1-31-1970

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Recommended Citation

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FLUID FRICTION REDUCTION BY WATER SOLUBLE LINEAR HIGH POLYMERS

BY

ARTHUR EDWARD DAVIS

A THESIS
PRESENTED IN PARTIAL FULFILLMENT OF
THE REQUIREMENTS FOR THE DEGREE
OF
MASTER OF SCIENCE IN CHEMICAL ENGINEERING
AT
NEWARK COLLEGE OF ENGINEERING

NEWARK, NEW JERSEY

1969

ABSTRACT

The effects of various dilute aqueous linear high polymer solutions on turbulent pipe flow were studied to determine the polymer most suitable for testing as the drag reducing component in the proposed coating. Results of this study are presented for commercial schedule 40 $\frac{1}{4}$ inch NPS black iron pipe. Tests were conducted at Reynolds numbers of 6.2×10^4, 8.3×10^4 and 9.8×10^4.

Attempts were made to prepare a coating containing a friction drag reducing polymer - Polyhall 295 polyacrylamide - utilizing various techniques of polymer incorporation into the paint including several grinding and dispersion methods, adding the polymer in a water in oil emulsion to a finished paint and adding the polymer in solution to a finished paint.

Pipes were flow coated to a dry film thickness of two to three mils with coatings representative of each type of incorporation method. The unmodified paints were composed of resins and pigmentations of which some components had a certain degree of water solubility to aid the leaching of the Polyhall 295 into the water.

Results of these tests showed negative results insofar as the dispersions produced were very coarse and the resultant films increased the friction loss in the pipes while the solution and emulsion techniques allowed only a

very small amount of the polymer to be added to the coating and resulted in no effect on the frictional resistance at all.

One apparently successful trial of a coating containing ten percent Polyhall 295 could not be duplicated.

APPROVAL OF THESIS

FLUID FRICTION REDUCTION BY WATER SOLUBLE LINEAR HIGH POLYMERS

BY

ARTHUR EDWARD DAVIS

FOR

DEPARTMENT OF CHEMICAL ENGINEERING

NEWARK COLLEGE OF ENGINEERING

BY

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NEWARK, NEW JERSEY

JANUARY, 1970

PREFACE

The experimental equipment utilized for this work was purchased by and constructed with funds, materials and labor supplied by Celanese Coatings Company. The guidance of Dr. Jerome Salamone in the design of the test equipment is gratefully acknowledged.

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INTRODUCTION

In the past decade much work has been published concerning drag reduction in the turbulent flow of dilute linear high polymer solutions in both pipe flow (internal flow) and flat plate (external flow) studies. It has been sufficiently demonstrated that the polymer additive need only be present at the wall to obtain drag reduction-e.g., Wells (Ref.1.). Any polymer in solution present outside the boundary layer contributes only to maintaining concentration constant throughout the system (internal flow) and is largely wasted in both pipe and plate flow regimes.

Techniques for injection of the polymer in solution into external flow systems have been studied by Wells, Wu and Kowalski (Ref. 1,2,3) with the conclusions that injection nearly tangential to the wall is the most efficient and economical method and that injection which would simulate a permeable wall approaches the optimum. Results of field tests of injection methods applied to ships for reducing hull drag as well as injection into sewer lines have been reported which were quite remarkable. (Ref.4.)

Because of the economics involved in the utilization of injection methods due to inefficient use of the polymer and the amounts required to obtain a substantial decrease in fluid friction, there appears to be sufficient need for making a coating containing these friction reducing polymers that could be applied to the internal walls of pipelines or the underwater exterior hulls of surface ships, submarines,torpedoes and the like which would allow the polymer to leach into the surroundings at a controlled rate thus affording the maximum of effeciency and effectiveness. Following is a description of the work performed to obtain such a coating.

EXPERIMENTAL

I. Test Apparatus-Flow System

The initial problem was to set up a system in which measurements could be obtained to study the effectiveness of the coating. It was decided to utilize the simplicity and extensive background of pipe flow systems to develop the required information since skin friction data may be obtained directly from pressure drop measurements.

The final test apparatus was constructed of schedule 40 ½ inch NPS black iron pipe with a removable test section of schedule 40 ½ inch NPS black iron pipe which was forty inches long. Pressure taps were made by drilling orifices 65 and 90 pipe diameters from the input end of the test section, carefully deburring the internal openings and soldering 1/8 inch copper tubing into the holes for pressure taps.

Flow rate was measured by a Wallace and Tiernan Glass Tube Varea-Meter (plug type flow meter) and a Meriam 20 inch well type manometer, using mercury as an indicator fluid, was utilized for pressure drop measurements. A centrifugal pump with a bypass arrangement was utilized for providing flow and flow control in a recirculating flow system. A schematic diagram of the apparatus is shown on Figure 1.

II. Operating Procedure

Initial evaluation of the test apparatus was conducted using Polyox WSR-301 (Union Carbide Chemical Company), which has a molecular weight of 2.6 million and is one of a class of polymerized ethylene oxide compounds which has been widely tested and evaluated as a friction reducing polymer. Solutions were prepared in concentrations of two to five percent in tap water by addition under a high speed mixer. The mixture was allowed to stand for two days then added in various amounts to the feed tank containing fifty gallons of tap water, mixed well and allowed to stand for fifteen minutes before being pumped through the system. Initially no reduction of skin friction was obtained with concentrations of up to 250 parts per million (ppm) of the Polyox at Reynolds numbers from 21,000 to 96,000. After several equipment modifications, it was discovered that this lack of effectiveness was due to shear degradation of the polymer while passing through the centrifugal pump in combination with shear effects encountered during preparation of the concentrated solutions. The test apparatus was then modified to permit injection of the polymer in solution into the flowing water stream through a grease fitting located at the entrance to the test pipe. The concentrated solutions were now prepared by adding the polymer in small increments to a slowly agitating container of water. When all the polymer was added agitation was stopped and the mixture allowed to stand for seven days to obtain complete solution. The number of days in solution was held constant to try to eliminate variables between runs of the same materials, since polymer degradation in static solution has been noted by some researchers (Ref.5.).

The polymer solutions were injected into the system relying on the turbulence in the entry length to effect uniform dilution of the materials before they reached the nine inch test section of the pipe. The injection was timed and the weight of solution injected was recorded from which the concentration of the polymer in the water stream was calculated. Data readings were taken while the solution was being injected.

III. Temperature and Soluble Salt Effects

Temperature effects and the effects of salts, such as are found in seawater, have been shown (Ref.6.) to be of little or no effect and no consideration was given to these factors other than in the aspect of calculating Reynolds numbers. The temperature of the test water ranged from 65 to 85 degrees F. during the course of the tests.

IV. Materials Tested as Drag Reducers

In order to determine the most effective drag reducer in the proposed system, a number of polymers from chemical families noted for their drag reducing potential were evaluated. These included the previously mentioned Polyox WSR-301, a poly (ethylene oxide) compound of 2.6 million molecular weight; Polyhall 295, a copolymer of polyacrylamide and polyacrylic acid with a molecular weight of 5-6 million (Ref.7.); Cyanamer P-250, a homopolymer of acrylamide with a molecular weight of 5-6 million (Ref. 8.); and several sodium carboxymethylcellulose polymers, including CMC 7H, 7H4 and 7L, ranging in molecular weight from 200,000 to 70,000 (Ref.9.).

