PUMPING CHARACTERISTICS OF RECIPROCATING ASYMMETRIC BAFFLES IN A PIPE

by

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Reciprocating asymmetric baffles in a pipe can produce a time averaged pressure difference and hence can be used to form the basis of a valveless pump.

This report describes the production of characteristic curves of head versus flow rate for a range of variables in a 50.8 mm I.D. tube agitated by reciprocated asymmetric baffles. The effect of amplitude and frequency of oscillation on the pumping of tap water is reported. Baffle length and the fitting of orifices to the pump are two other modifications considered. The pumping characteristics for two fluids other than tap water, namely glucose and a filter pulp slurry, are also described.

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I. INTRODUCTION

The pumping of fluids is an essential part of chemical processes. Research undertaken into novel forms of pumps has often a direct industrial application as well as the possibilities which exist in other fields, for example, biomedical engineering.

There are three major classes of pump which are widely used [(1)&(2)]: Centrifugal, Rotary and Reciprocating. Centrifugal pumps are probably the most commonly used in industry because of their high efficiency over a wide range of capacities and pressures. The basic principle behind their operation is to produce kinetic energy by centrifugal force and then convert this energy partially to pressure by efficiently reducing velocity in accordance with Bernoulli's equation. The efficiency of the pump depends, among other things, on sound sealing of the drive shaft and high maintenance costs may result from the passage of corrosive liquids. If a non-return valve is not incorporated in either the delivery or suction lines, the liquid will simply run back into the suction tank. If slurries or suspensions are pumped the impeller blades may have to be decreased in length or their numbers reduced to prevent blockages developing. Another disadvantage is that this type of pump is usually not self-priming.

Positive displacement rotary pumps operate efficiently to pump very viscous liquids and against high pressures. The principle of operation is that energy is imparted to the fluid by the meshing of one driving and one free rotating gear wheel. The liquid is carried round in the space between consecutive teeth and the casing and then ejected as the teeth come into mesh. The pump has no valves or troublesome seals, but it cannot be used for suspensions as these jam up the gear teeth.

Reciprocating pumps can efficiently deal with large throughputs and are adaptable to high pressure operations. The principle of operation rests on the conversion of the kinetic energy of a driven piston into increased pressure energy of the fluid. The discharge usually fluctuates sinusoidally unless multiple pumps are used. Problems occurs with corrosive liquids as the body is generally cast-iron, the valves bronze, and the piston and piston-rods are made of steel. Slurries containing abrasive particles cannot be handled as damage can be done to valves and the machined surfaces of cylinders and pistons. Sealing of the piston in the cylinder can also cause problems.

Whilst the three classes of pump described above are found to be satisfactory in many applications, their limitations are acknowledged.

It is the purpose of this report to describe the operation of one type of pump which might be especially suited to dealing with very corrosive or hot fluids, slurries and suspensions. The pump is made up of reciprocating conical perspex baffles mounted on a brass rod oscillated by a compressed air system. Reciprocating pumps employing non-return valves have been used in industry for many years; the advantage of the pump described here is that it contains no small clearances or valves and thus eliminates a feature which is liable to failure with abrasive or corrosive fluids.

El Sayed[3] demonstrated that a net time-averaged pressure was produced by reciprocating asymmetric baffles in a pipe and that this could be the basis of a valveless pump. A pressure transducer was employed to make measurements of the pressure produced at various amplitudes and frequencies for a variety of baffle shapes and sizes and these measurements were made under "no flow" conditions. El Sayed found one particular shape of baffles (see Figure 1) produced the largest pressure difference over the range of operation considered and it was decided that this baffle would be used throughout the tests to be carried out. The objective of El Sayed's work was to demonstrate the feasibility of using the reciprocating baffles to pump fluids; this report aims to obtain performance data under a variety of conditions with a view to evaluating the practical applications. This pump is one particular type of fluid diode, which imposes low resistance to flow in one direction and high resistance to reverse flow and has no moving parts, an advantage over non-return valves.

Baker[4] has produced a comparative study of three types of fluid diodes operating on entirely different principles. The performance, defined as ratio of the pressure drop in the reverse-flow direction to that in the forward flow direction, was correlated with Reynold's Number under steady state conditions. Baker concluded that the vortex diode gave the best overall performance although good results were obtained with the fluid flow rectifier. The latter had the disadvantage of being rather expensive.

Manor and Popper[5] have suggested a novel way of moving corrosive and toxic fluids based on progressive transverse vibration of the walls of the conduit or container. A P.V.C. cylindrical container was taken and four rollers mounted on a common rotating disc. When the rollers are run over the outer side of the container an elastic wave is generated and rotation sets in immediately in the liquid. This arrangement eliminates all mechanical contact between rotating parts and the fluid.

Work has also been undertaken by the C.E.G.B.[6] into the particular problem of pumping hot liquid slag from a combustion furnace. The fluid is too hot and too corrosive to employ a pump with moving metal parts. The pump consists of a chamber containing inlet and outlet ports and a source of compressed air which provides the energy to force liquid through the exit port. The design is such that flow out of the outlet and in through the inlet are the preferred directions. Thus the ports act as leaky non-return valves.

Pulsation has been studied by many workers and for use in many applications. Lo and Karr[7] developed a reciprocating plate extraction column and concluded that reciprocating motion produced high volumetric efficiencies. This column was found to be suitable for liquids containing suspended solids, one of the classes of fluids which can cause problems in conventional columns. Karr[8] columns have manufactured in sizes up to 450 mm. diameter and have proved effective for solvent extraction. The enhancement of heat transfer by pulsation has been studied by Keil and Baird[9] who found that heat transfer coefficients in a shell and tube heat exchanger were increased at the expense of increased pressure drop. They conclude that air pulsation may be economically feasible particularly in those areas of the world where water costs are high. However, it must be said that although much research has been undertaken in this field, this writer has not found any large-scale industrial use of pulsation in heat transfer reported.

An interesting application of pulsation to solids transport has been reported by Chan and Baird[10]. Experiments were performed using asymmetric baffles reciprocating with frequencies between 0.6 and 1.1 Hz and an amplitude of 115 mm and it was found that the rate of solids transport increased strongly with the product of amplitude and frequency. There is motion of sand particles along a horizontal pipe in the absence of any net flow of the carrying fluid, namely water. Chan and Baird[11] reported on wall friction in oscillating liquid columns and concluded that for a sand-water system, less energy was required to suspend sand in oscillatory flow than in steady flow. If a steady pressure is applied to a suspension there is a tendency towards compaction and consequent increased pressure drop or in the extreme case blockage; pulsation eliminates that possibility. The applications of pulsation range over heat and mass transfer, fluid diodes, solids transport and pumping. This report deals with only one part of the last class mentioned.

II(a). PRINCIPLE OF OPERATION

The apparatus used (see Figure 2) consisted of a perspex baffle (see Figure 1) mounted on a central brass rod oscillated in a glass U-shaped vessel. The principle of operation is as follows: The liquid flows in the annulus between the baffles and the wall in an opposite direction to the baffle motion. Since the baffles are asymmetric, the flow pattern during the upstroke is different from that during the downstroke. A contraction coefficient may be defined in terms of the minimum areas through which liquid flows upstream and downstream of the baffle. For upward motion, for example, the contraction coefficient would be defined as area B divided by area A (see Figure 3).

$$\text{Contraction Coefft.} = \frac{\text{Cross-section of annular "vena contracta"}}{\text{Cross-section of annulus between large end of baffle and tube wall}}$$

Because of asymmetry, the contraction coefficient for downward motion of the baffles is smaller than that for the upward motion implying a greater resistance to fluid motion on the downward stroke. This means that the pressure produced on the downstroke of the baffle exceeds the back pressure produced on the upstroke, the result being a net pressure in the downward direction. Mathematical analysis of the situation in terms of Bernoulli's energy equation is difficult because the values of the contraction coefficients are not known. One way around this difficulty would be to use high speed photography in an attempt to provide direct measurement of the areas occupied by fluid on either side of the baffle. The efficiency of the pump is dependent on the relative values of the contraction coefficients, but it is unlikely to reach the values of 60-70% common for centrifugal pumps[12].

II(b). APPARATUS (Figure 2)

The U-section was built with lengths of Q.V.F. glass pipeline of nominal internal diameter 50.8 mm connected together by metal flanges and rubber seals. Orifice plates could be fitted into the apparatus between any two glass sections. The structural attachments consisted of STD pipeline support bolted onto a vertical steel channel fixed to the wall of the building. The right hand side of the apparatus could be extended by .305 m to allow for greater differences in head to be measured. The central brass shaft 9.5 mm (3/8 ins.) diameter on which the baffles are mounted was connected to a compressed air driving system (MAXAM Compair Canada Ltd.). The principle of operation depends on the action of a metal ring or a pair of valves (Figure 4). The diagram shows the rod at the top its stroke with one of the two cylinders full of compressed air and the other empty. When the top valve was struck the full cylinder was exhausted to atmosphere and air (supplied from a 2.76×10^5 Pa. (40 p.s.i.g.) laboratory line through a metered valve) began to fill the empty cylinder and hence push the rod in a downward direction. When the bottom valve was struck the reverse occurs, the full cylinder was exhausted, the empty cylinder filled and the consequent motion of the rod end baffle assembly was upwards. The use of a wide ring ensures that, even at high frequencies, the valves were pressed for a sufficiently long time to ensure that, it was impossible for the system to retain, say, an upward motion past the top valve resulting in the system completely stopping. The positions of the valves on the screwed shaft were adjustable and hence an important pulsation variable, amplitude, could be controlled.

The frequency of pulsation could be altered by varying the pressure of the air reaching the MAXAM system by means of the throttle valve connected to the laboratory air supply.

A high resistance, high tensile strength electrical (80/20) resistance wire of diameter .20 mm (0.008 ins.) Greening Donald Ltd., was connected to the top of the driving shaft, as in Figure 5, running on a copper pulley and kept under tension with elastic bands. As the piston moved up and down, the length of wire between points A and B varied in direct proportion to the motion. This variable resistance formed one arm of a Wheatstone Bridge circuit which was purposely kept unbalanced so that a potential difference, which varied linearly with the length of wire AB was produced. Resistance is proportional to the length of wire. This variable voltage was fed into a chart recorder (SANBORN Co. Model SANBORN 150) where paper (SANBORN Permapaper) passes over a knife edged writing plateau and was wiped by a hot wire ribbon stylus for true rectilinear coordinates. The chart speed used was 5mm/s. This stylus mapped out a waveform representation of the motion of piston which was permanently recorded so that the amplitude and frequency could be studied and interpreted after the experiment had been completed.

Liquid was fed to the left hand side of the apparatus by means of a constant head apparatus (Figure 6) which had a wide overflow pipe to ensure that the level remained constant. The liquid height was marked by a string tied round the outside of the tank. This string was then stretched horizontally until it made contact with a scale which consisted of strips of graph paper attached to the side of the vertical steel channel. In this way a measurement of the difference in height between the water in the tank and exit overflow point M(fixed) was obtained; this was the head which the pump had overcome when liquid flowed. Collection of the liquid was made in a 15 liter bucket and by measuring the time necessary to fill the container the liquid flow rate was obtained. Thus from these two quantities, head and flow rate, the familiar "characteristic curve" for the pump under any conditions was obtained. The importance of the curve is great as it allows the maximum flow rate to be calculated for any particular head and hence the performance of the pump can be simply read from a graph. The characteristic curve of flow rate versus head can be considered as the dependent variable measured repeatedly during the experimental programme for different values of various independent variables.

II(c). EXPERIMENTAL PROCEDURE.

The first adjustment made to the apparatus was to fix the amplitude. This was accomplished by adjusting a pair of nuts on a threaded shaft which fixed the position of the valves associated with the MAXAM system. It should be pointed out that the term amplitude is used throughout this report to mean the distance between the top and bottom of a stroke not the distance travelled in one complete cycle. The amplitude was taken to be the distance measured by ruler between the centre point of each valve. This decision was taken after close observation of the system actually in motion. The water supply was turned on and a check was made to ensure that the constant head apparatus was functioning correctly. The air supply was turned on and adjusted by means of the fitted valve until the required frequency was reached. This frequency was measured by timing oscillations for one minute. A calibration between the valve setting and the frequency was found to be impracticable for two reasons. Firstly the scale of the valve was rather cramped making accurate judgements of settings difficult. Secondly the pressure needed to produce a particular frequency of oscillation varied, meaning that a separate calibration would be necessary for each amplitude.

The next step was to move the constant head tank to produce the required head difference across the pump. The tank was supported by a a movable cross-shaped support of 50.8 mm (2 ins.) steel channel attached to a vertical groove in the wall by means of two bolts. The frame and hence the tank could be moved up or down by slackening the bolts, sliding the frame in the groove, then re-tightening the bolts securely. The actual procedure was as far as possible to try and move the tank downwards i.e. gradually increase the head, because with a weight of 20 Kgs. or more it was a difficult proposition to manoeuvre upwards. Whilst these preparations were made and between runs the liquid being pumped was collected in 55 liter vessels. When the pump had operated undisturbed for two minutes a steady state was judged to have been atained. The flexible pipe coming from the overflow section was placed in the graduated 15 liter bucket and the time noted. Generally the full 15 liters was collected and the time again recorded so that by subtraction a value for the flow rate was determined.

At first it was thought that the frequency would remain at its initial setting throughout the duration of an experiment (three hours). However, checks showed that after two or three flow rate measurements the frequency had wandered and that this deviation was most pronounced with the higher frequencies used. Accordingly it was decided that a check could be made after each run (at high frequency) or after every other run (at low frequency) to ensure the accuracy of this important variable.

The SANBORN recorder was switched on for short periods during the experiments to provide several readings of the waveform from which an average, overall frequency could be found. When the liquid pumped was water, the inlet to the constant head tank was connected to the cold water tap. However, when another fluid was used, the supply came from a large container placed on top of a tall stand at a level that was always above that of the tank. Thus a flexible tube could simply be run down directly into the top of the tank to supply the pump.

III. RESULTS AND DISCUSSION

(i) The first 10 runs were carried out using tap water with a range of settings employed for the amplitude and the frequency. The three settings employed for amplitude were: 97 mm, 145 mm and 183 mm whilst frequency had four nominal values: 1.23 Hz, 1.43 Hz, 1.77 Hz and 2.13 Hz. The error in the measurement of the frequency was greater than that in measuring amplitude for reasons mentioned above namely the tendency for the frequency to decrease with time. No such behaviour was possible with amplitude as this variable was controlled by the fixing of the positions of two valves on a threaded shaft by securing nuts. The rationale behind the selection of these values was to provide a reasonable range of experimental settings within the limitations of the apparatus. With the present driving system an upper limit on frequency was about 2.35 Hz, but it was found that 2.13 Hz was a safer upper limit, because of the problems of reproducibility and shooting up past the top valve. The former problem stems from the fact that high amplitude-high frequency settings consumed much more energy than low amplitude-high frequency ones did. The latter arises because the momentum of the shaft at high frequency is sufficient to carry it past the valve. The top limit for amplitude was determined by the physical arrangement of the brass shaft which was located in the U-tube system by a "spider" bolted in between two sections of glass tube. At large amplitudes the brass shaft tended to jump clear of the central hole on the upstroke and to jam on the main body of the spider on the following downstroke. The lower limits for amplitude and frequency were chosen so that "reasonable" size heads could be overcome; a minimum of 140 mm was chosen as the lower limit.

Several conclusions can be drawn from the data (see Figures 8-17). The simplest one is that an increase in amplitude or an increase in frequency leads to an increase in the flow rate at any particular head, the value of the head at zero flow (the "shut-off head") and the maximum flow rate possible. It could be seen, even from the raw data however, that the effect which frequency and amplitude had on say shut-off head were not equivalent. For example, if the values of the product of amplitude and frequency for tables 2 and 9 are compared they are nearly the same, but the shut-off head for run 9 (i.e. the run at higher frequency) is much greater than that for run 2. Thus it was decided to plot both amplitude at fixed frequency and frequency at fixed amplitude against the shut-off head using log-log paper. The shut-off head is important, because it represents the maximum possible pressure drop across a pump. If a number of pumps are placed in series, say in a pipeline, then their spacing is limited by the value of the shut-off head. The results presented in Figure 18 show slopes for amplitude and frequency of 1.05 and 2.1 respectively. Figure 19, Head versus Af^2 gives some idea of the error involved in the correlation. These values, close to unity and two, suggest the possibility of the correlation having some theoretical basis. However, because of the non-uniform waveform produced by the apparatus an analytical approach was considered too complex to attempt within the scope of this report.

The waveform, as recorded on the SANBORN machine, was a non-uniform triangle. The downward velocity of the baffles was greater than the upward velocity for all cases. However, at high frequency when shaft weight effects became less important, the waveform approached more nearly an isosceles triangle.

(ii) It was decided to investigate the effect of fitting orifice plates to the system at two points P and Q (Figure 2). Two sizes of brass plate were used with diameter 38.1 mm and 25.4 mm which compare to a pipe diameter of 50.8 mm. The orifice plates were placed with the bevelled sides facing downstream so as a strict comparison could be made between plates irrespective of the method of machining. Figures 20 and 21 summarise the results obtained.

