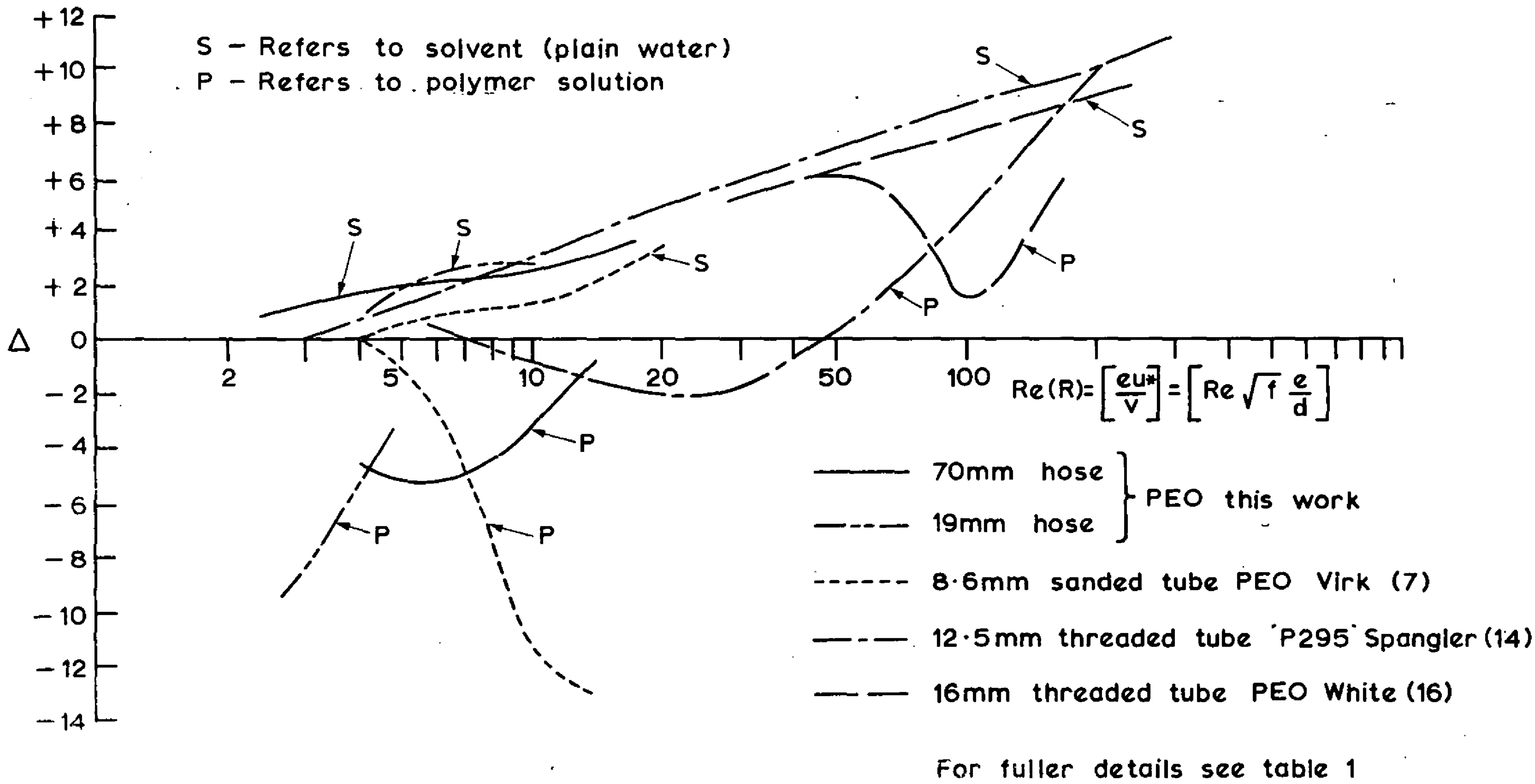


FIG. 8 THE FUNCTION Δ FOR SOLVENT AND POLYMER SOLUTIONS IN ROUGH PIPES

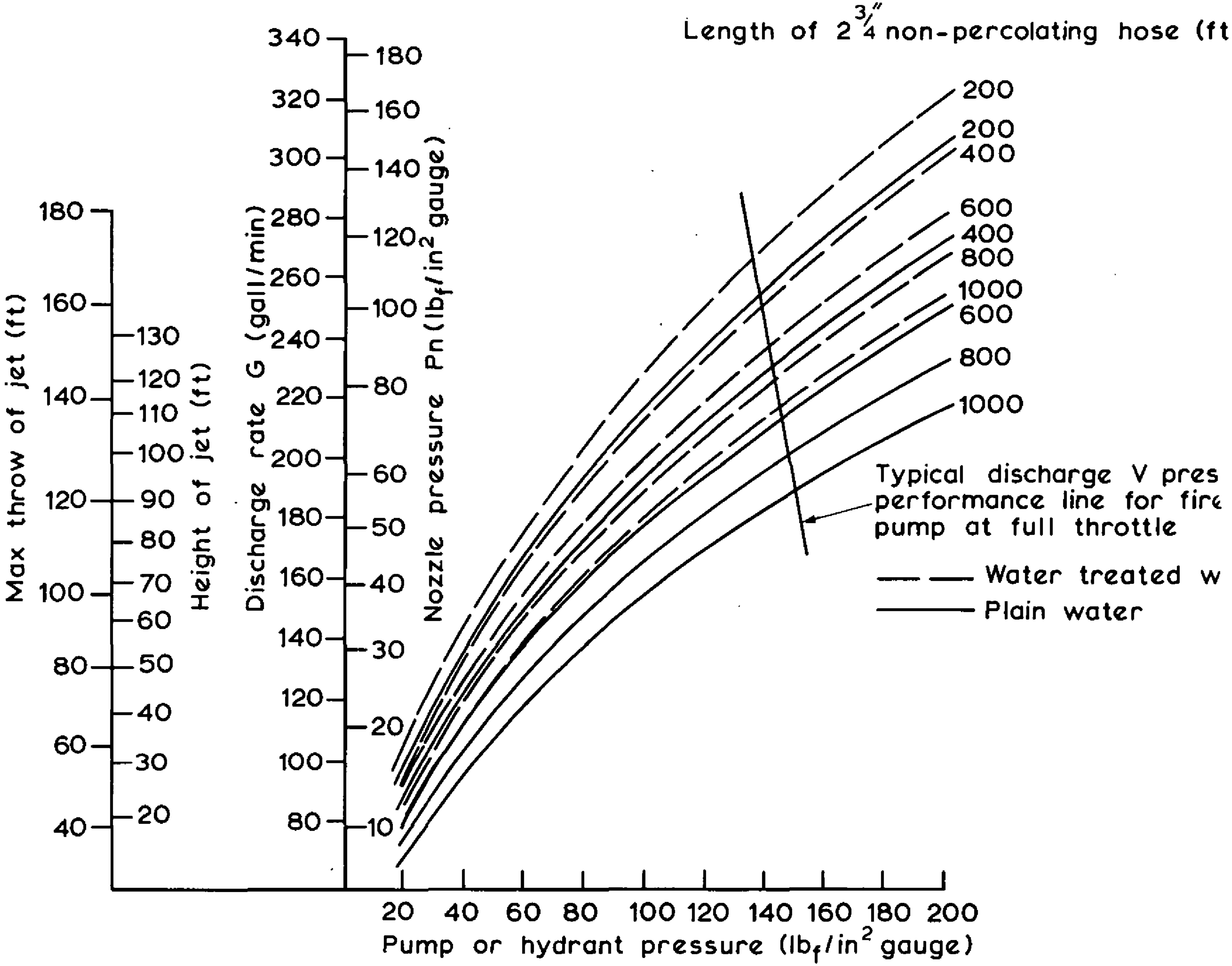


FIG. 9 HEIGHT AND THROW OF JETS; DISCHARGE RATE AND NOZZLE FOR DIFFERENT HOSE LENGTHS AND PUMP PRESSURES WITH AND WATER TREATED WITH 30ppm PEO. NOZZLE DIAMETER