RESULTS

I. Polymer Effectiveness-Test Results

Figures 2, 3 and 4 show plots of percent friction reduction versus concentration for the polymers tested at Reynolds numbers of 98,000, 83,000 and 62,000 respectively. Figures 5, 6 and 7 are plots of percent friction reduction versus velocity at various concentrations of the polymers.

Percent friction reduction is derived from the following formula which is the definition of the drag reduction (Ref. 10.).

$$D_r = \frac{\Delta P \text{ solution}}{\Delta P \text{ solvent}} \Bigg| \quad \text{constant flow rate}$$

It is the ratio of pressure drop of a solution to the pressure drop of the pure solvent at the same flow rate. If the drag ratio is less than unity the solution is said to be drag reducing.

The most effective polymer was found to be Polyhall 295, the polyacrylamide-polyacrylic acid copolymer. Although equal in molecular weight to the Cyanamer P-250 polyacrylamide homopolymer, its slightly anionic nature appears to have rendered it vastly more effective. This polymer exhibited a peak drag reducing efficiency of about 65% at a concentration near 60 ppm at Reynolds number of 83,000. The peak friction reduction at a Reynolds number of 98,000 was about 60% and also occurred at a concentration near 60 ppm. No maximum was achieved at the 62,000 Reynolds number level due to insufficient development of shear at that flow condition.

Figures 5, 6 and 7 show a decrease in effectiveness of drag reduction based on equal concemtrations after a velocity of 29.5 feet/second (Reynolds number 83,000) has been obtained. This is an indication of polymer degradation by shear in the turbulent boundary layer, since increasing concentrations at increasing Reynolds numbers, as shown in Figures 2, 3 and 4, give larger percent drag reductions in all cases except where maximums have been reached and further polymer addition is ineffective.

See tables 1 and 2 for experimental data.

COATINGS CONTAINING POLYHALL 295

I. Types and Preparations

There are two basic types of coatings into which incorporation of Polyhall 295 was attempted. The first was an insoluble matrix type based on a chemically cured epoxy vehicle system with a pigmentation such that the critical pigment volume concentration (CPVC)-the point at which there is no longer a sufficient amount of vehicle to wet all the pigment surfaces and fill all voids-was exceeded, thus leaving a permeable film allowing water to reach the Polyhall 295 and dissolve it into the boundary layer. The critical PVC was determined empirically, by partially immersing test panels painted with the coating in question in a tank of dyed water for twenty four hours and examining them for capillary type conveyance of moisture up through the porous film.

Incorporation of the Polyhall 295 was attempted in two different ways, namely dry and wet addition. The dry addition consisted of adding the powdered polymer to part of the proposed coating and milling in a steel ball mill for eighteen hours. This resulted in no dispersion and was discarded.

The second method was addition of the Polyhall 295 in solution into the finished paint. A solvent combination was developed to be sufficiently water miscible so that a solution of the polymer in water and solvent could be added without causing incompatibility in the final coating. This solvent lineup consisted of ethyl cellosolve, butanol and xylol. The polymer solution solvent was water and ethyl cellosolve. Due to the high viscosity of the polymer solutions, a maximum of one half of one percent of the polymer could be added to the paint by weight before application by spray and handling became too difficult. This concluded the work with insoluble matrix type paints.

The second type of paint attempted was the soluble matrix type based on film formers such as fish oil, vinyl and polyamide resins with soluble vehicle additions such as rosin and pigment solubles such as cuprous oxide, zinc oxide and calcium sulfate. The water sensitive materials were to aid in the leaching out of the Polyhall 295 by dissolving away from the polymer thus exposing it to water. The type of paint selected for the initial attempts of polymer addition was high in water sensitive materials and based on fish oil as the film former. Attempts at dry incorporation of the Polyhall 295 included high speed dispersion, sand grinding, steel ball and pebble milling. None of these methods showed any tendency to disperse the polymer. On the contrary, the finished product showed agglomeration of the Polyhall 295 in small clusters rather than a dispersion. Addition of surfactants, mainly the non-ionic and anionic types, was attempted to provide wetting of the polymer by the vehicle and solvent system. This produced no improvement in dispersability. Another area of attack was to prepare an emulsion of a Polyhall 295 solution and add it to the finished paint. This was a water in oil emulsion, prepared by making a concentrated solution of the polymer in water and adding surfactants, followed by slow incorporation of an aromatic solvent under low speed agitation until the mixture "turned over" and the Polyhall 295 solution was emulsified. By this approach it was hoped to be able to add larger amounts of the polymer into the finished paint with no effect on viscosity and result in an easily applied smooth film. The emulsion technique proved to have a limited success, increasing the amount of polymer in the coating up to about 4 or 5 percent on a solids basis, and enabling a smooth film to be cast.

A variation on the soluble matrix type paint is a hot melt composition in which there are no solvents and the materials are solids at room temperature. To be applied, this type of coating must be heated until sufficiently liquified. An attempt was made to prepare a hot melt vehicle system consisting of rosin, wax and Polyhall 295. A mixture of rosin and wax was heated to approximately 200 degrees F. after which Polyhall 295 was added under agitation. The mixture was heated to over 370 degrees F. and no solution of the Polyhall 295 was obtained. Even this temperature is too high to make this means of coating preparation and application a practical one. Therefore this approach was abandoned.

The last attempt to get a dispersion of a dry addition of Polyhall 295, was to perform the milling operation in a vehicle having a chemical composition somewhat similar to that of the polymer. A high molecular weight polyamide resin of the type used in hot melt applications was selected. A solvent solution was prepared into which the Polyhall 295 was added in a steel ball mill. Once again, no dispersion was obtained, only small agglomerates of the Polyhall 295. The next step would be to test the coatings which had been made in a pipe flow system.

II. Testing of Coatings Containing Polyhall 295

Before any coatings were applied to the test pipes, each pipe was checked in the flow system for agreement with the theoretical pressure drop at various flow rates. A variation of ten percent was allowed but most pipes were within five percent of the theoretical. Calibration data may be found in table 3.

A test section was coated with a paint not containing any Polyhall 295 to test the method of application and the effect of the coating on the pressure drop. Application was performed by sealing one end of the pipe with a cap and plugging the pressure taps down to the wall of the pipe, then filling the pipe completely with a measured amount of paint. After standing a few minutes, the pipe was then drained and the amount of paint removed measured. The pipe was tilted and rotated periodically to insure as even an application as possible. The theoretical dry thickness could be calculated since the amount of paint inside the pipe was known. After being allowed to dry for one week, the pipe was inserted into the test apparatus and checked for pressure drop at various flow rates. There was only a slight difference between the coated and uncoated condition, with the coated pipe showing about a five percent decrease in pressure drop compared to its original uncoated condition. See table four for numerical results.

The theoretical paint thickness in the pipe was calculated to be near three dry mils. After testing was completed the pipe was cut up into four sections and sliced in half lengthwise to permit inspection of the paint film. Film thickness was checked with a General Electric Dry Film Thickness Tester. Visually the film appeared smooth and even with no ridges or other imperfections. The measured film thickness ranged from two to three and one half dry mils, which was considered satisfactory for the type application.