It is clear by comparing Figures 20 and 21 with Figure 9 (the same amplitude and frequency, but no orifice fitted) that in none of the four cases considered was performance improved by the presence of an orifice, the major deterioration being seen with the smaller plate. The area of an orifice is proportional to diameter squared and hence the ratio of size is not 38.1:25.4 or 3:2, but rather 9:4. It was observed that the shut-off head was not radically decreased, but the maximum flow rate was cut back considerably. The upper position, Q, was selected as it was reasoned that an orifice might restrict the small backward motion associated with the baffles. Observation of the fluid in the area of the plate showed, however, that liquid was thrown up through the orifice and that an "interference" effect was set up. It appeared that liquid was descending in the area of the plate whilst the baffles were ascending and vice versa.

(iii) The number of baffles in the system was doubled by making another assembly exactly like the original (see Figure 1). In order to fit the two sets onto the brass shaft the "spider" had to be removed; the extra weight of the second baffle ensured that the whole system remained relatively fixed in a vertical plane. The results are presented in Figures 22-24 (c.f. Figures 8-10). El Sayed found that doubling the number of baffles from 6 to 12 resulted in an increase of almost 100% in the pressure produced for a given velocity. In doubling from 12 to 24 the increase in head is only 10-20% and so we may conclude that no linear relationship exists between the number of baffles and the maximum head that they can produce. This finding may be a result of the increased friction with the larger number of baffles present or it may be that within a certain length of pipe there is a maximum net pressure attainable.

(iv) As Lacey[13] has reported, the effect of a very dilute solution of polyethylene oxide is to reduce the drag by the apparent suppression or diminution of turbulence. A solution of polyethylene oxide $\{(CH_2)_2O\}_n$, a white powder, was made up in ethanol and added to the constant head tank so that the concentration was around 50 parts per million (p.p.m.). Further supplies were added during the course of the experiment and whilst the exact amount of polyethylene oxide present was not known, its concentration was kept above 10 p.p.m. Four runs were undertaken (Figures 25-28) and the improvement in performance was (c.f. Figures 8-11) confined to a slightly larger throughput at lower values of the head. It therefore appears that the use of polyox in pulsating systems fitted with baffles is of only small value.

(v) It was decided to investigate the effect on characteristic curves of a change in the kinematic viscosity (viscosity ÷ density) of the liquid being pumped by performing experiments with glucose solution. Glucose was chosen because it is relatively cheap, easily available and straightforward to handle. An inhibitor, Sorbic acid (0.02% by weight), was added to reduce bacterial growth and fermentation. The glucose solution had a viscosity of 5.7×10^{-3} Pa.s (5.7 c.p.), at 20°C measured in a viscometer. Because glucose is not available from a mains supply certain modifications to the equipment described in Figure 2 had to be undertaken (see Figure 7). Basically the supply came from a large reservoir located at a higher level than the constant head tank and after the glucose had been pumped and measurements taken it was poured manually back into the large reservoir. The results are presented in Figures 29-32 (c.f. Figures 8-11 and Figure 16). It is noticeable that for each set of conditions used there is a decrease in both the flow at any particular head and the head attained at each flow. In other words the curves are moved down towards the origin; for instance the shut-off head is reduced by approximately 20-30%. This result is expected as the energy used to overcome the increased drag caused by the use of a more viscous liquid means a consequent decline in performance.

(vi) The liquids used thus far could be handled successfully with a regular pump. It was therefore decided to obtain characteristic curves for the pump using a filter pulp slurry as the liquid. 408.9 g of Filter Pulp (Ash-free Analytical Pulp, Schleicher & Schvell Inc.) was mixed into 45 liters of tap water and the resultant slurry (9.1 g of pulp per liter) was fed into the pump using the apparatus shown in Figure 7. A larger exit tap from the feed tank had to be used as the original one became clogged with pulp and prevented flow from occuring. Whilst the slurry was not very viscous it was highly non-Newtonian. The results (Figures 33-35) show that the pump was successful in handling the slurry without becoming clogged and without a separation of water and pulp occuring. The heads and flow rates obtained were comparable with those recorded for the pumping of Glucose and are thus reasonably satisfactory. Despite the small concentration of pulp used, the fact that the fibres absorb water means that they occupy a much greater volume and have a much greater effect on the liquid's properties than would be expected. Concentrations of pulp in the region of 9.1 g/l have been used by other workers. Hamer and Blakeborough[14] state that if concentrations were measured on a wet volume basis 5 g/l would occupy a volume approaching 20% of that of the system.

IV. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

The apparatus can be successfully and reliably operated as a valveless pump. Flow rates of up to 150 ml/s of water (120 gallons per hour) have been achieved and the maximum head recorded was 470 mm (18.5 ins.) (Figure 14) of water. These figures are sufficiently promising to warrant further research to be undertaken. This work could develop in several different directions.

A larger scale model could be constructed and the pulsation system modified to allow higher velocities. One refinement, which was excluded from the above work through lack of time, was the investigation of a non-symmetrical triangular waveform. This was to have been achieved by adjusting the rate of air escape from the driving cylinders in the MAXAM system. The installation of throttle valves on the exit pipes would allow say a slow upward motion of the baffles followed by a fast downward motion. Another possibility would be to produce a sinusoidal waveform which would allow a mathematical analysis of the system to be undertaken.

The experiments with glucose and filter pulp show that the pump can handle viscous liquids or slurries quite easily, albeit with a reduced performance from that recorded with water as the fluid.

Energy considerations have not been mentioned in this report. It would be useful to evaluate the efficiency of the pump accurately by using a strain gauge attached to brass shaft. El Sayed, using rough calculations based on the area under the Pressure-Volume diagram, reported on efficiency of 10-20% almost the same as a liquid jet pump tested by Walkden and Kell(15).

The fact that the flow rates produced are large whereas the heads are only moderate to small suggests a possible use of the pump in a mixing vessel. The baffles would act to produce a circulating pattern within a mixing tank by pumping liquid from the base of the tank to the top.

TABLE OF EXPERIMENTAL ERRORS

The estimated errors of the principal variables are:

- Pipe diameter: Nominally given as 50.8 mm. Taking into account deviations from roundness, caliper error, etc. the uncertainty is about ±2%

- Measurement of amplitude: Error is estimated as ±4 mm

- Frequency: An error of ±1% is estimated

- Flow Rate: Due to the errors in timing an uncertainty exists of about ±5%

- Head: An error of ±5 mm exists

- Viscosity of Glucose: The error in viscometer readings is ±2%

TABLE 1 (Figure 8)

Flow Rate (ml/s)	Head (mm)
31.91	124
63.82	52
63.82	31
48.39	82
37.97	103
28.85	133
68.18	65
50.00	94
76.92	11
61.22	73
0	183
21.43	144

A = 145 mm f = 1.43 Hz

TABLE 2 (Figure 9)

Flow Rate (ml/s)	Head (mm)
100.0	78
50.00	125
125.0	44
120.0	68
74.95	112
39.47	168
125.0	46
136.4	26
73.17	154
0	240

A = 145 mm f = 1.43 Hz

TABLE 3 (Figure 10)

Flow Rate (ml/s)	Head (mm)
86.24	152
68.18	224
130.4	102
136.4	53
136.4	24
83.33	148
25.42	321
34.88	268
18.99	328
0	365
48.39	294
47.62	276
51.72	236
45.45	257
52.63	176
45.45	205
14.93	336
25.86	303

A = 145 mm   f = 1.75 Hz

TABLE 4 (Figure 11)

Flow Rate (ml/s)	Head (mm)
107.1	240
166.7	76
166.7	34
130.4	136
130.4	182
166.7	96
50.00	344
55.56	285
60.00	314
38.46	401
53.57	337
38.96	400
44.78	366
39.47	378
15.87	430
81.08	272
0	465

A = 145 mm   f = 2.13 Hz

TABLE 5 (Figure 12)

Flow Rate (ml/s)	Head (mm)
62.50	102
71.43	56
78.95	20
76.92	38
65.22	73
63.83	89
55.56	112
27.78	168
36.59	158
38.96	148
18.29	186
75.00	37
54.55	114
78.95	11
0	224

A = 85 mm   f = 1.75 Hz

TABLE 6 (Figure 13)

Flow Rate (ml/s)	Head (mm)
45.45	128
76.92	12
62.50	70
68.18	44
61.22	88
38.96	158
58.82	118
44.78	135
25.86	166
0	220
57.69	43
71.43	16
50.00	103
62.50	48
52.63	82

A = 183 mm , f = 1.22 Hz

TABLE 7 (Figure 14)

Flow Rate (ml/s)	Head (mm)
96.77	153
107.1	84
96.77	118
90.90	19
96.77	47
52.63	176
100.0	132
52.63	303
54.55	246
48.39	229
53.57	270
36.14	361
30.30	380
12.27	422
47.61	335
0	470

A = 183 mm f = 1.75 Hz

TABLE 8 (Figure 15)

Flow Rate (ml/s)	Head (mm)
21.74	146
65.22	35
62.50	63
50.85	89
69.77	20
61.22	53
53.57	82
58.82	73
42.25	102
31.91	112
34.48	136
0	180

A = 97 mm   f = 1.74 Hz

TABLE 9 (Figure 16)

Flow Rate (ml/s)	Head (mm)
93.75	116
62.50	196
66.66	150
93.75	44
85.71	75
81.08	106
76.92	132
68.18	168
90.91	114
96.77	32
30.00	234
27.27	273
44.78	200
41.10	234
0	348
16.48	300

A = 97 mm   f = 2.15 Hz

TABLE 10 (Figure 17)

Flow Rate (ml/s)	Head (mm)
50.85	199
81.08	98
88.24	32
81.08	59
63.83	152
68.18	138
58.82	179
40.00	216
81.08	124
0	294
25.42	251
11.27	270
27.52	227

A = 183 mm   f = 1.44 Hz

TABLE 11 (Figure 20)

Flow Rate (ml/s)	Head (mm)
41.66	150
57.69	103
75.00	50
75.00	23
60.00	70
55.56	94
47.62	130
61.22	78
58.82	114
42.85	162
19.20	208
39.47	162
0	231

A = 145 mm   f = 1.43 Hz

TABLE 12 (Figure 20)

Flow Rate (ml/s)	Head (mm)
73.17	108
44.12	153
83.33	53
78.94	21
50.85	128
25.86	178
66.66	94
71.43	38
68.18	46
50.00	116
0	216

A = 145 mm   f = 1.43 Hz

TABLE 13 (Figure 21)

Flow Rate (ml/s)	Head (mm
45.45	82
57.69	40
56.60	25
48.39	70
35.38	114
29.70	132
15.96	152
35.72	104
49.18	60
54.55	24
0	180

A = 145 mm   f = 1.43 Hz

TABLE 14 (Figure 21)

Flow Rate (ml/s)	Head (mm)
8.20	119
4.12	160
16.00	92
17.78	58
20.83	76
21.28	12
0	200

A = 145 mm f = 1.43 Hz

TABLE 15 (Figure 22)

Flow Rate (ml/s)	Head (mm)
107.1	55
56.60	121
45.45	176
55.56	142
83.33	78
107.1	31
81.08	75
56.60	120
66.67	98
51.72	132
31.58	160
30.00	176
20.13	192
0	232

A = 143 mm f = 1.43 Hz

TABLE 16 (Figure 23)

Flow Rate (ml/s)	Head (mm)
46.88	99
81.08	39
66.67	62
53.57	89
42.25	112
22.22	136
58.82	70
93.75	28
71.43	56
0	174

A = 145 mm f = 1.43 Hz

TABLE 17 (Figure 24)

Flow Rate (ml/s)	Head (mm)
57.69	174
103.5	109
136.4	41
115.4	66
90.91	135
68.18	178
44.12	232
125.0	69
130.4	30
35.29	300
47.62	261
32.97	302
25.64	325
0	372

A = 154 mm f = 1.75 Hz

TABLE 18 (Figure 25)

Flow Rate (ml/s)	Head (mm)
28.84	131
60.00	78
90.91	16
76.92	68
50.00	94
25.64	116
90.91	46
90.91	36
25.93	132
0	174

A = 145 mm f = 1.23 Hz

TABLE 19 (Figure 26)

Flow Rate (ml/s)	Head (mm)
29.17	162
76.92	73
73.17	126
111.1	89
130.4	7
130.4	34
96.77	66
73.77	100
48.00	138
0	208

A = 145 mm f = 1.45 Hz

TABLE 20 (Figure 27)

Flow Rate (ml/s)	Head (mm)
157.9	66
88.24	138
73.17	191
46.15	226
88.24	168
68.18	206
150.0	50
130.4	100
63.83	250
29.41	286
10.21	320
0	345

A = 145 mm f = 1.76 Hz

TABLE 21 (Figure 28)

Flow Rate (ml/s)	Head (mm)
63.82	406
78.95	318
120.0	235
66.67	340
73.17	380
107.1	301
136.4	205
0	464
157.9	161
166.7	80

A = 145 mm f = 2.15 Hz

TABLE 22 (Figure 29)

Flow Rate (ml/s)	Head (mm)
70.00	74
37.84	102
93.33	50
35.90	110
84.21	36
47.06	132
70.00	86
64.00	65
43.75	108
0	180

A = 145 mm   f = 2.12 Hz

TABLE 23 (Figure 30)

Flow Rate (ml/s)	Head (mm)
50.00	100
76.92	31
34.48	88
55.56	90
71.43	43
45.45	76
38.46	110
35.71	140
20.00	126
0	145

A = 145 mm   f = 1.77 Hz

TABLE 24 (Figure 31)

Flow Rate (ml/s)	Head (mm)
77.77	138
58.93	192
76.92	126
62.50	136
111.1	64
83.33	108
66.67	180
52.63	216
41.67	220
71.43	156
111.1	60
52.63	206
125.0	32
0	250

A = 145 mm f = 1.23 Hz

TABLE 25 (Figure 32)

Flow Rate (ml/s)	Head (mm)
35.71	172
125.0	80
62.50	136
66.67	132
111.1	49
100.0	76
83.33	114
52.63	206
52.63	168
45.45	190
0	250

A = 97 mm f = 1.42 Hz

TABLE 26 (Figure 33)

Flow Rate (ml/s)	Head (mm)
125.0	56
83.33	116
125.0	62
111.1	76
100.0	100
58.82	180
71.43	140
142.9	34
167.7	18
100.0	110
76.92	146
42.19	206
0	250

A = 97 mm   f = 2.14 Hz

TABLE 27 (Figure 34)

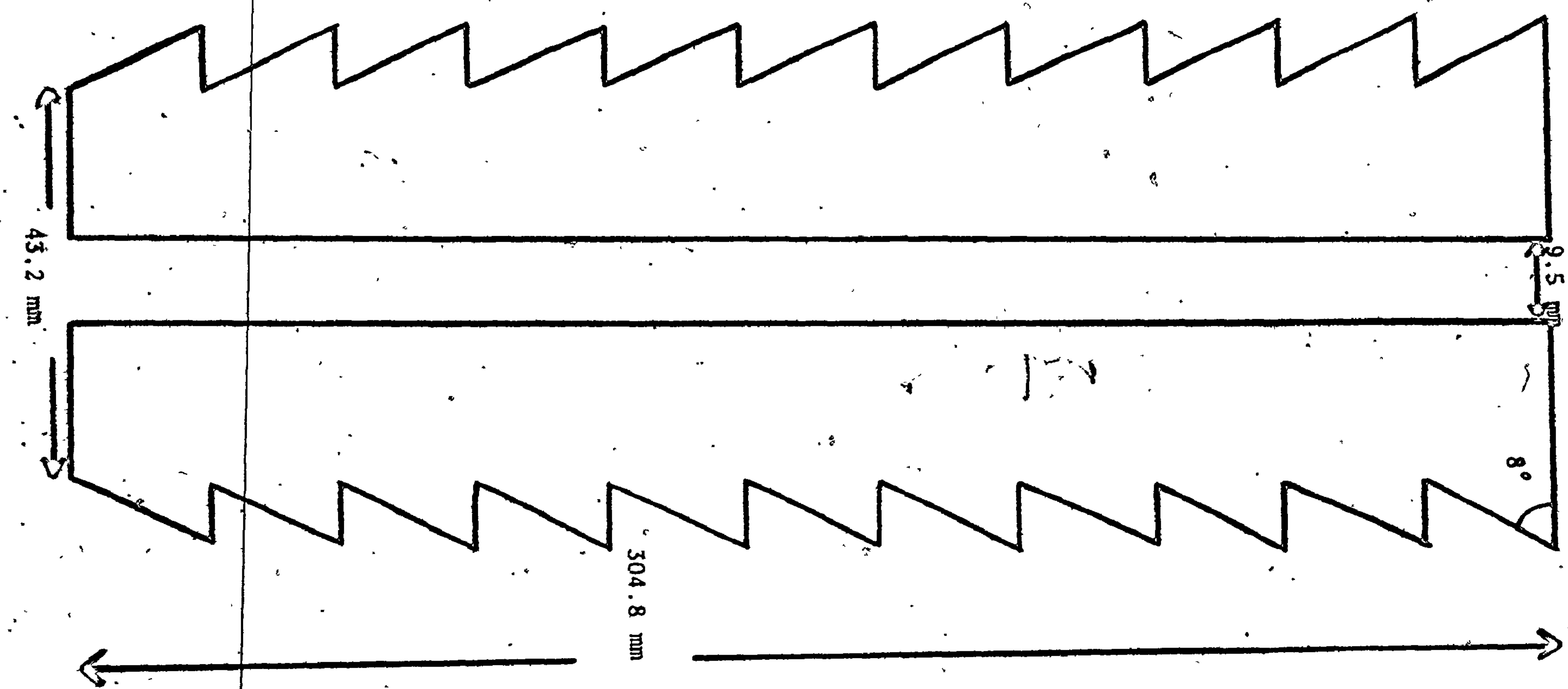
Flow Rate (ml/s)	Head (mm)
111.1	136
125.0	64
142.9	22
125.0	96
83.33	178
111.1	125
100.0	146
133.3	100
153.8	36
62.50	234
111.1	130
100.0	224
0	270