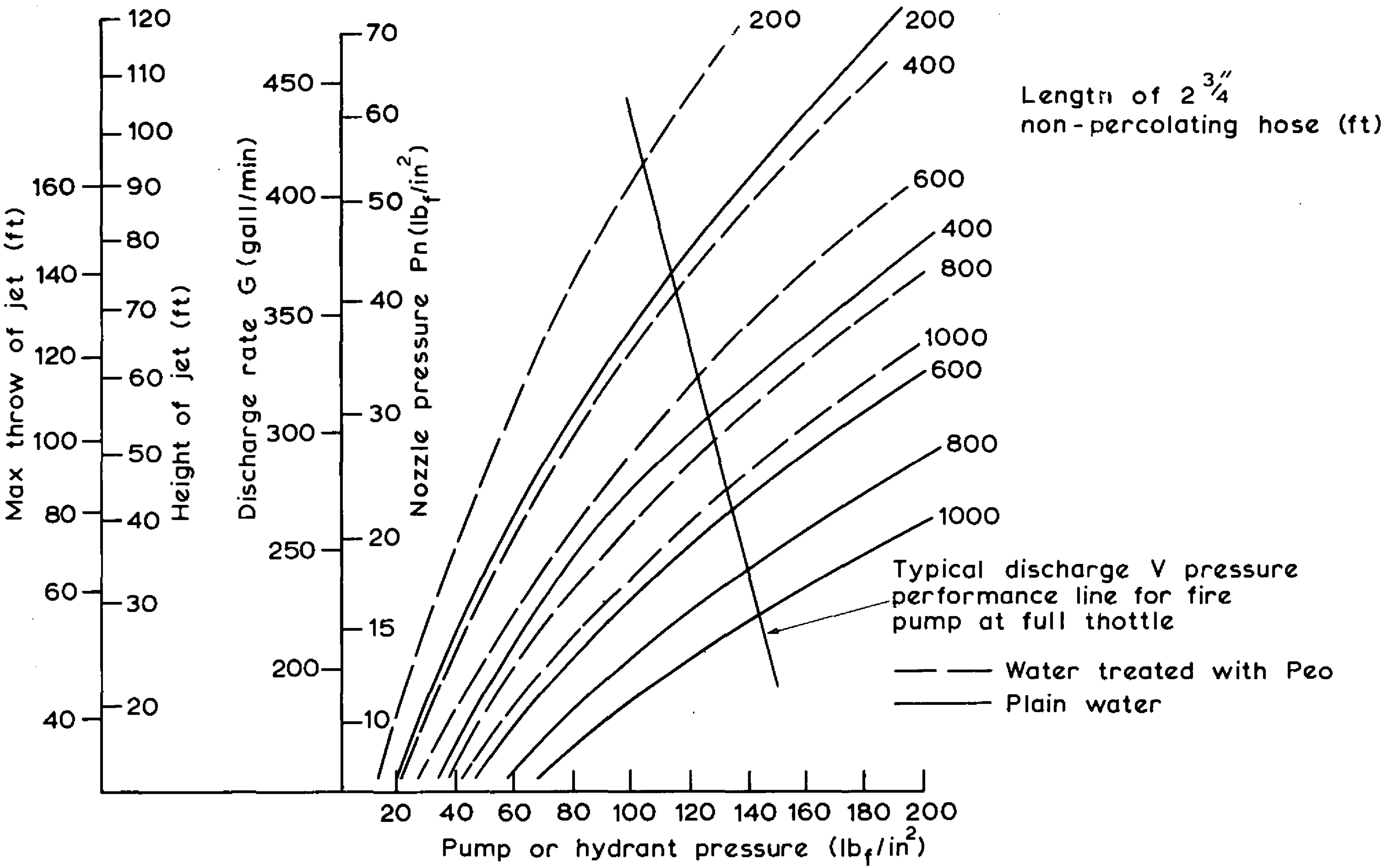


FIG. 10 HEIGHT AND THROW OF JETS; DISCHARGE RATE AND NOZZLE PRESSURE FOR DIFFERENT HOSE LENGTHS AND PUMP PRESSURES WITH PLAIN WATER AND WATER TREATED WITH 30ppm PEO. NOZZLE DIAMETER $1\frac{1}{2}''$