Since paints were to be applied which contained agglomerates of Polyhall 295, therefore introducing surface roughness to the test section, a paint was prepared which contained pumice of a size and amount which would yield a film somewhat similar to the films with the polymer aggregates. This paint was applied in the same manner as the previously described standardization paint, then tested for pressure drop. A large increase in friction was obtained and maximum flow rate in the test section was reduced by fifteen percent. See table 5.

Paints containing 10 and 15 percent by weight of total solids of Polyhall 295 were prepared by dry addition and a paint containing 5 percent by weight of total solids of Polyhall 295 was prepared by the emulsion addition method. The paints were then applied, allowed to dry and tested.

III. Test Results

The pipe coated with the paint containing the emulsified Polyhall 295 showed no lessening of frictional pressure drop, the pipe coated with a paint containing no polymer additive showed an average five percent decrease in skin friction, the pipe coated with the ten percent dry addition of Polyhall 295 (solids basis) showed a 66.7% decrease in pressure drop at a Reynolds number of 83,000 and a velocity of 29.5 ft/sec. See tables 6 and 7.

The decrease in pressure drop did not occur immediately, but rather after a running time of about three minutes. The pressure drop then remained constant for approximately thirty minutes when the run was discontinued. The test section was removed from the apparatus and dried. After one week it was re-tested in the flow system but did not show any decrease in frictional resistance. On the contrary, an increase in pressure drop of about 20 to 30 percent was evidenced. See table 7.

In an attempt to repeat these results, pipes were again coated similarly to those in the original testing. Once again the painted pipe with no polymer added showed a small decrease in skin friction. The pipes coated with paints containing 10 and 20 percent Polyhall 295 (on solids basis) incorporated by dry addition showed no decrease in drag, only a significent increase, up to 50 percent, probably due to roughness effects. See tables 7 and 8.

Assuming that the polymer did not attain a fast enough leaching rate, the pipes were placed in a constant flow heat exchanger piping system for approximately three weeks and re-tested in the flow system. The pipe containing no Polyhall 295 remained unchanged from the previous test and the pipe containing 20 percent Polyhall 295 continued to give readings approximately 50 percent higher than in the uncoated condition.

CONCLUSIONS

1. Polyhall 295 is a very effective drag reducer at low concentrations when added to flowing water streams in dilute solution.

2. None of the polymers tested showed any tendency to be readily dispersed in an oleoresinous paint system. All were easily dissolved in water.

3. Coatings containing Polyhall 295 in amounts of ten to twenty percent by weight of dry film, showed increases in frictional drag due to increased roughness of the wall surface with one exception which was non-reproducible.

4. No explanation is readily available or definitive for the one successful trial, except that a portion of the Polyhall 295 may have been readily available at the surface for leaching initially and later became inaccessible or not available in large enough amounts to produce drag reduction after the film had dried out.

RECOMMENDATIONS

A method for incorporation of friction-reducing polymers into solvent type paints, which would give adequate dispersion to produce smooth film surfaces, is required to make this approach to skin friction reduction practical. Since high shear conditions cause breakdown of the polymer chain, any dispersions would have to be done in the dry state. One method which may be applicable could be to cast a thin free film of a dilute solution of the polymer, dry it and pulverize the remainder. If this proved feasible, further studies into the dry incorporation could be started.

In the absence of a method to incorporate the polymer into a paint film, it would appear worthwhile to try to study uncontrolled leaching from a wall by coating the wall with a solution of the polymer, allowing it to dry and then testing for frictional resistance. Some interesting data may be obtained from such a test, since theoretically all of the polymer in the test section would be effective.

SAMPLE CALCULATIONS

CONDITION A: Water at 77 degrees F. flowing at 11.3 gallons per minute through clean ¼'' Schedule 40 pipe. Pressure taps located nine inches apart record a differential pressure reading of 11.45 inches of mercury on a well type manometer.

OBJECTIVE A: Compare this reading with the theoretical pressure drop expected under the above conditions.

$D = .364\text{inches} = .0303\text{ft}$ $\qquad$ $q = 11.3\text{gal/min}$

$S = .00072\text{ft}^2$

$$\overline{V} = \frac{11.3 \text{ gal/min}}{\frac{1 \text{ hr}}{60 \text{ min}} \times .00072\text{ft}^2 \times 7.48 \frac{\text{gal}}{\text{ft}^3}} = 126{,}000\text{ft/hr}$$

$$G = \overline{V}\rho = 126{,}000\text{ft/hr} \times 62.4\text{lb/ft}^3 = 7.87\text{x}10^6 \text{ lb/hrft}^2$$

$$N_{Re} = \frac{D}{\mu} G = \frac{.0303\text{ft} \times 7.87 \times 10^6 \text{ lb/hrft}^2}{2.42\text{lb/fthr}} = 98{,}000$$

$K/D = \frac{.00015\text{ft}}{.0303\text{ft}} = .005$ $\qquad$ $f = .0066$

$$H_{fs} = \frac{2fL\overline{V}^2}{Dg_c}$$

$$H_{fs} = \frac{2 \times .0066 \times .75\text{ft} \times (35)^2 (\text{ft/sec})^2}{.0303\text{ft} \times 32.17\frac{\text{ft-lb}}{\text{lb}_f \text{ sec}^2}} = 12.18\frac{\text{ft-lb}_f}{\text{lb}}$$

$$p_a - p_b = H_{fs}\rho = 12.18\text{ft-lb}_f/\text{lb} \times 62.4\ \text{lb/ft}^3$$

$$= 770\text{lb}_f/\text{ft}^2 = 5.38\text{lb}_f/\text{in}^2$$

$$= 5.38\text{psi}$$

$5.38\text{psi} \times \dfrac{2.04\ \text{in Hg}}{1\ \text{psi}} = 10.95$ in Hg Theoretical Pressure Drop

$$\Delta p = R_m\,(\rho_{Hg} - \rho_{H_2O})$$

$$= \frac{11.45}{12.0}\ (62.4 \times 13.6 - 62.4 \times 1.0)$$

$$= 750\text{lb/ft}^2 = 5.20\text{lb/in}^2$$

$= 5.20\text{psi} \times \dfrac{2.04\ \text{in Hg}}{1\ \text{psi}} = 10.60$ in Hg Observed Pressure Drop

CONDITION B: Water containing 18 ppm of Polyhall 295 is flowing under the same conditions as in A. The manometer reads 9.45 inches of mercury.