A = 145 mm   f = 1.76 Hz

TABLE 28 (Figure 35)

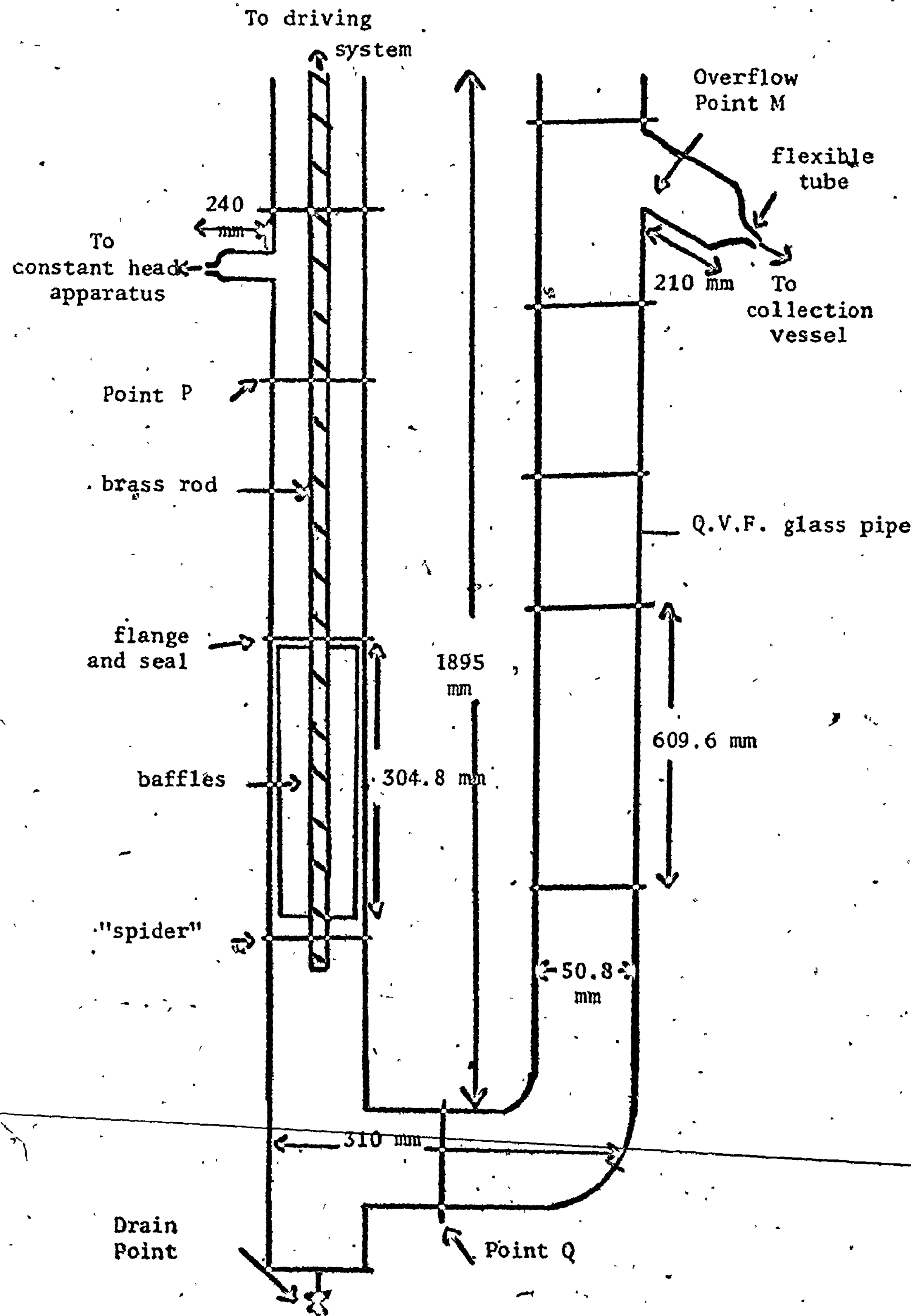
Flow Rate (ml/s)	Head (mm)
55.56	122
111.1	41
76.92	82
133.3	6
76.92	84
111.1	40
90.91	60
83.33	98
105.3	35
76.92	96
71.43	106
105.3	34
0	186

A = 145 mm f = 1.33 Hz

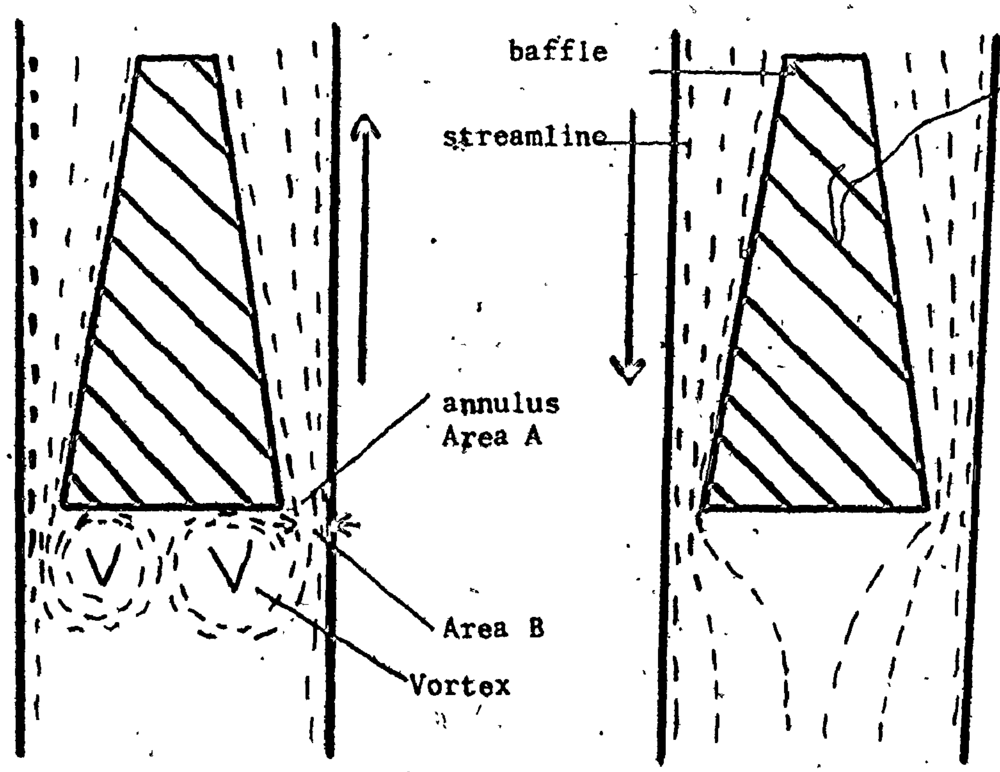


Baffle Assembly

FIGURE 1



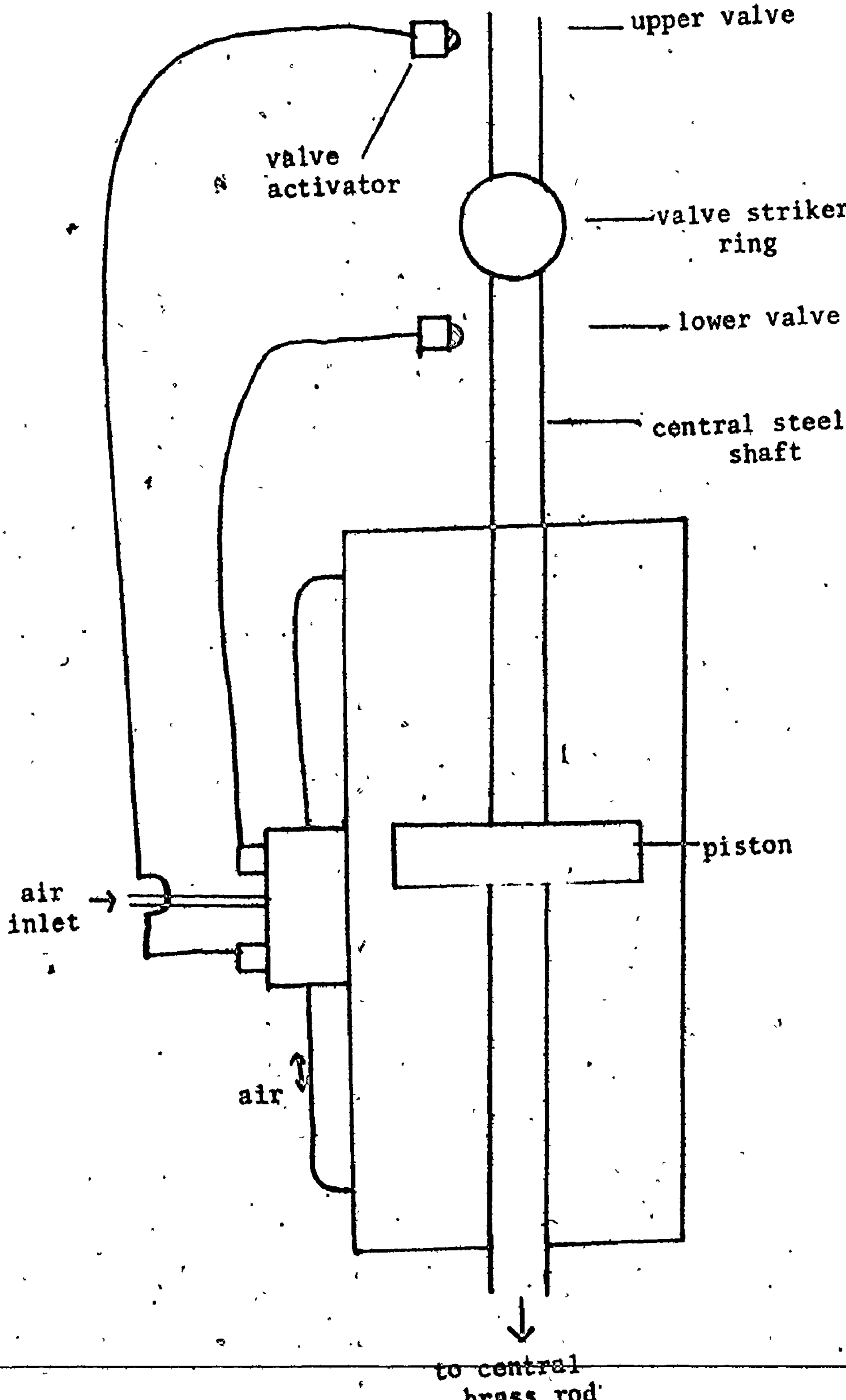
The Valveless Pump



Principle of Operation

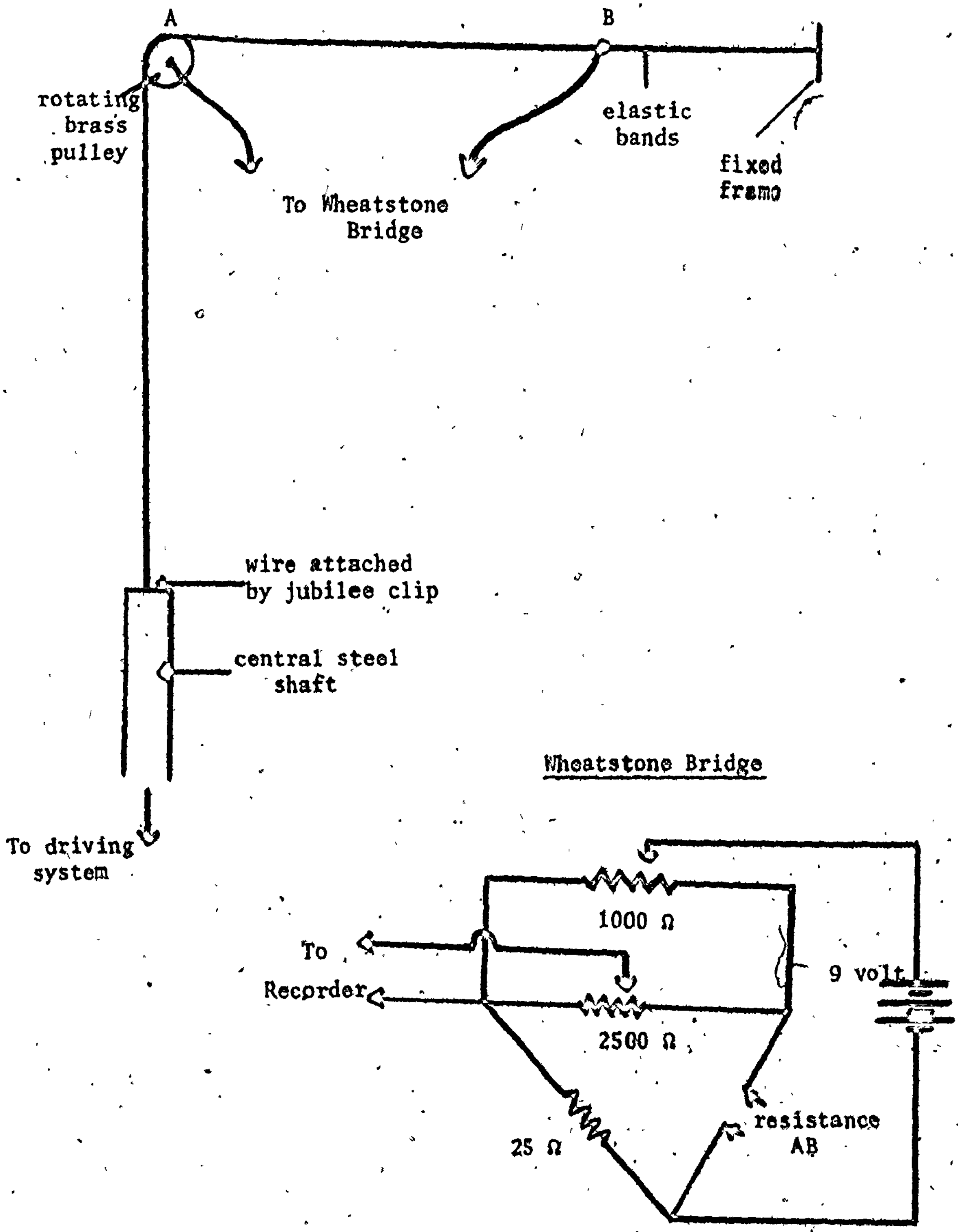
Arrows indicate direction of baffle movement