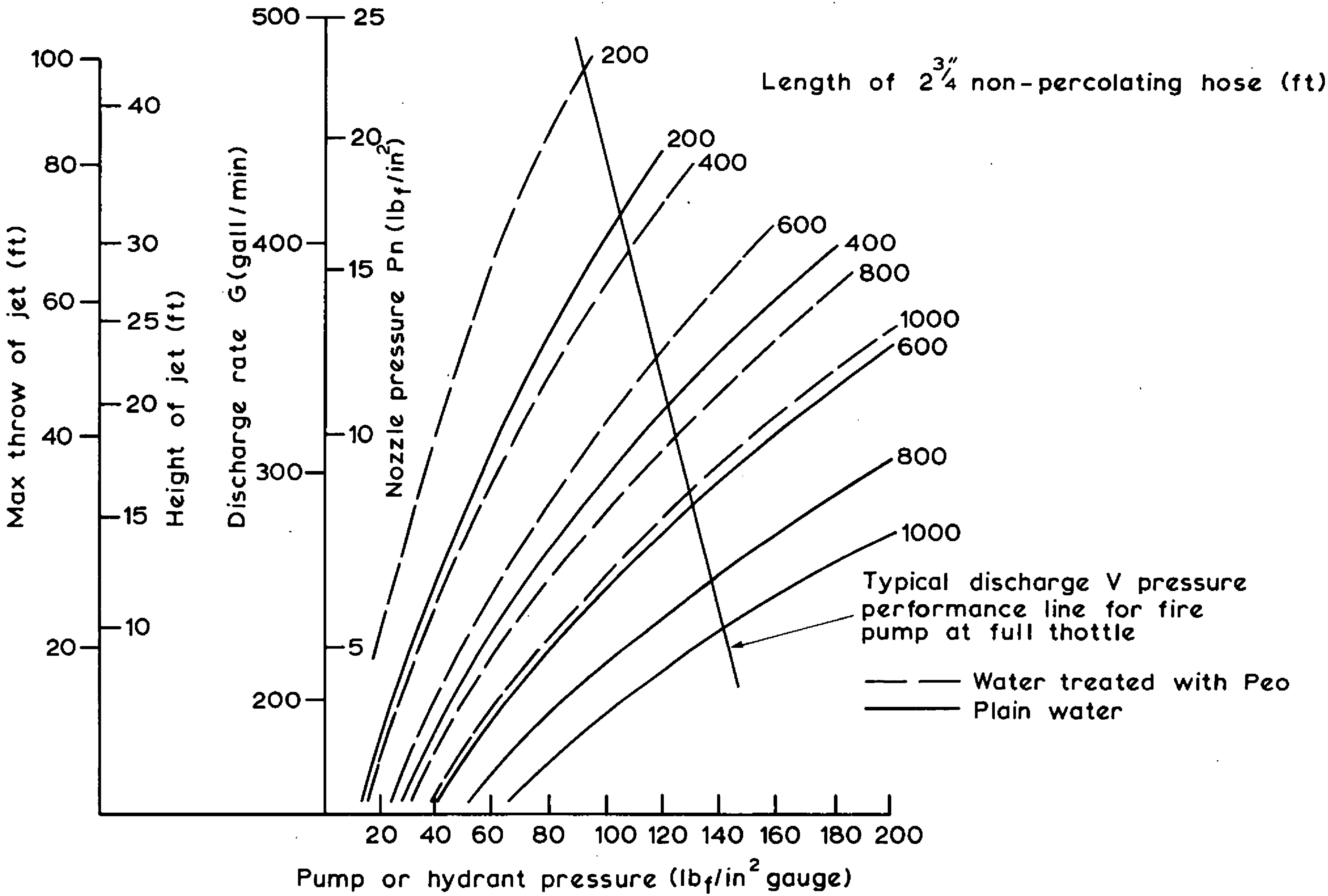


FIG. 11 HEIGHT AND THROW OF JETS; DISCHARGE RATE AND NOZZLE PRESSURE FOR DIFFERENT HOSE LENGTHS AND PUMP PRESSURES WITH PLAIN WATER AND WATER TREATED WITH 30ppm PEO. NOZZLE DIAMETER 2"