OBJECTIVE B: What is the percent drag reduction caused by the addition of the Polyhall 295?

$$\Delta p = R_m(\rho_{Hg} - \rho_{H_2O})$$

$$= \frac{9.45}{12.0} \; (62.4 \times 13.6 - 62.4 \times 1.0)$$

$$= \frac{9.45}{12.0} \quad (786)$$

$$= 620 \text{ lb/ft}^2$$

$$= 4.31 \text{ psi} \times \frac{2.04 \text{ in Hg}}{1 \text{ psi}}$$

$$= 8.80 \text{ in Hg}$$

$$\%Dr = \left(1 - \frac{\Delta p \text{ solution}}{\Delta p \text{ solvent}}\right) \times 100$$

$$= \left(1 - \frac{8.80}{10.60}\right) \times 100$$

$$= .17 \times 100$$

$$= 17\%$$

TABLE OF NOMENCLATURE

Symbols

D	Diameter, ft
G	Mass velocity, $\overline{V}\rho$ lb/hr ft^2
g_c	Newton's-law conversion factor, 32.174 ft-lb/lb$_f$ sec^2
k	Roughness parameter, ft
L	Length, ft
p	Pressure, lb$_f$/ft^2; p_a, at upstream station; p_b, at downstream station
q	Volumetric flow rate, gal/min
Rm	Reading of manometer, ft
S	Cross section of conduit, ft^2
$\overline{V}$	Volumetric average velocity, ft/hr

Greek Letters

μ	Viscosity, absolute lb/ft-hr
ρ	Density, lb/ft^3

TABLE OF NOMENCLATURE(con't)

Dimensionless Groups

Dr	Drag reduction, percent, $\left(1-\frac{\Delta p\ \text{solution}}{\Delta p\ \text{solvent}}\right) \times 100$
f	Fanning friction factor, $H_{fs}\, D g_c / 2L\bar{V}^2$
N_{Re}	Reynolds number, $\frac{DG}{\mu}$

TABLE 1a

Decrease in Skin Friction vs Concentration at $N_{Re} = 98,000$

Polymer	Conc. ppm	ΔP_{Std} in Hg	ΔP_{obs} in Hg	% Drag Reduction
Polyhall 295	18	10.60	8.80	17
Polyhall 295	38	10.60	7.85	26
Polyhall 295	68	10.60	4.85	54
Polyhall 295	146	10.60	5.95	44
Cyanamer P-250	19	10.60	10.05	5
Cyanamer P-250	41	10.60	9.55	10
Polyox 301	20	10.60	9.95	6
Polyox 301	34	10.60	9.85	7
Polyox 301	115	10.60	9.75	8
CMC 7H4	23	10.60	10.20	4
CMC 7H4	48	10.60	9.60	9
CMC 7H	10	10.60	10.50	1
CMC 7H	48	10.60	10.20	4

TABLE 1b

Decrease in Skin Friction vs Concentration at $N_{Re} = 83,000$

Polymer	Conc. ppm	ΔP_{Std} in Hg	ΔP_{obs} in Hg	% Drag Reduction
Polyhall 295	18	7.80	6.80	13
Polyhall 295	33	7.80	5.55	29
Polyhall 295	82	7.80	2.80	64
Polyhall 295	170	7.80	3.00	62
Cyanamer P-250	24	7.80	7.20	8
Cyanamer P-250	62	7.80	6.70	14
Polyox 301	22	7.80	7.10	9
Polyox 301	57	7.80	7.00	10
Polyox 301	130	7.80	6.90	12
CMC 7H4	22	7.80	7.30	6
CMC 7H4	54	7.80	6.95	11
CMC 7H	10	7.80	7.60	3
CMC 7H	20	7.80	7.60	3
CMC 7H	51	7.80	7.35	6

TABLE 1c

Decrease in Skin Friction vs Concentration at $N_{Re} = 62{,}000$

Polymer	Conc. ppm	ΔP_{Std} in Hg	ΔP_{obs} in Hg	% Drag Reduction
Polyhall 295	26	4.60	4.05	12
Polyhall 295	40	4.60	3.50	23
Polyhall 295	46	4.60	3.30	29
Polyhall 295	117	4.60	2.10	55
Cyanamer P-250	38	4.60	4.40	5
Cyanamer P-250	77	4.60	4.45	3
Polyox 301	29	4.60	4.60	0
Polyox 301	72	4.60	4.50	2
Polyox 301	170	4.60	4.30	7
CMC 7H4	32	4.60	4.55	1
CMC 7H4	70	4.60	4.20	9
CMC 7H	22	4.60	4.55	1
CMC 7H	65	4.60	4.40	5

TABLE 2a

Decrease in Skin Friction vs Velocity at Concentration = 30 wppm (from graphs 2, 3 and 4)

Polymer	$\overline{V}$ ft/sec	% Drag Reduction
Polyhall 295	22.2	15
Polyhall 295	29.5	26
Polyhall 295	36.0	20
Cyanamer P-250	22.2	5
Cyanamer P-250	29.5	10
Cyanamer P-250	36.0	8
Polyox 301	22.2	0.5
Polyox 301	29.5	9
Polyox 301	36.0	7
CMC 7H4	22.2	2
CMC 7H4	29.5	7
CMC 7H4	36.0	5

TABLE 2b

Decrease in Skin Friction vs Velocity at Concentration = 45 wppm (from graphs 2, 3 and 4)

Polymer	$\overline{V}$ ft/sec	% Drag Reduction
Polyhall 295	22.2	30
Polyhall 295	29.5	38
Polyhall 295	36.0	35
Cyanamer P-250	22.2	5
Cyanamer P-250	29.5	12
Cyanamer P-250	36.0	11
Polyox 301	22.2	1
Polyox 301	29.5	10
Polyox 301	36.0	7
CMC 7H4	22.2	3
CMC 7H4	29.5	11
CMC 7H4	36.0	8

TABLE 2c

Decrease in Skin Friction vs Velocity at Concentration = 75 wppm (from graphs 2, 3 and 4)

Polymer	$\overline{V}$ ft/sec	% Drag Reduction
Polyhall 295	22.2	45
Polyhall 295	29.5	59
Polyhall 295	36.0	55
Polyox 301	22.2	6
Polyox 301	29.5	10.5
Polyox 301	36.0	7.5

TABLE 3

Standardization of Uncoated Pipes, P = inches of Mercury

$N_{Re} \times 10^{-4}$	ΔP_{theo}	ΔP_1	ΔP_2	ΔP_3	ΔP_4	ΔP_5	ΔP_6	ΔP_7	ΔP_8	ΔP_9
10.29	12.09	11.7	11.7	12.5	11.6	12.2	11.5	12.5	12.2	11.8
9.80	10.95	10.6	10.6	10.9	10.3	10.7	10.5	11.2	10.5	10.7
9.30	9.87	9.6	9.6	9.7	9.3	9.6	9.4	10.2	9.4	9.6
8.31	8.32	7.7	7.8	8.0	7.6	7.9	7.5	8.5	8.2	7.9
7.19	6.23	5.8	6.1	6.0	6.0	6.0	5.6	6.3	6.1	5.9
6.20	4.89	4.3	4.6	4.5	4.6	4.5	4.2	4.9	4.6	4.4
5.21	3.44	3.0	3.3	3.2	3.2	3.2	3.0	3.2	3.3	3.3
3.47	1.83	1.5	1.7	1.7	1.6	1.7	1.5	1.6	1.6	1.6

TABLE 4

Test Data for Coated Pipe - No Polymer Added

Pipe No. 4	ΔP Std in Hg	ΔP act in Hg	% Drag Reduction
	11.6	10.8	6.9
	10.3	9.8	4.9
	9.3	8.7	6.5
	7.6	7.2	5.3
	6.0	5.7	5.0
	4.6	4.5	2.2
	3.2	3.1	3.1
	1.6	1.5	6.2

TABLE 5

Test Data for Coated Pipe - Pumice Added

Pipe No. 7	ΔP std in Hg	ΔP act in Hg	% Drag Reduction
	12.5	-	-
	11.2	-	-
	10.2	off scale	-
	8.5	19.5	-130 (increase)
	6.3	not run	-
	4.9	not run	-
	3.2	not run	-
	1.6	not run	-