FIGURE 3



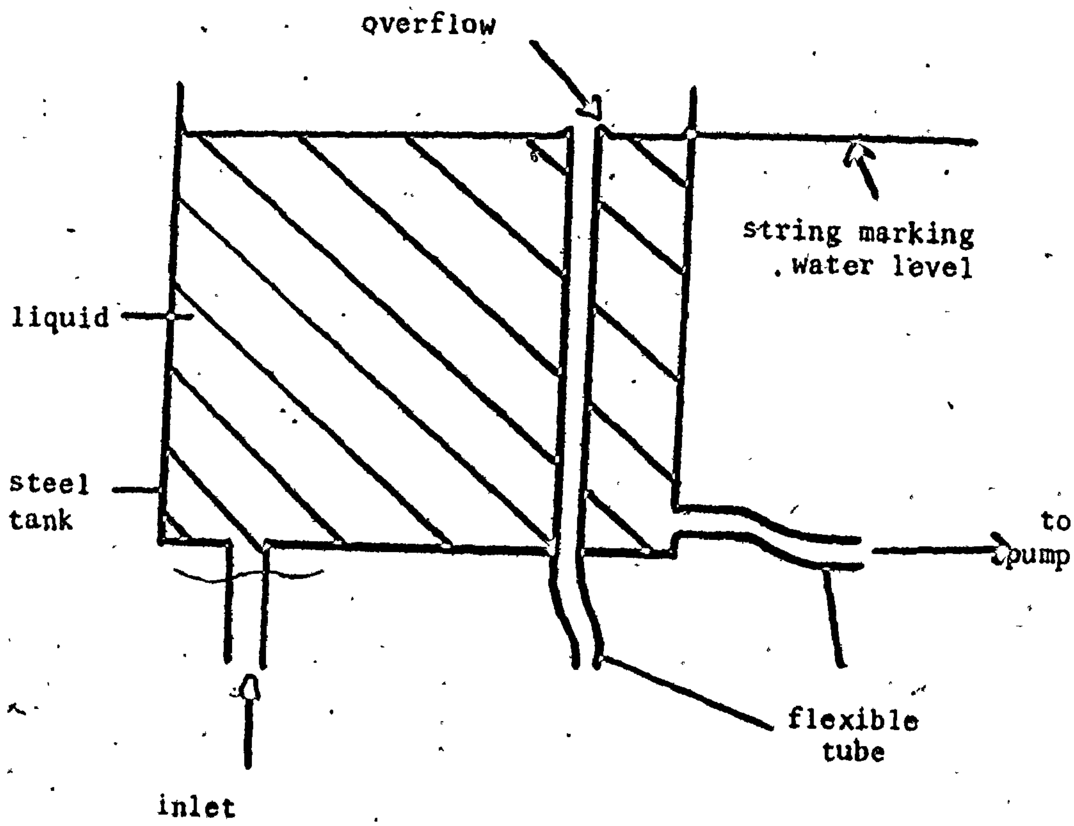
MAXAM Driving System

FIGURE 4



Displacement Recording System

FIGURE 5



Constant Head Apparatus

FIGURE 6

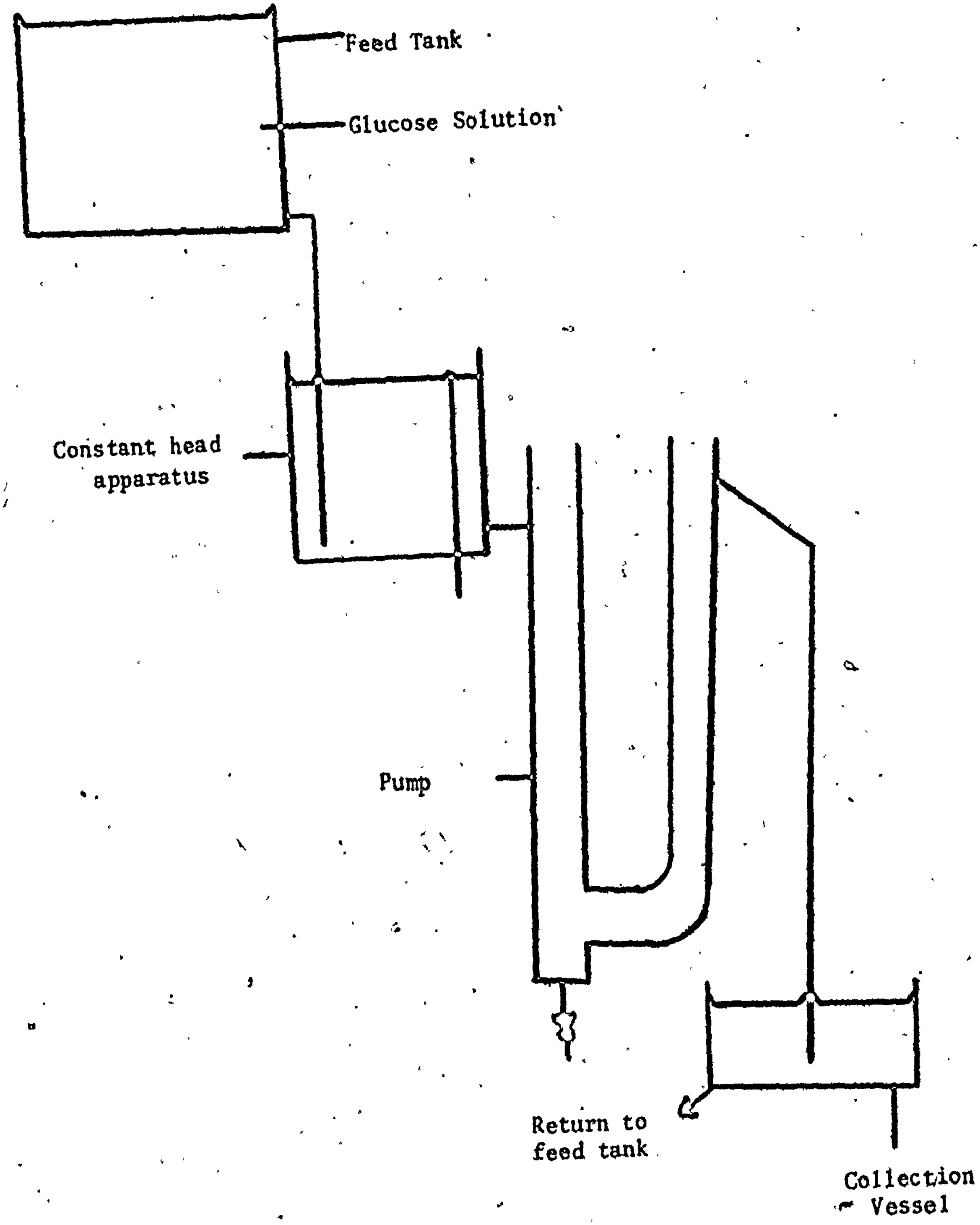


Diagram of Glucose Supply System

FIGURE 7

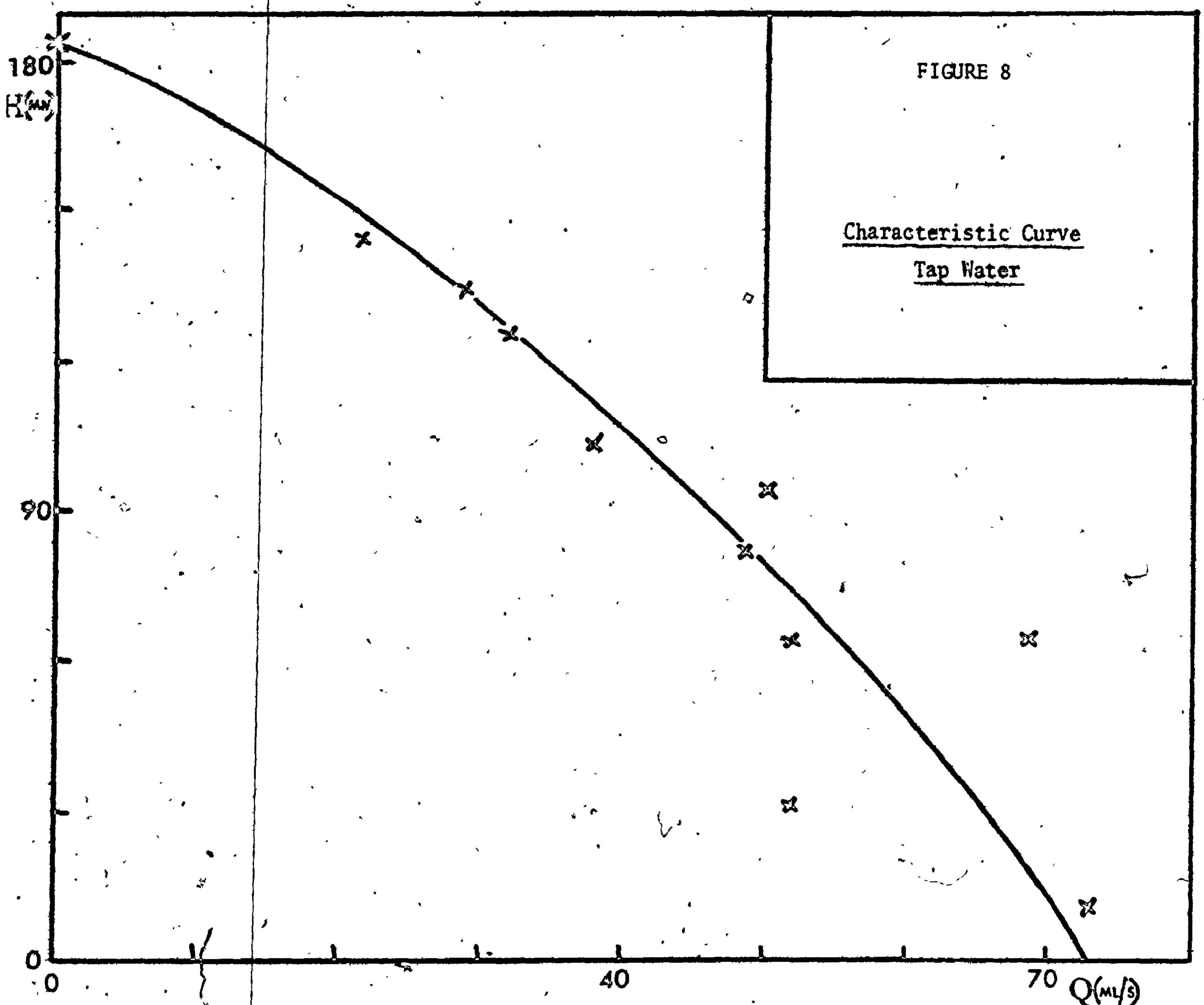


FIGURE 8

Characteristic Curve

Tap Water

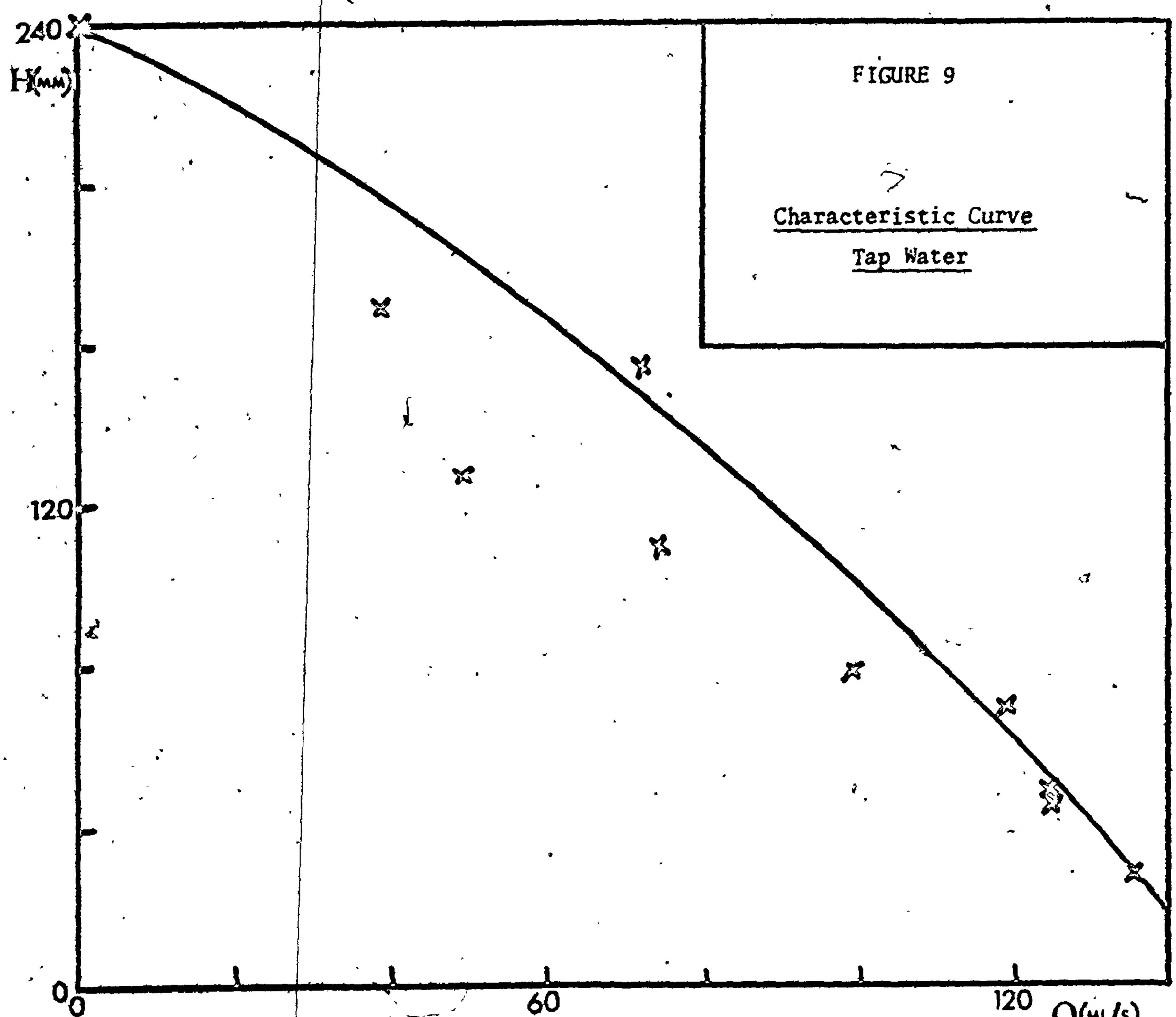


FIGURE 9

Characteristic Curve

Tap Water

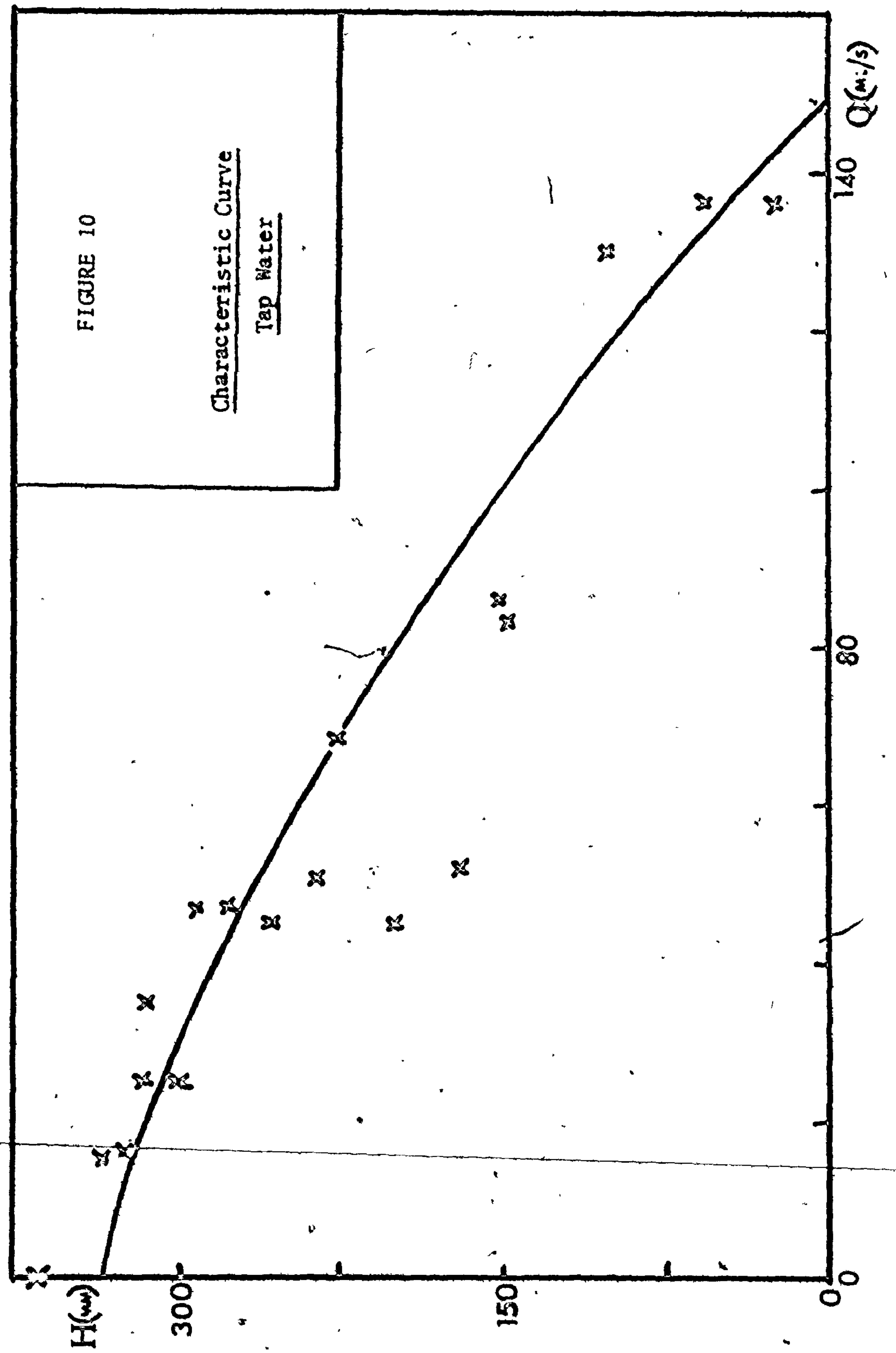
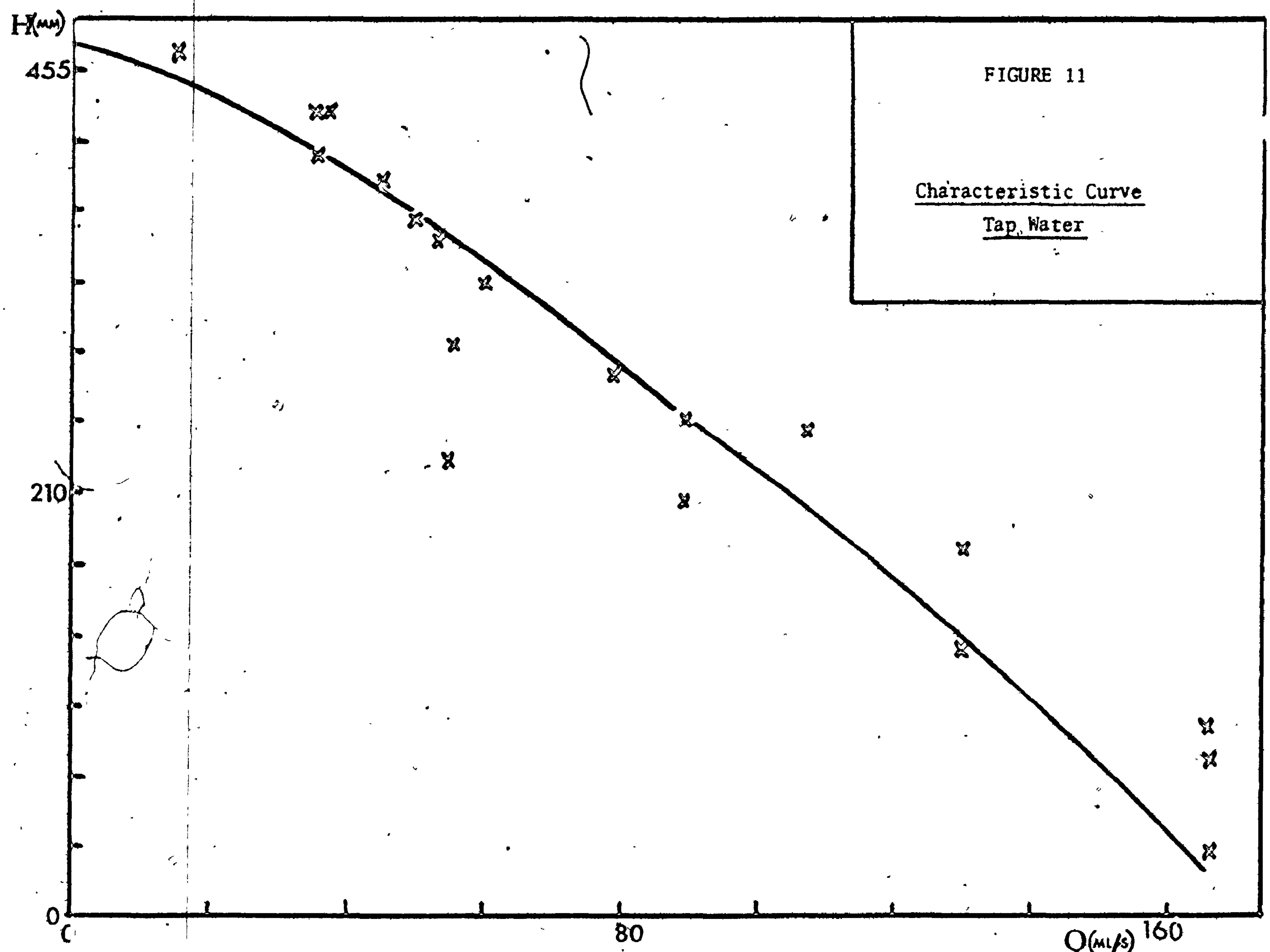