TABLE 6

Test data for Coated Pipe - 5% Polyhall 295 added by Emulsion

Pipe No. 3	ΔP_{std} in Hg	ΔP_{act} in Hg	% Drag Reduction
	12.5	12.1	3.2
	10.9	10.5	3.7
	9.7	9.4	3.1
	8.0	7.7	3.8
	6.0	5.9	1.7
	4.5	4.2	6.7
	3.2	3.0	6.3
	1.7	1.5	11.7

TABLE 7

Test Data for Coated Pipe - 10 % Polyhall 295 by Dry Addition

Pipe No. 1	ΔP std in Hg	ΔP act in Hg @ init.	ΔP act in Hg @ 3 min.	ΔP act in Hg @ 1 week	% Drag Reduction		
					init	3 min	1 week
	11.7	off scale	-	14.9	-	-	-27
	10.6	off scale	-	13.5	-	-	-27
	9.6	off scale	-	11.8	-	-	-26
	7.7	off scale	2.45	9.0	-	66.7	-17
	5.8	-	-	6.8	-	-	-17
	4.3	-	-	5.0	-	-	-16
	3.0	-	-	3.6	-	-	-20
	1.5	-	-	1.9	-	-	-27

TABLE 8

Test Data for Coated Pipe - 10% Polyhall 295 by Dry Addition

Pipe No. 5	ΔP_{std} in Hg	ΔP_{act} in Hg	% Drag Reduction
	12.2	15.6	-28 (increase)
	10.7	14.0	-27 (increase)
	9.6	12.1	-27 (increase)
	7.9	9.2	-28 (increase)
	6.0	7.0	-19 (increase)
	4.5	5.1	-13 (increase)
	3.2	3.7	-16 (increase)
	1.7	2.0	-18 (increase)

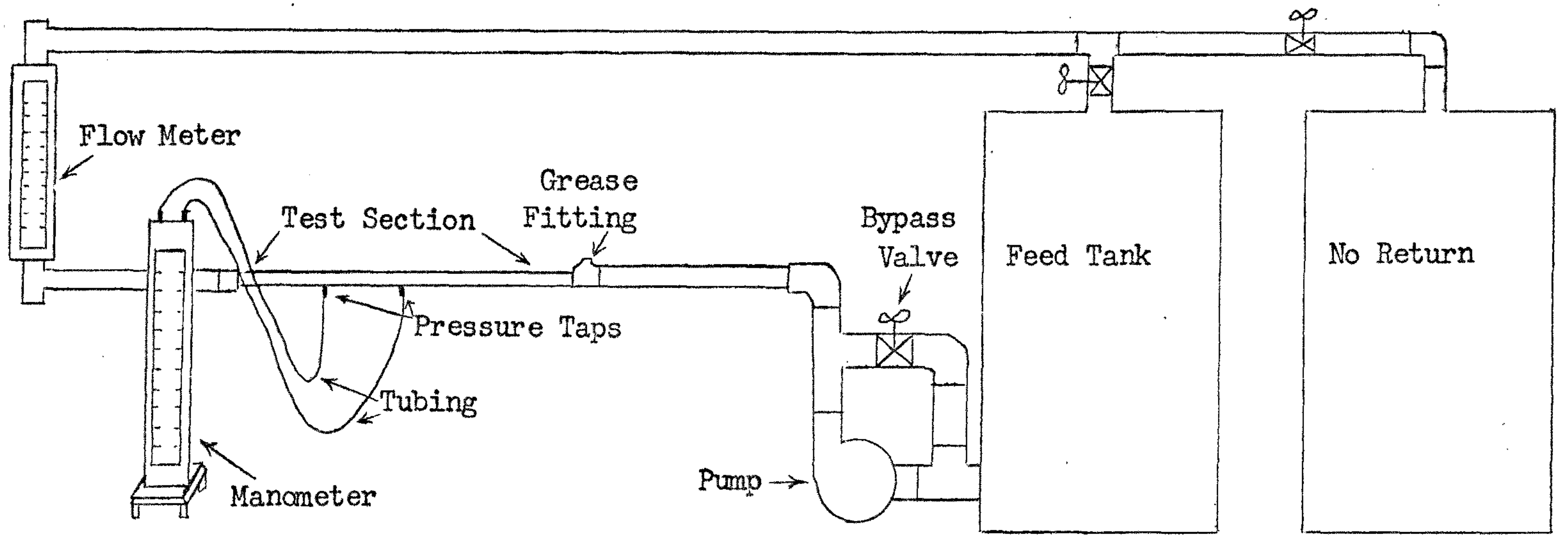
TABLE 9

Test Data for Coated Pipe - 20% Polyhall 295 by Dry Addition

Pipe No. 6	ΔP_{std} in Hg	ΔP_{act} in Hg	% Drag Reduction
	11.5	17.1	-49 (increase)
	10.5	14.9	-42 (increase)
	9.4	13.5	-42 (increase)
	7.5	9.7	-32 (increase)
	5.6	7.3	-30 (increase)
	4.2	5.7	-36 (increase)
	3.0	4.0	-33 (increase)
	1.5	2.1	-40 (increase)