FIGURE 10
Characteristic Curve
Tap Water
H(mm)
300
150
0
Q(ml/s)
80
140


H(MM)
455
210
0
0
80
160
Q(ML/S)
FIGURE 11
Characteristic Curve
Tap Water

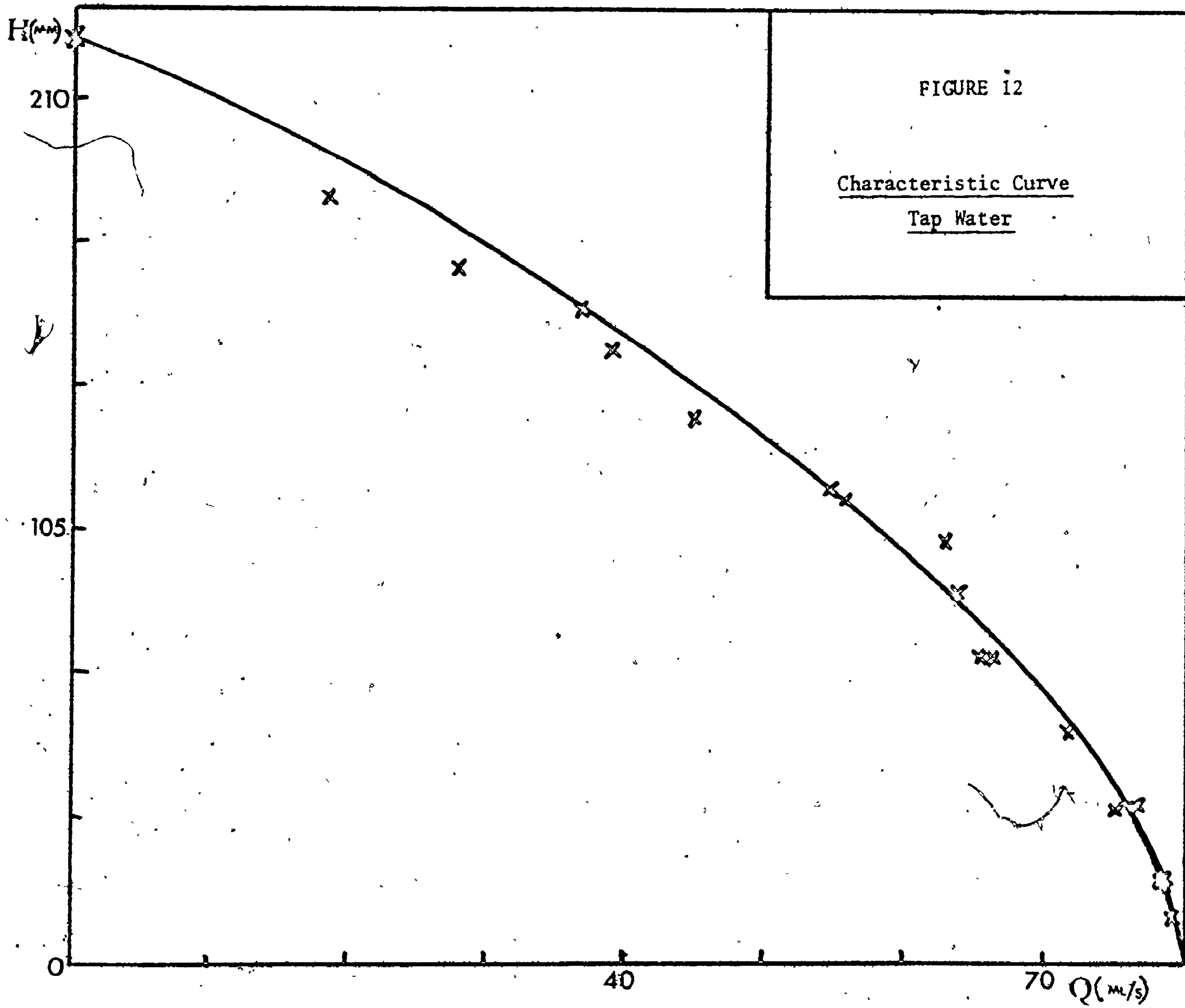


FIGURE 12

Characteristic Curve

Tap Water

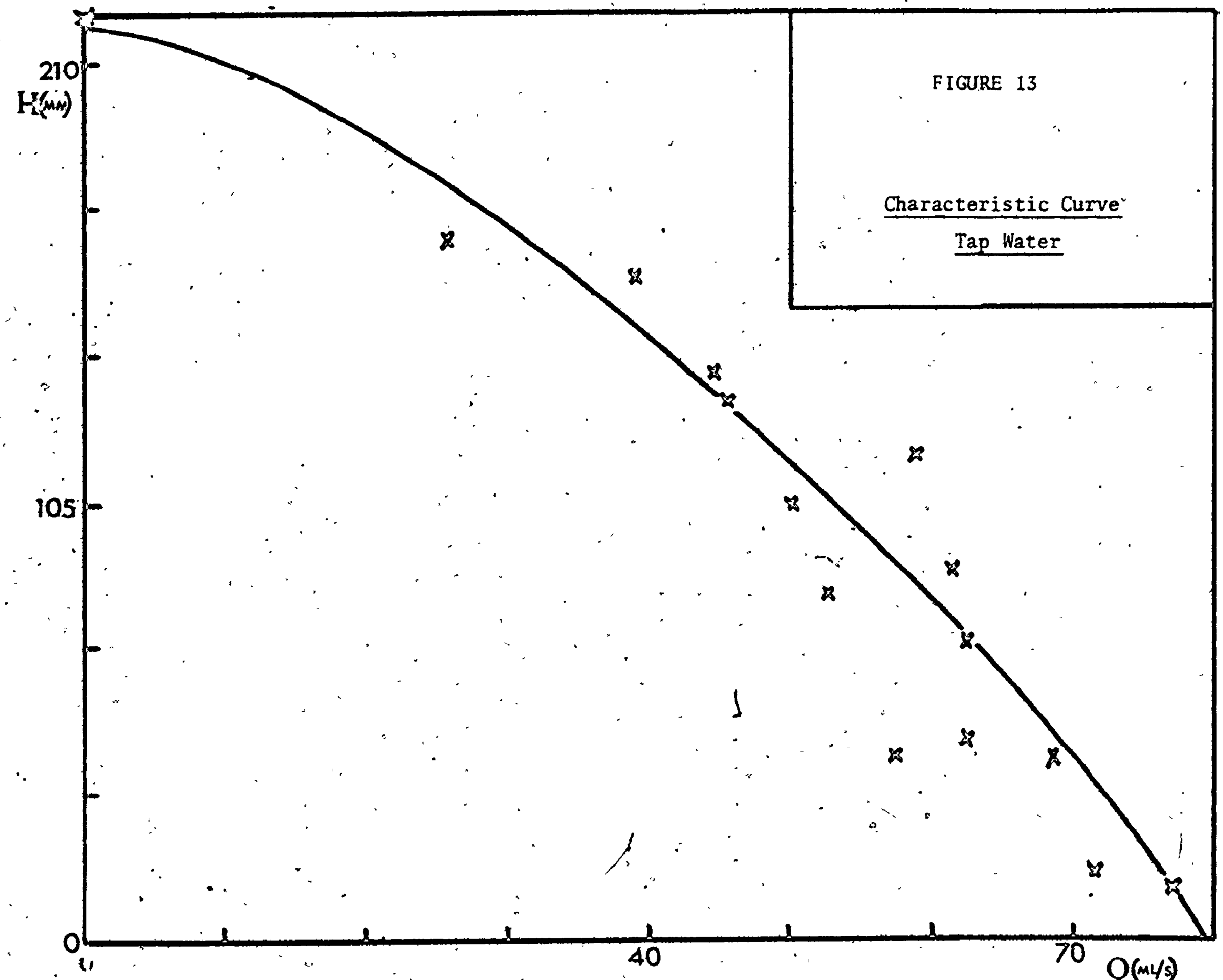
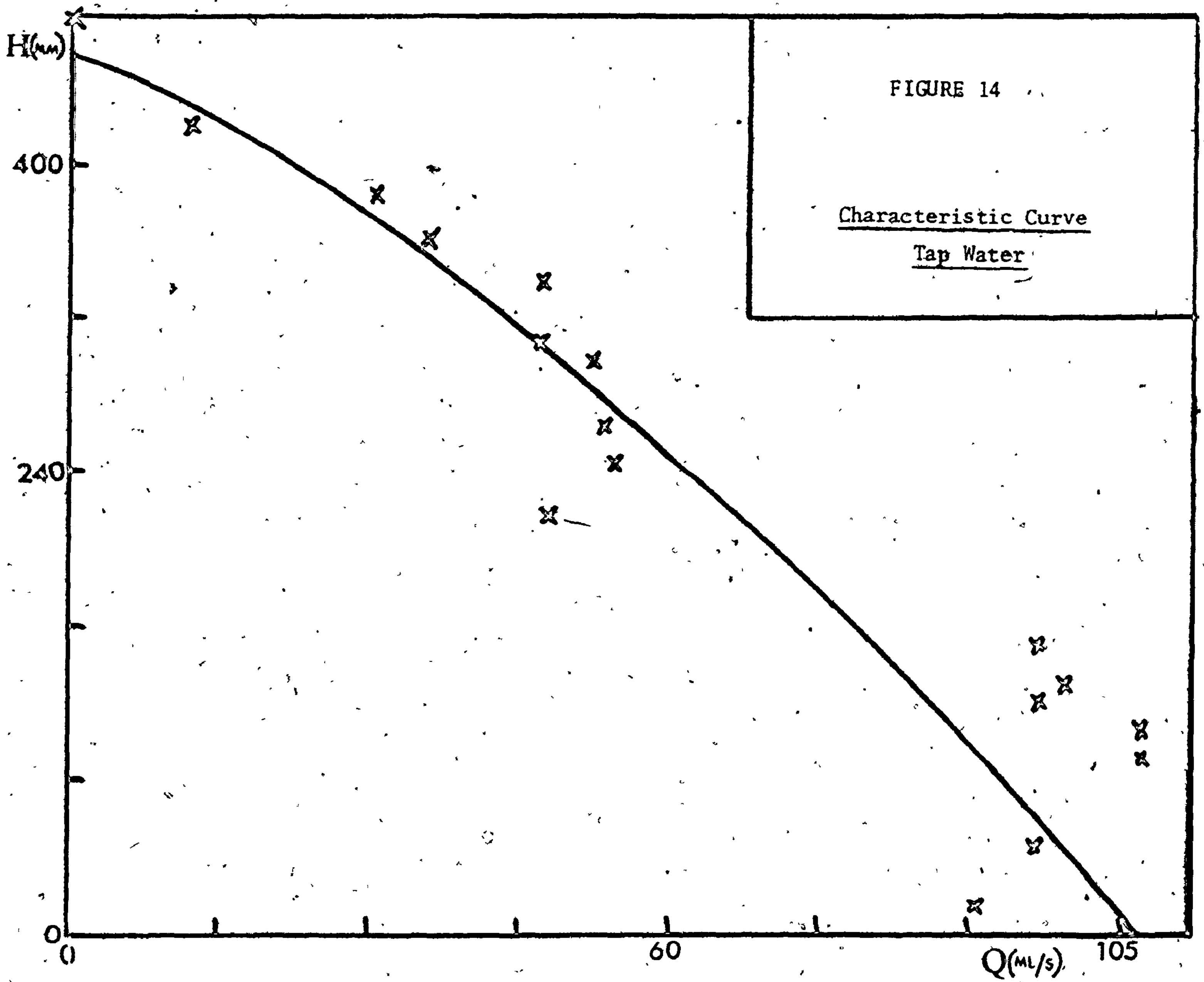