FIGURE 1

TEST APPARATUS



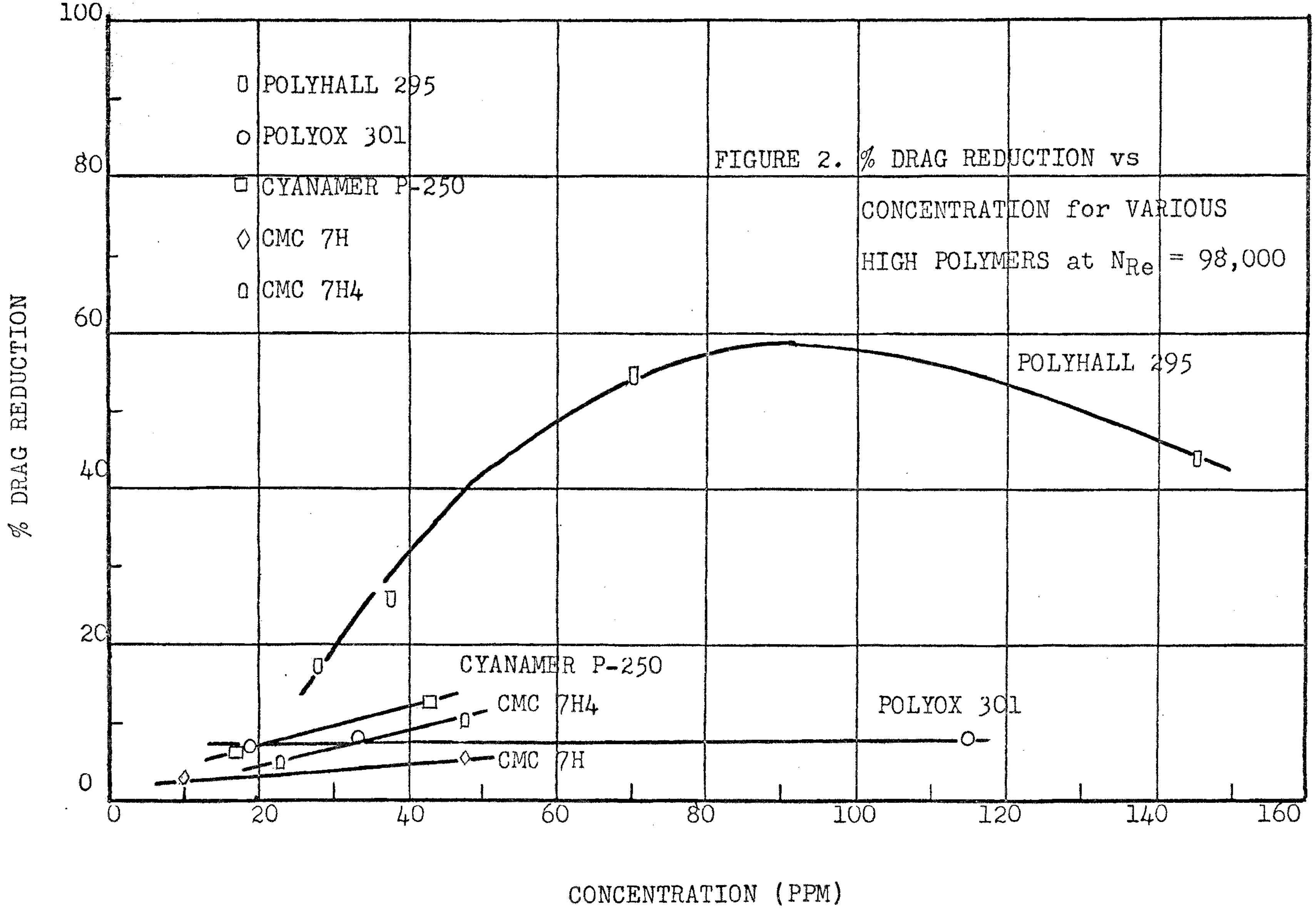


FIGURE 2. % DRAG REDUCTION vs CONCENTRATION for VARIOUS HIGH POLYMERS at N_{Re} = 98,000

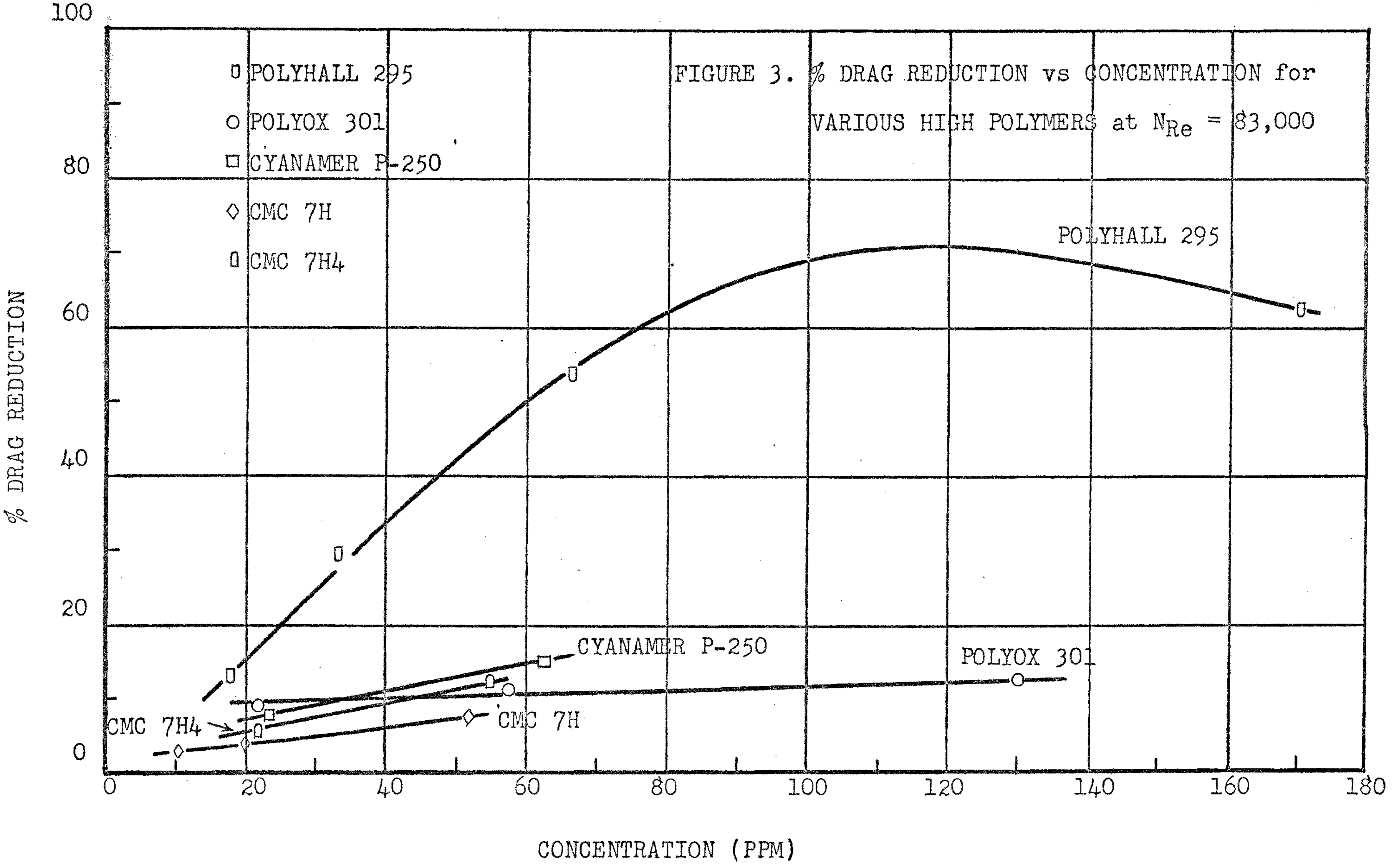


FIGURE 3. % DRAG REDUCTION vs CONCENTRATION for VARIOUS HIGH POLYMERS at N_{Re} = 83,000