FIGURE 13

Characteristic Curve

Tap Water


H(MM)
400
240
0
0
60
105
Q(ML/S)
FIGURE 14
Characteristic Curve
Tap Water

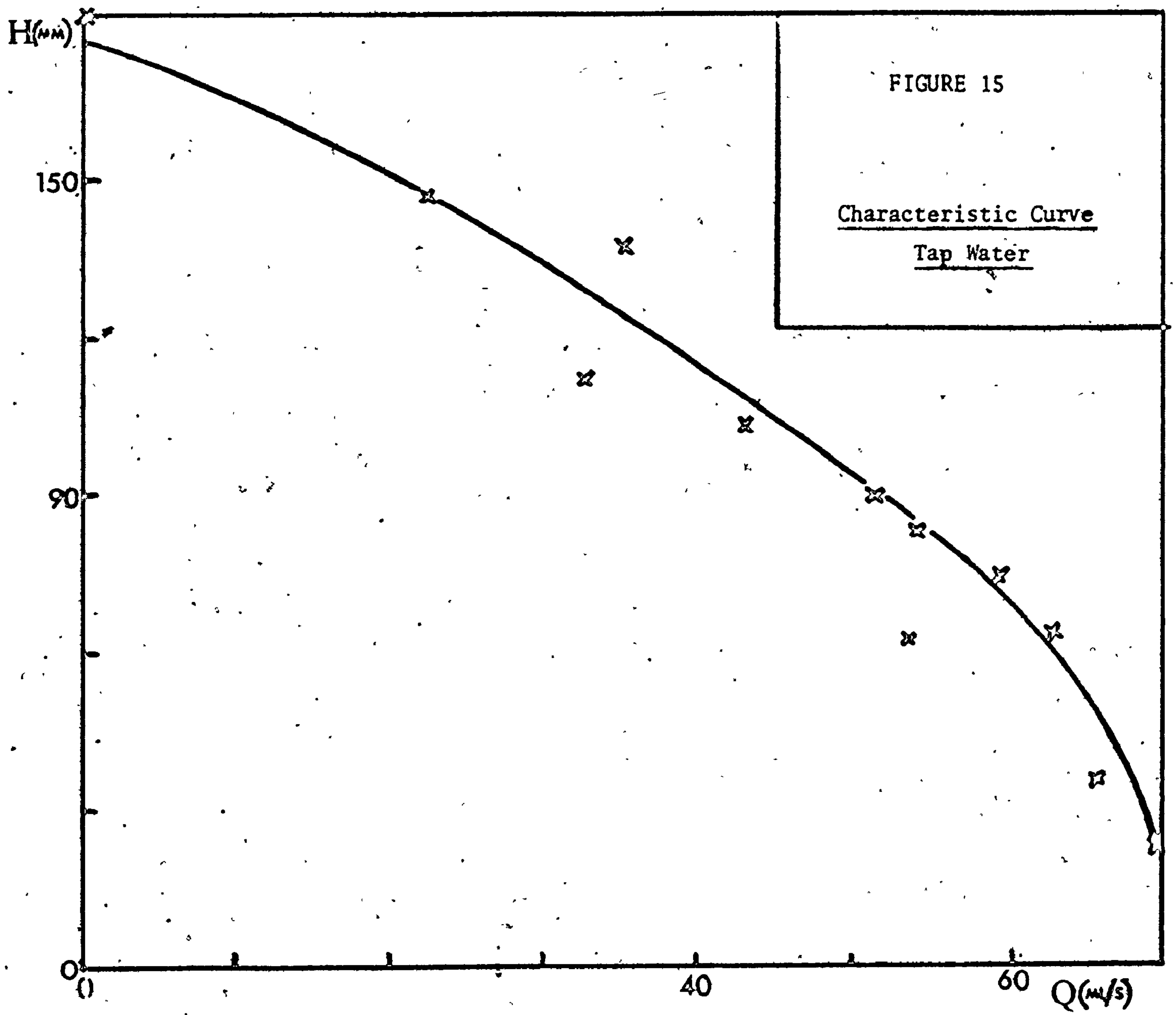


FIGURE 15

Characteristic Curve

Tap Water

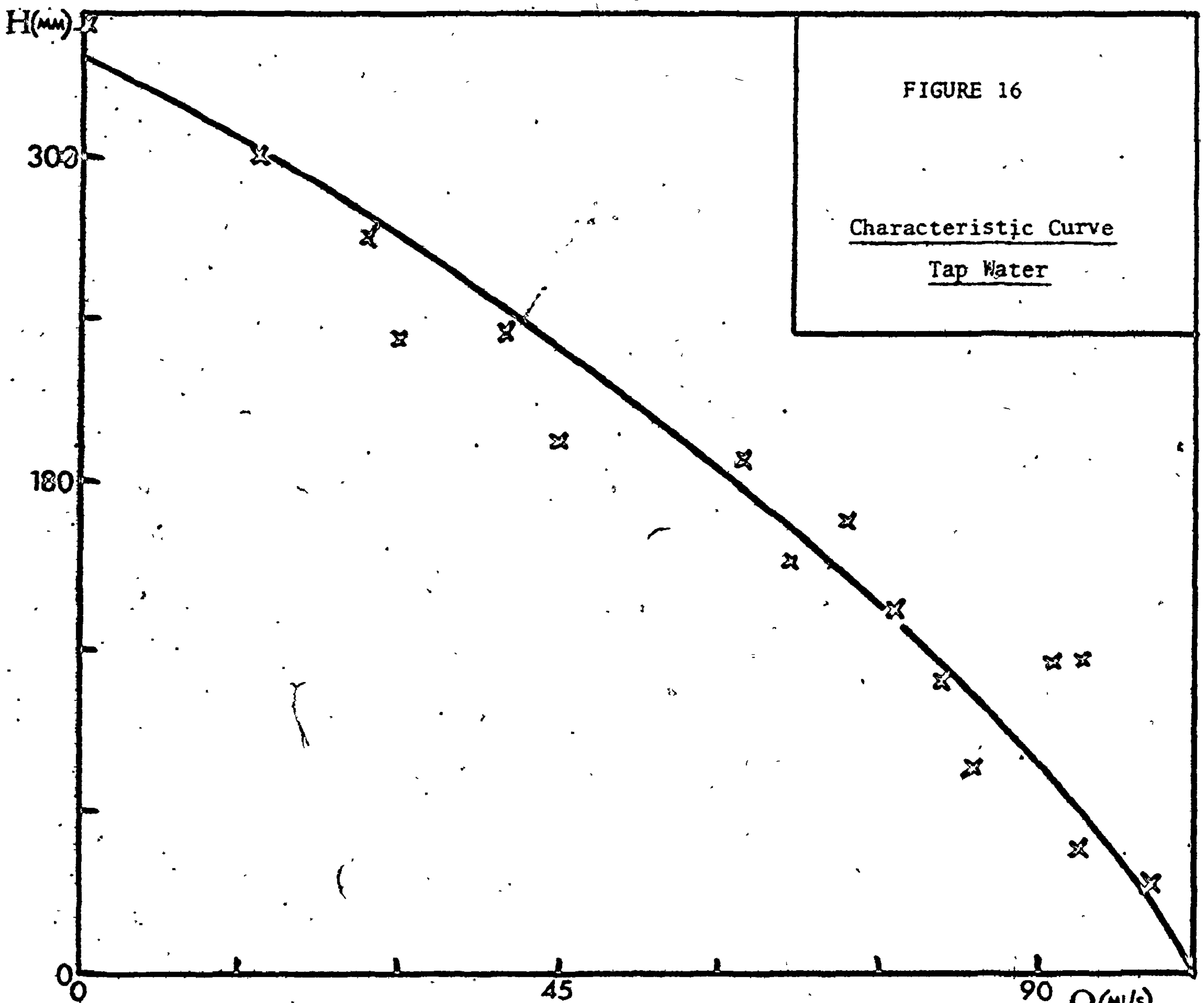


FIGURE 16

Characteristic Curve

Tap Water

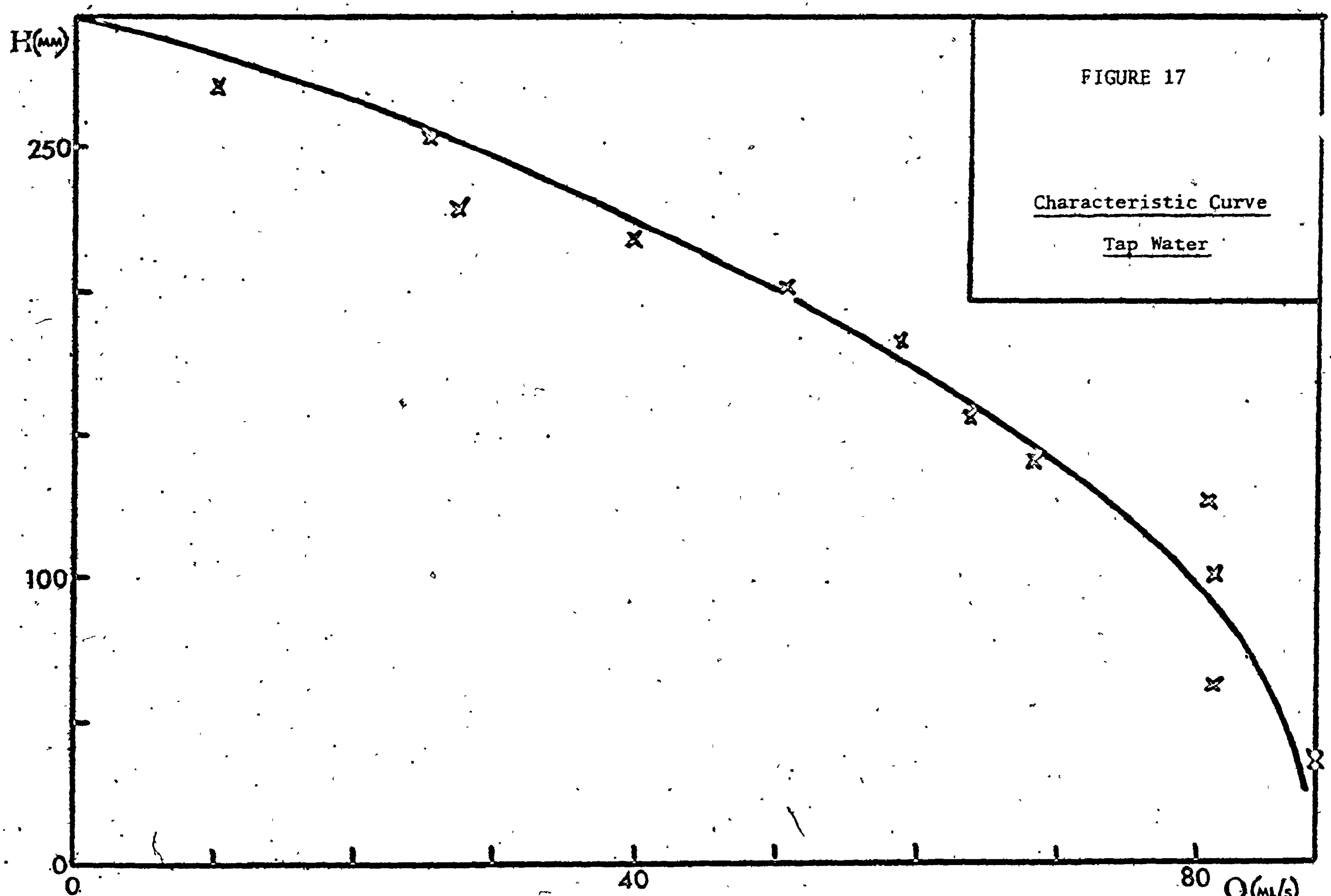
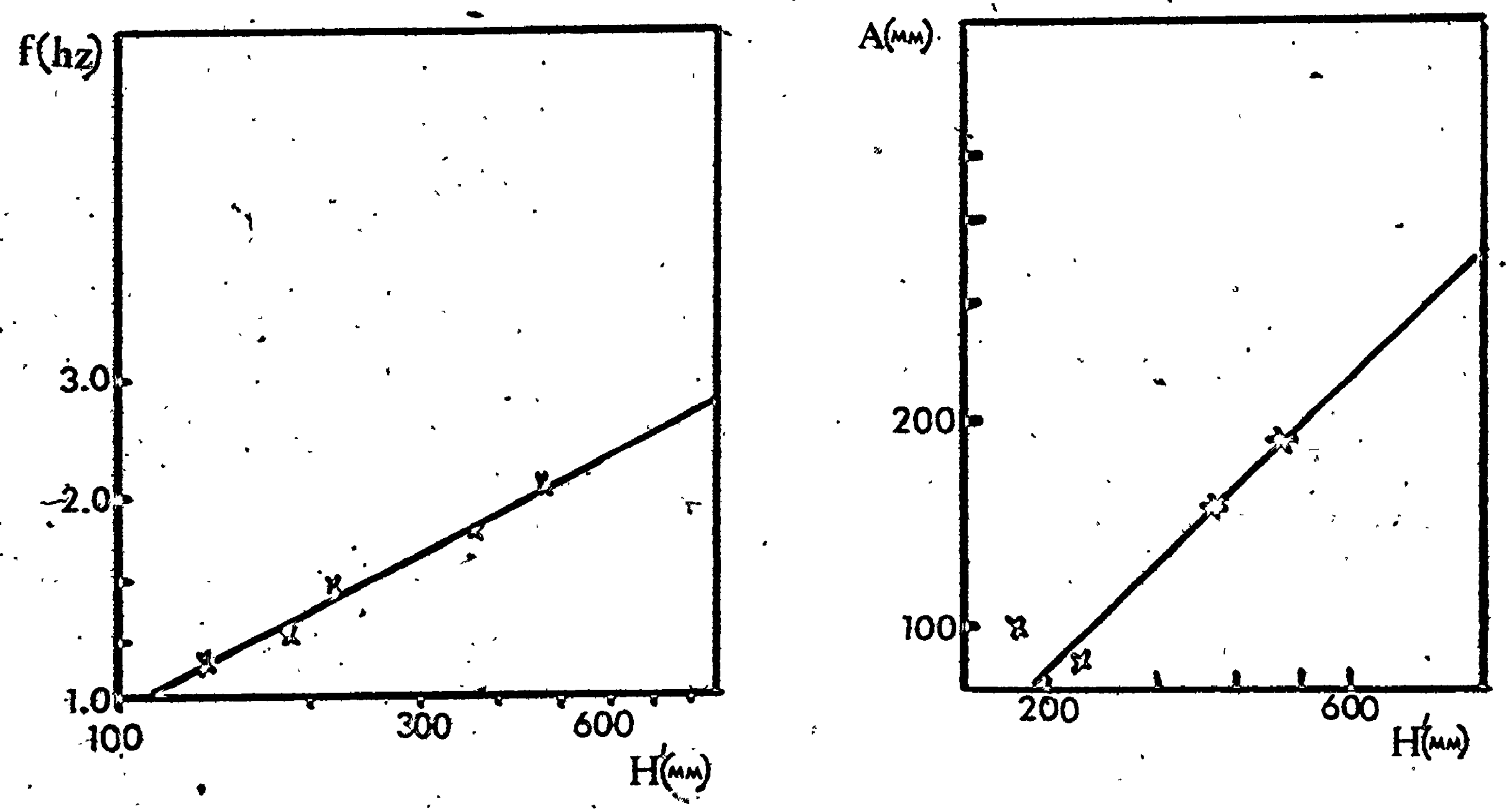