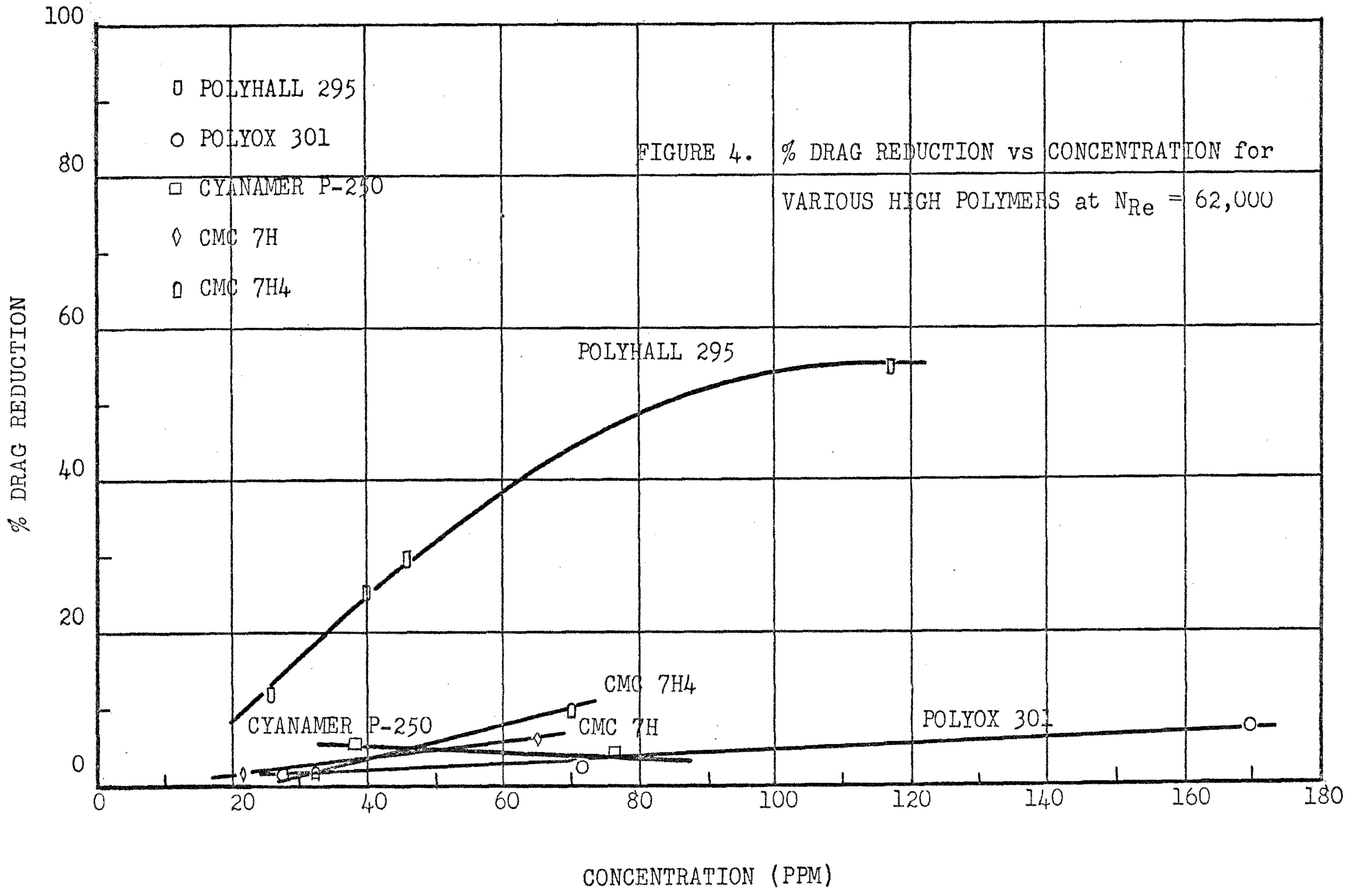


FIGURE 4. % DRAG REDUCTION vs CONCENTRATION for VARIOUS HIGH POLYMERS at N_{Re} = 62,000

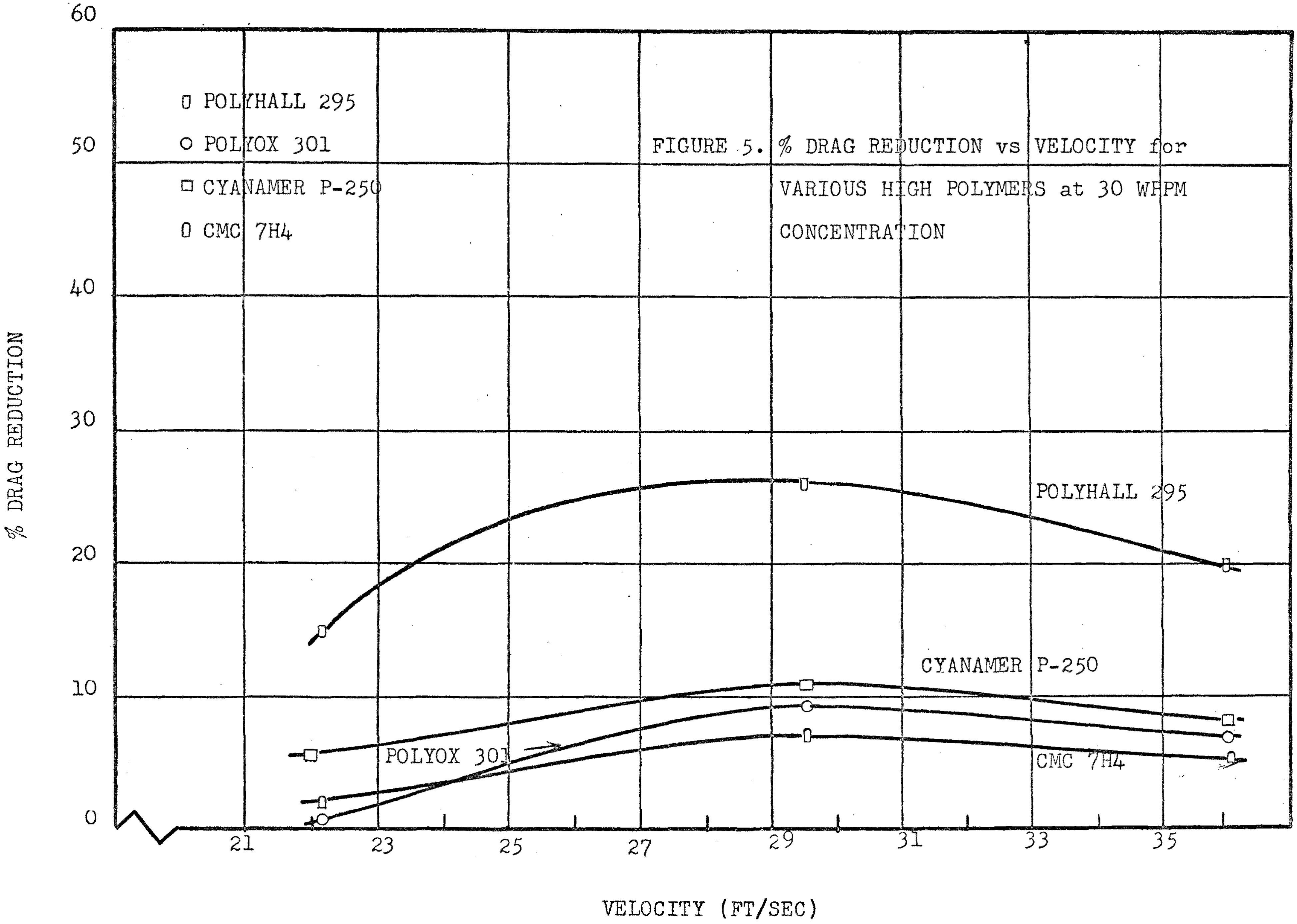


FIGURE 5. % DRAG REDUCTION vs VELOCITY for VARIOUS HIGH POLYMERS at 30 WPPM CONCENTRATION

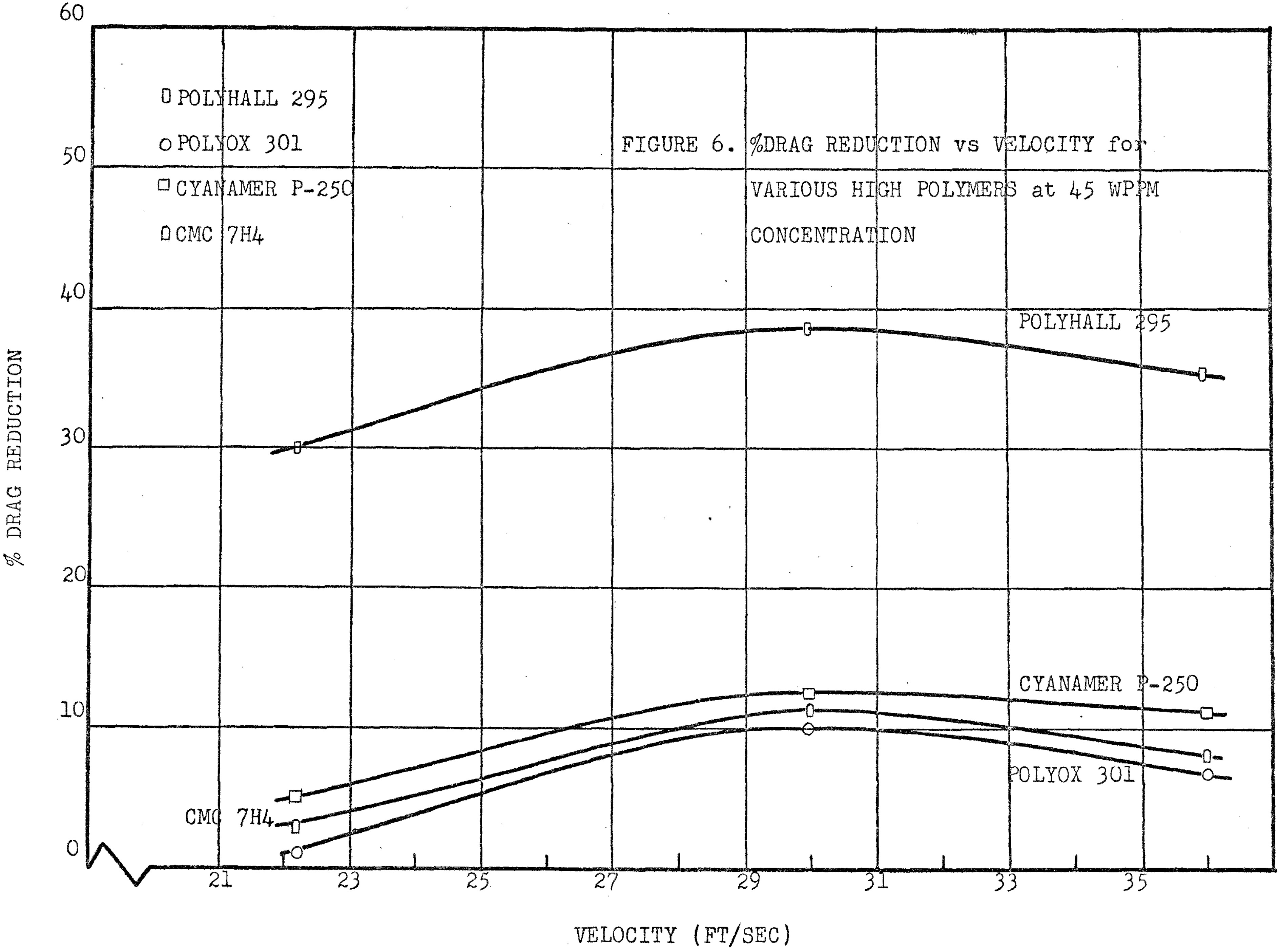