FIGURE 17

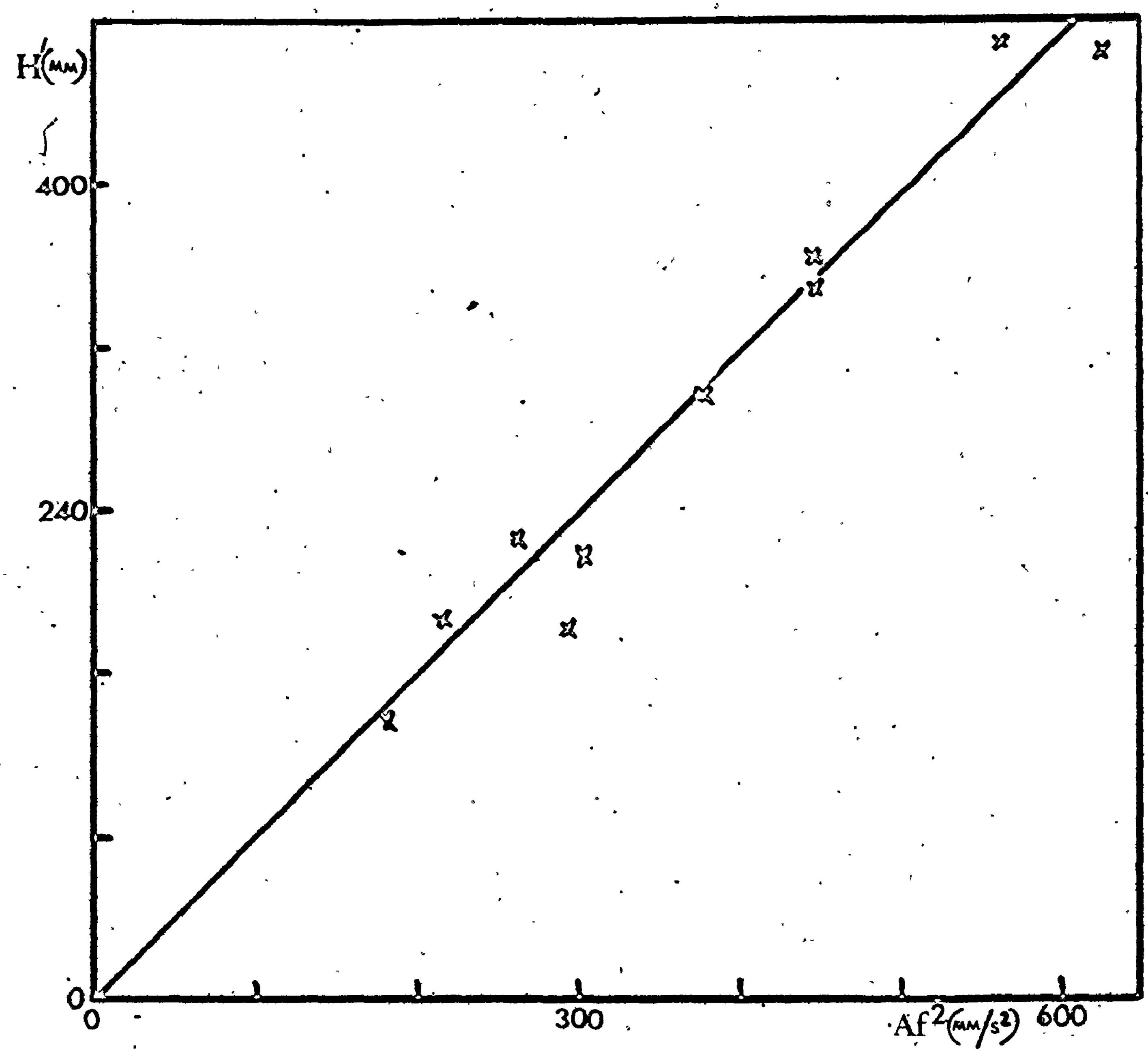
Characteristic Curve

Tap Water



Effect of amplitude and frequency on Shut-Off head

FIGURE 18



Plot of Shut-Off head versus Amplitude x Frequency squared

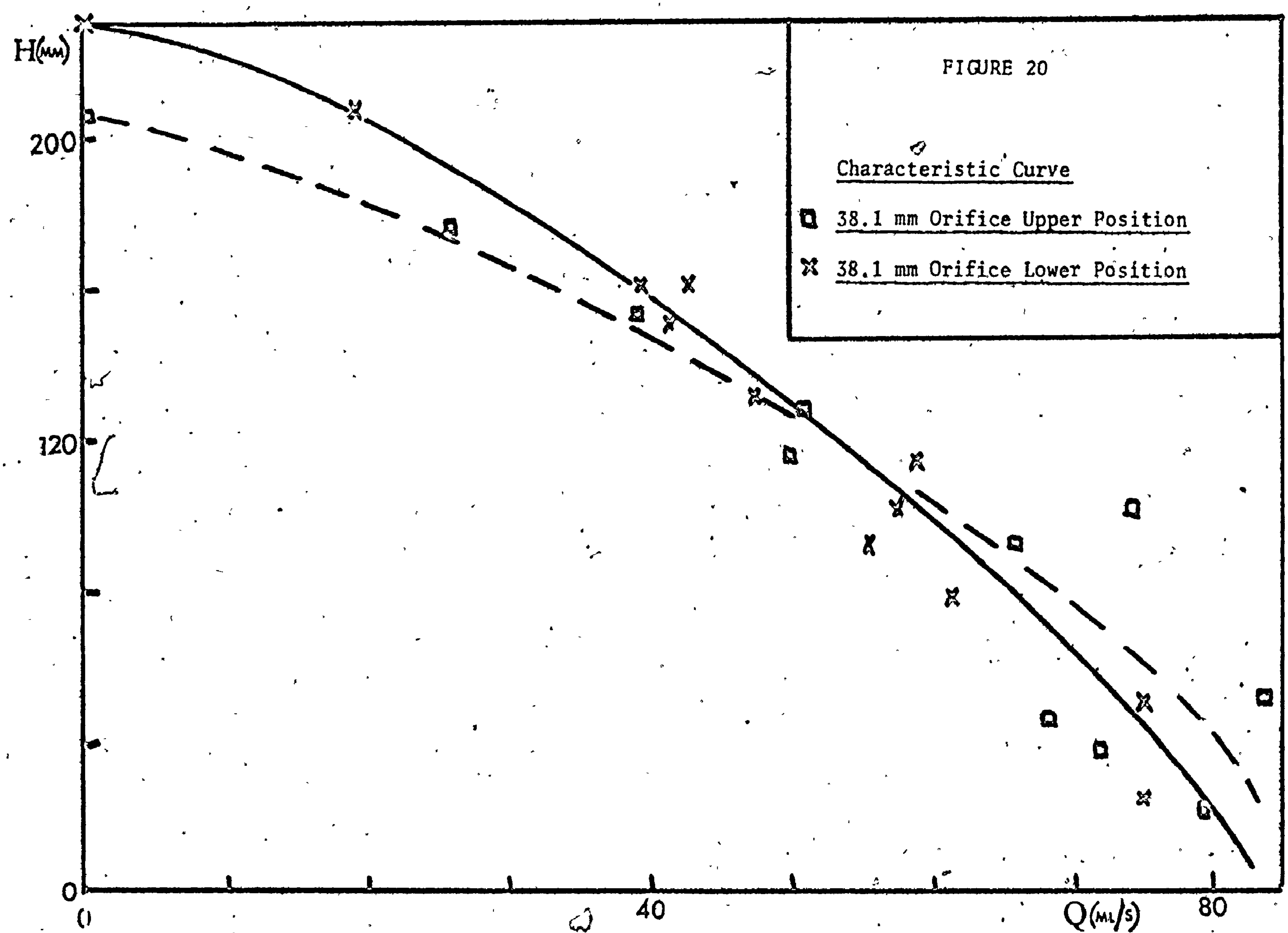
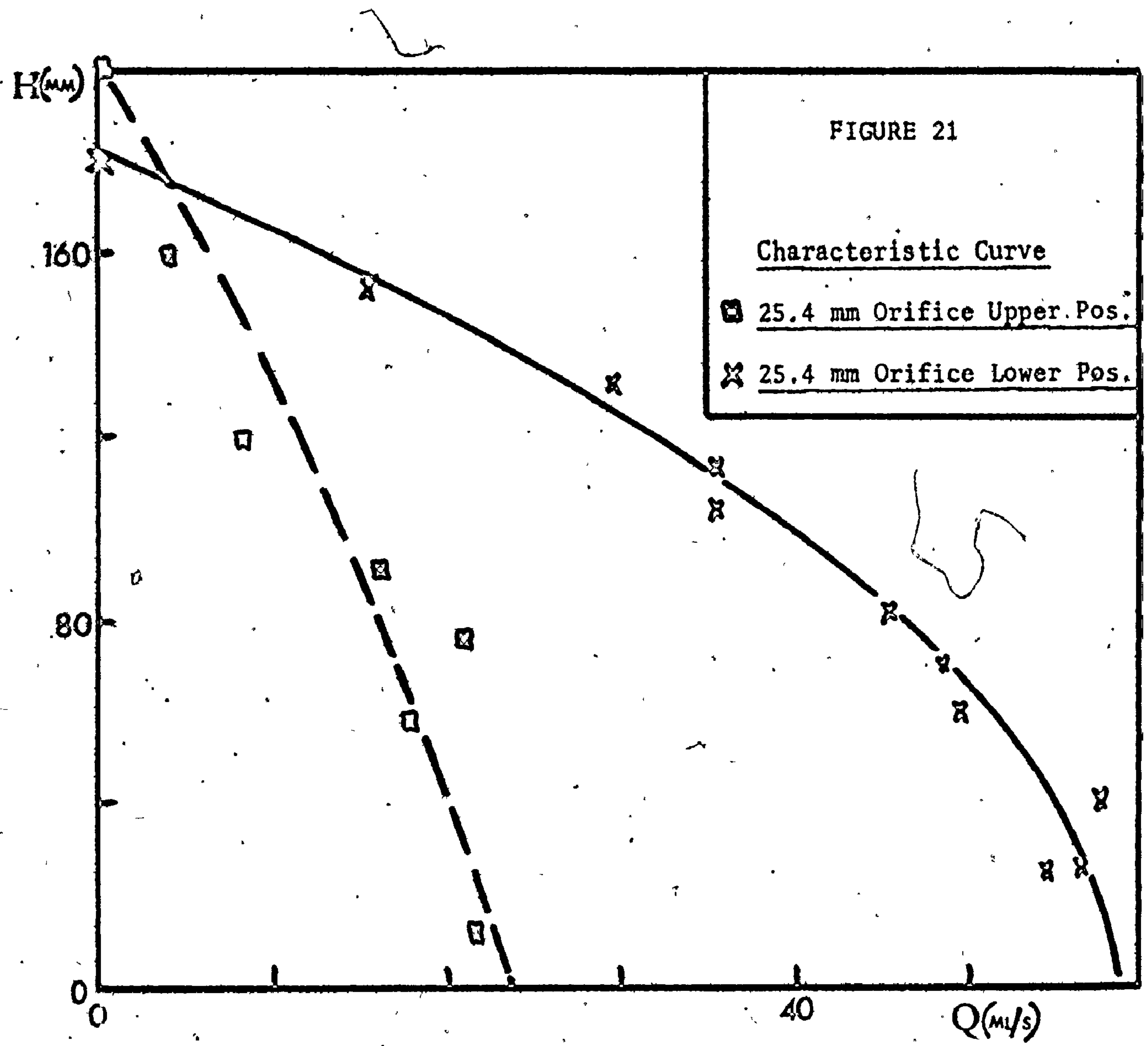


FIGURE 20
Characteristic Curve
38.1 mm Orifice Upper Position
38.1 mm Orifice Lower Position
H(MM)
200
120
0
0
40
80
Q(ML/S)


H(MM)
160
80
0
0
40
Q(Ml/s)
FIGURE 21
Characteristic Curve
25.4 mm Orifice Upper Pos.
25.4 mm Orifice Lower Pos.

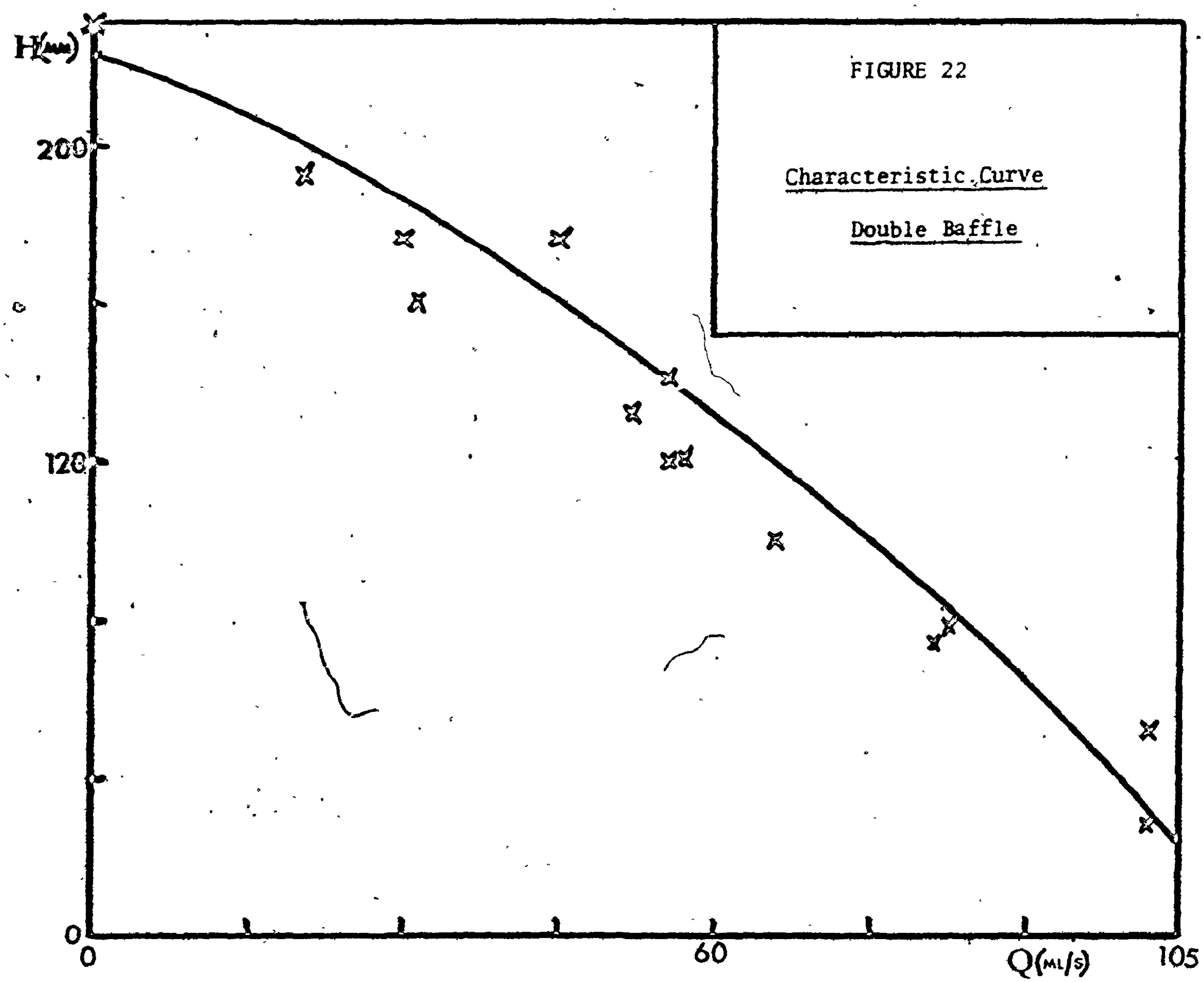


FIGURE 22
Characteristic Curve
Double Baffle
H(mm)
200
120
0
60
105
Q(ml/s)