FIGURE 6. %DRAG REDUCTION vs VELOCITY for VARIOUS HIGH POLYMERS at 45 WPPM CONCENTRATION

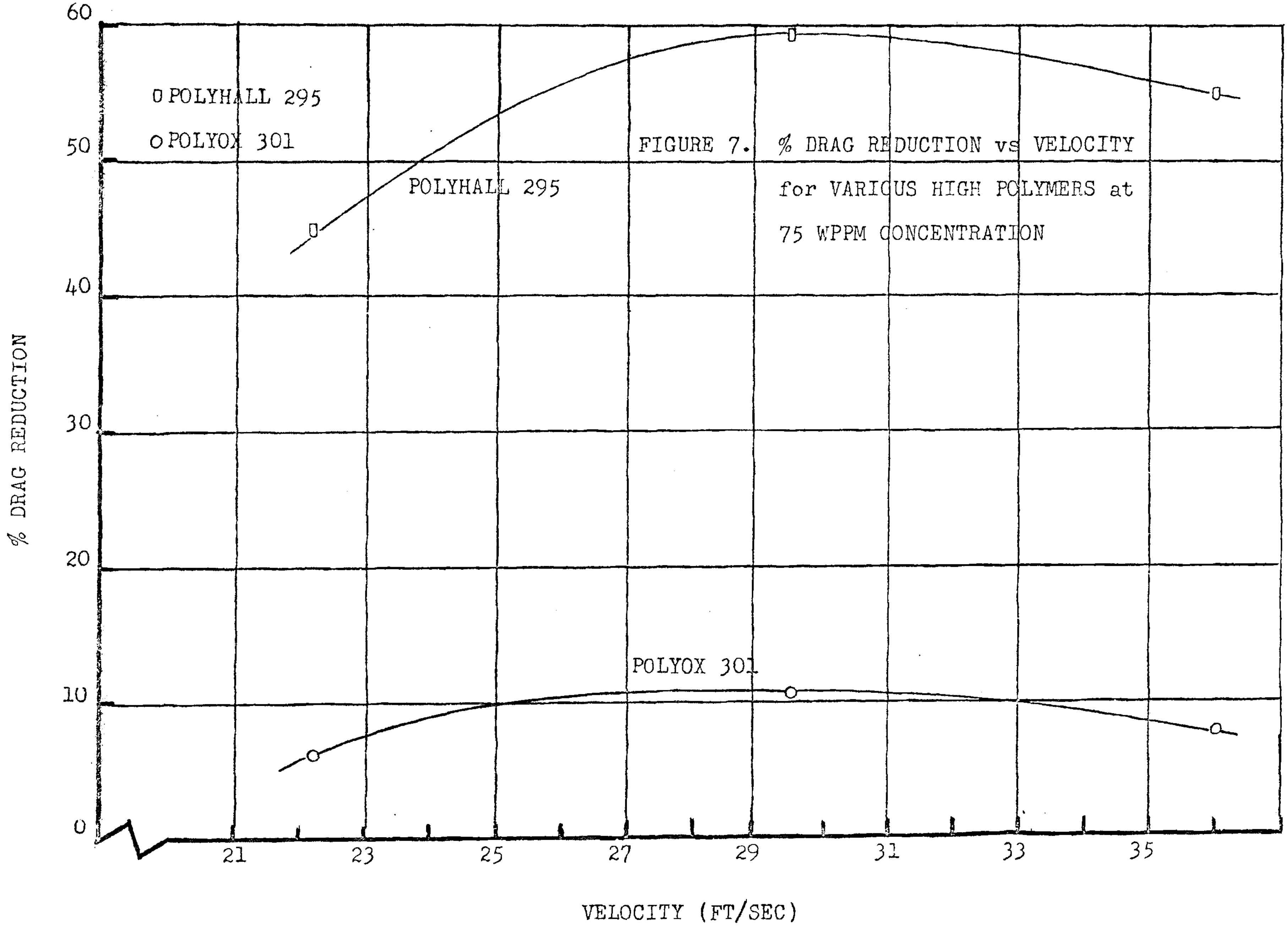


FIGURE 7. % DRAG REDUCTION vs VELOCITY for VARIOUS HIGH POLYMERS at 75 WPPM CONCENTRATION

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