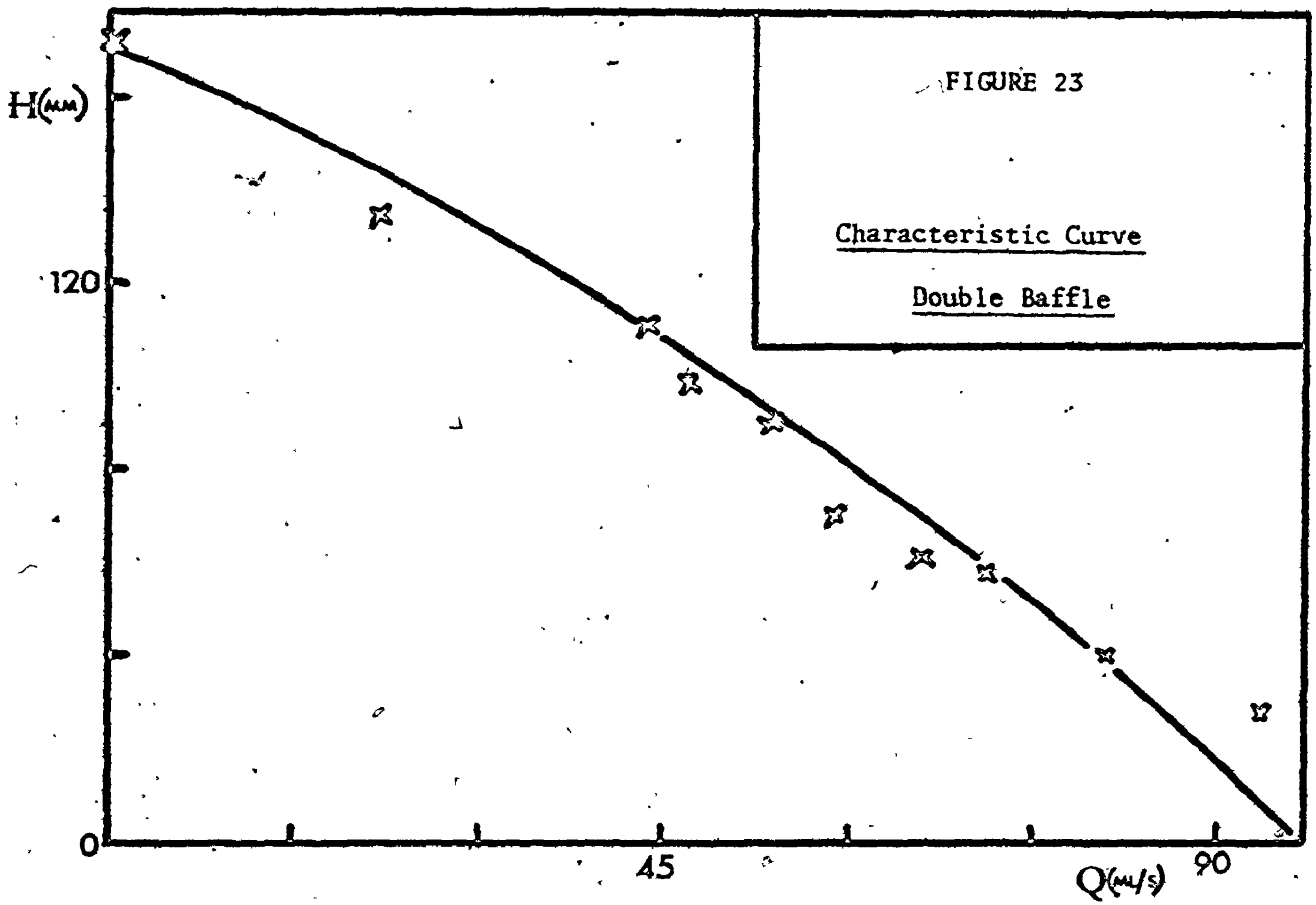


FIGURE 23

Characteristic Curve

Double Baffle

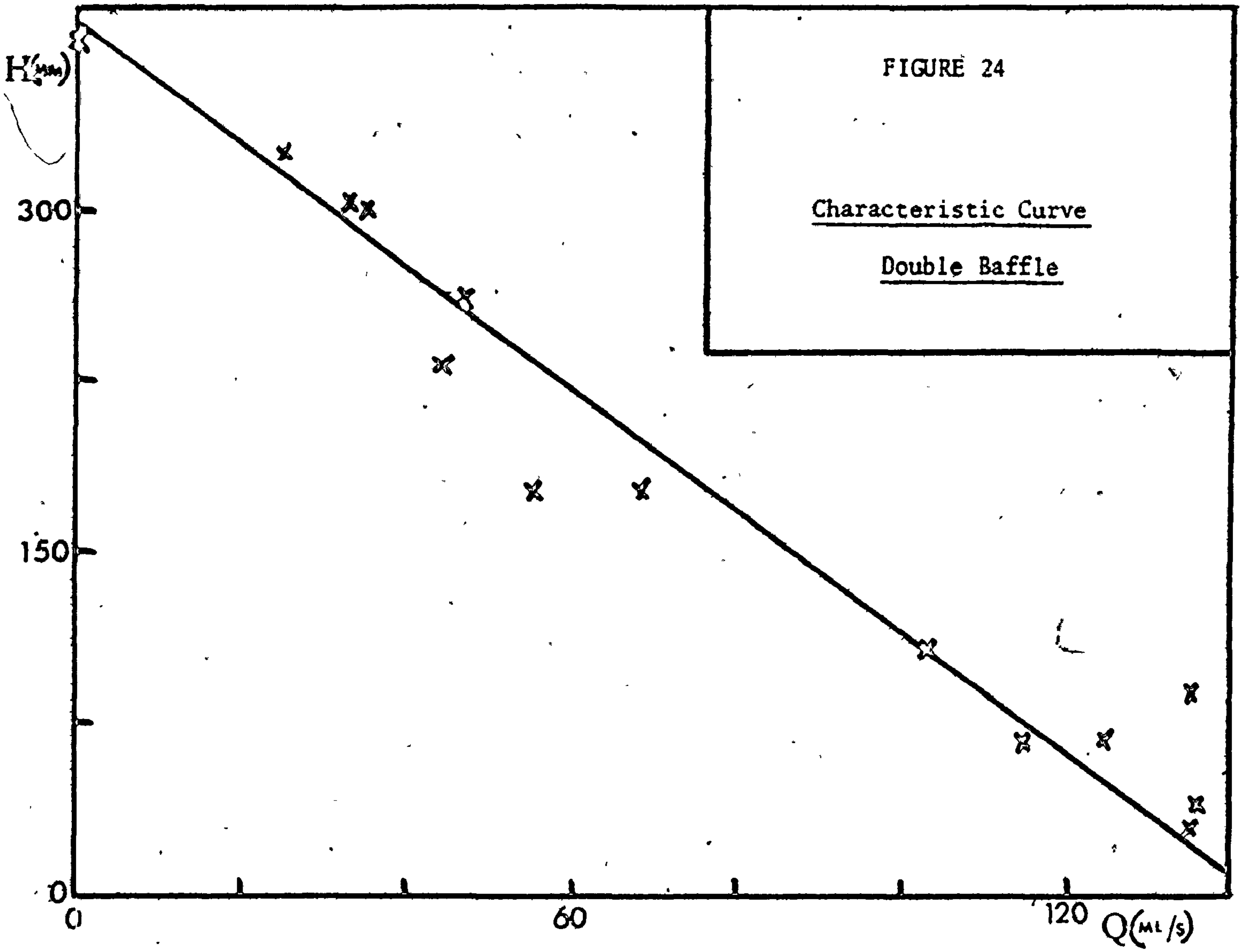


FIGURE 24

Characteristic Curve

Double Baffle

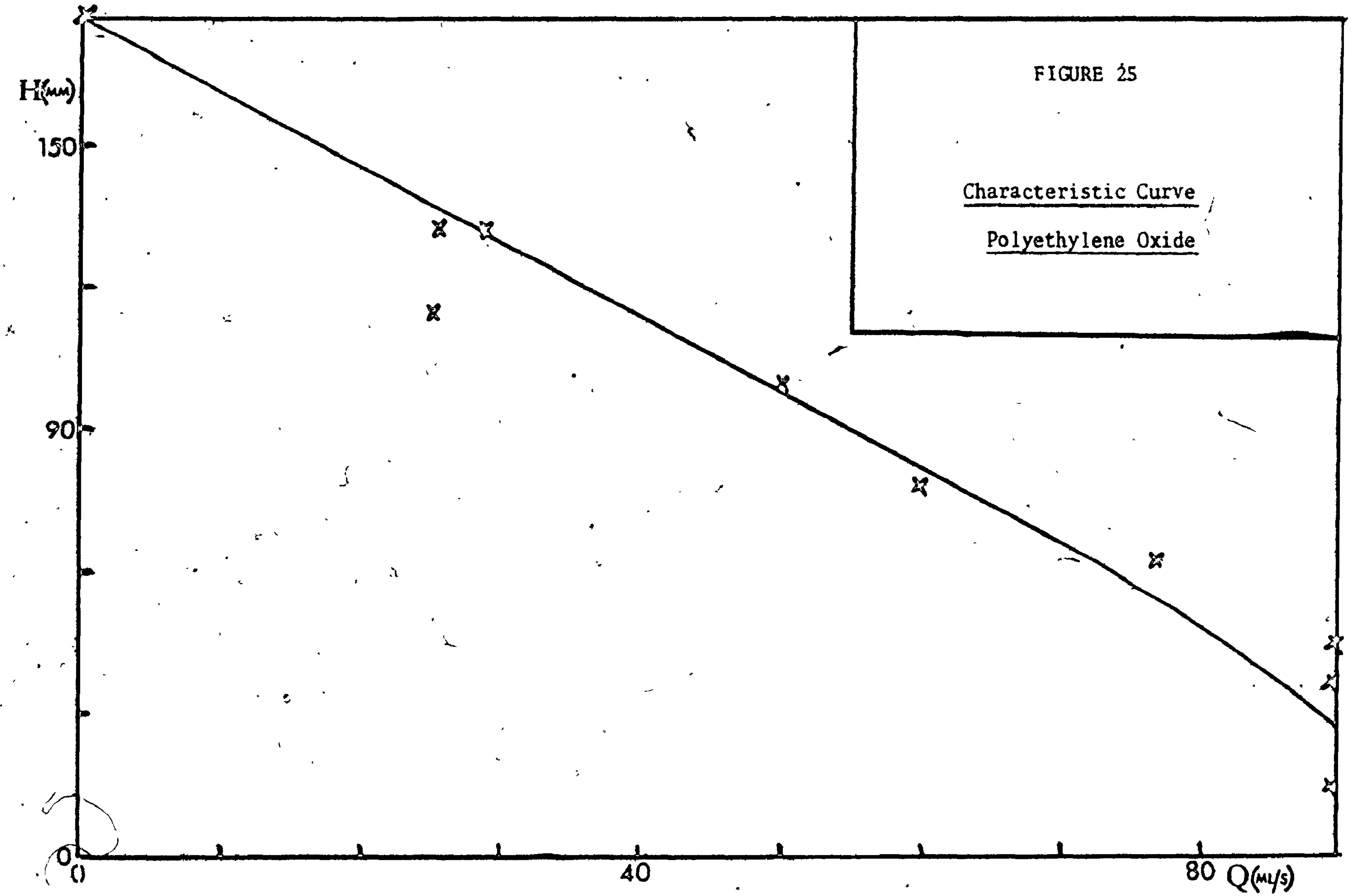


FIGURE 25

Characteristic Curve

Polyethylene Oxide

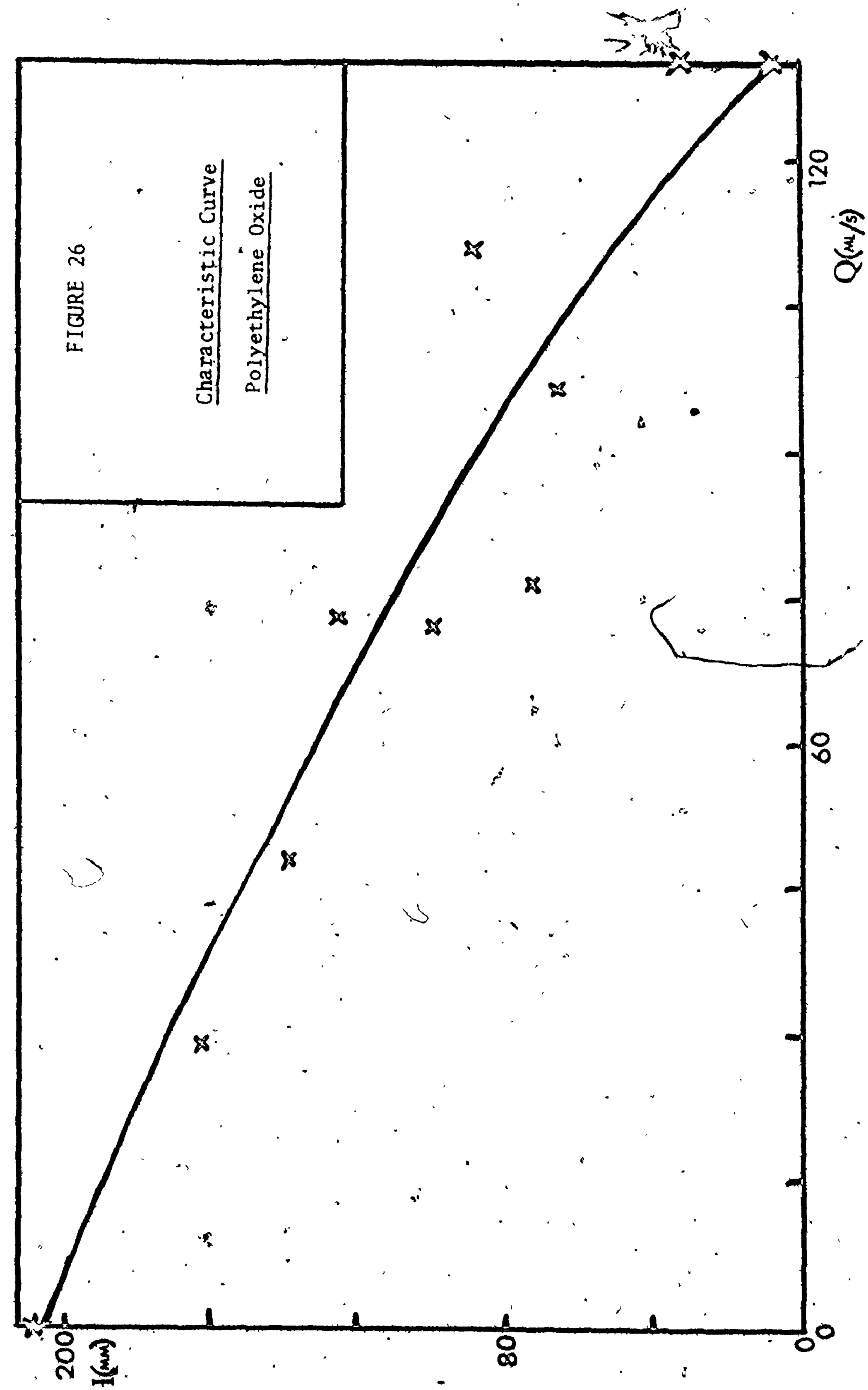


FIGURE 26

Characteristic Curve

Polyethylene Oxide

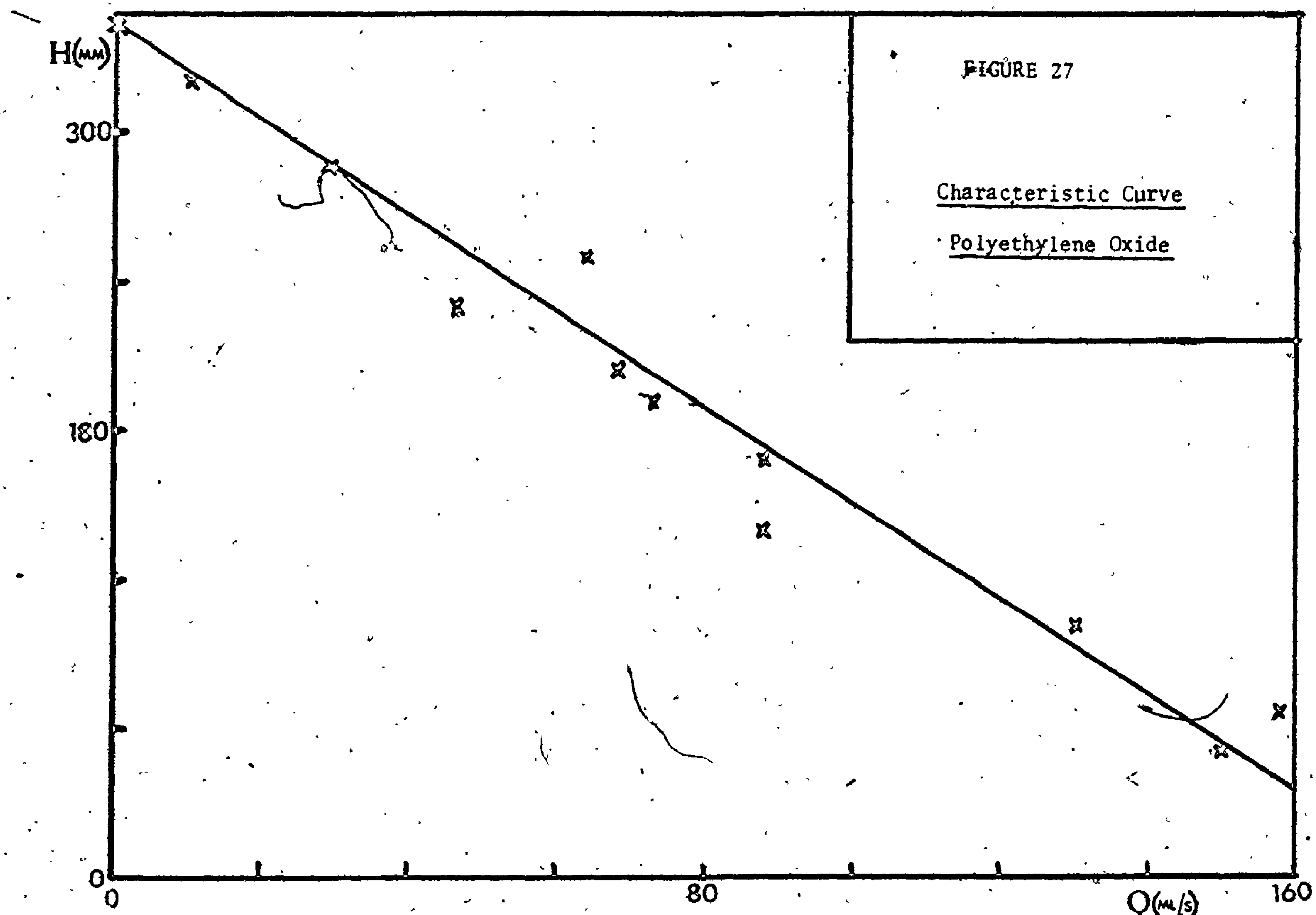


FIGURE 27
Characteristic Curve
Polyethylene Oxide
H(MM)
300
180
0
0
80
Q(ML/S)
160

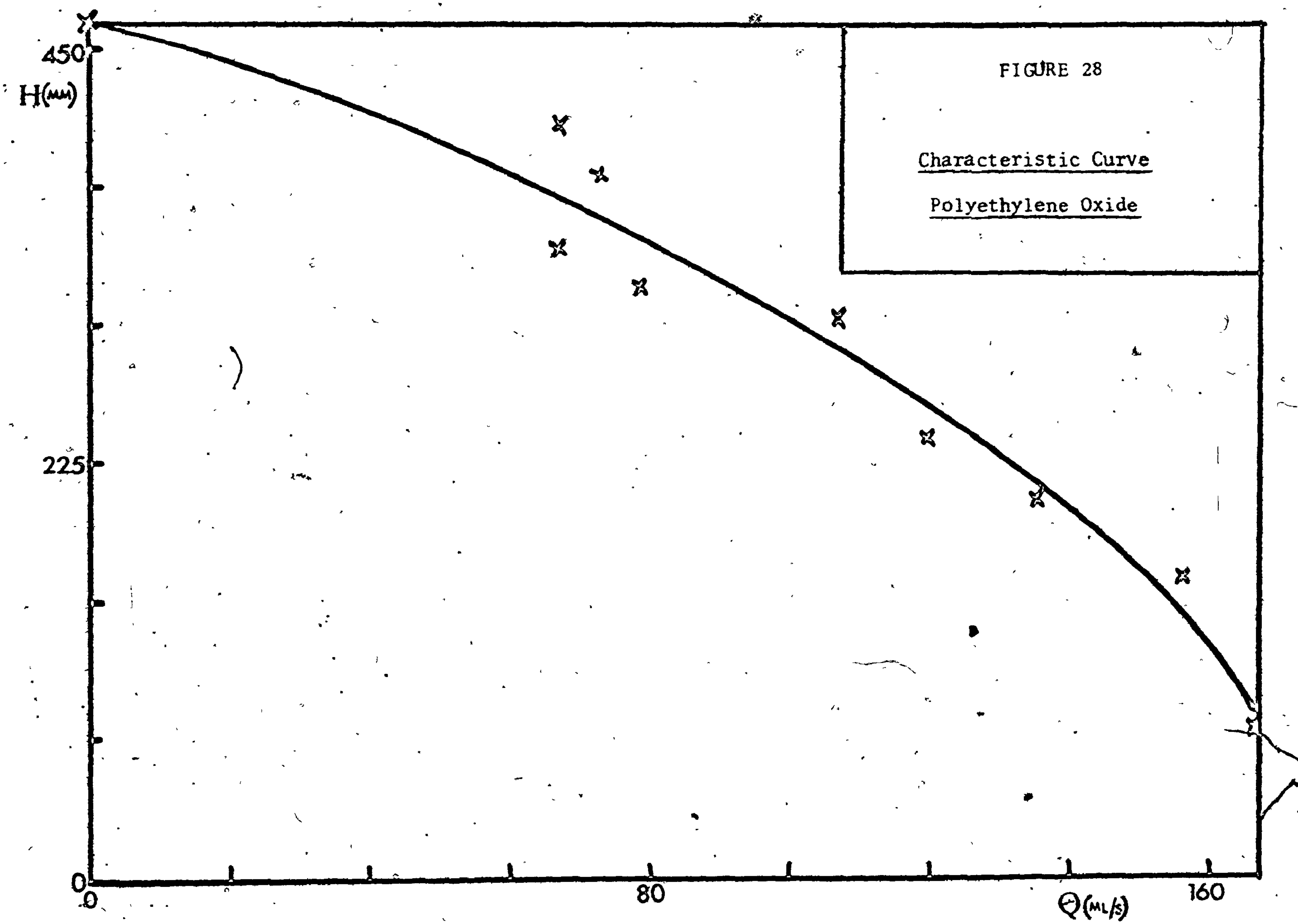
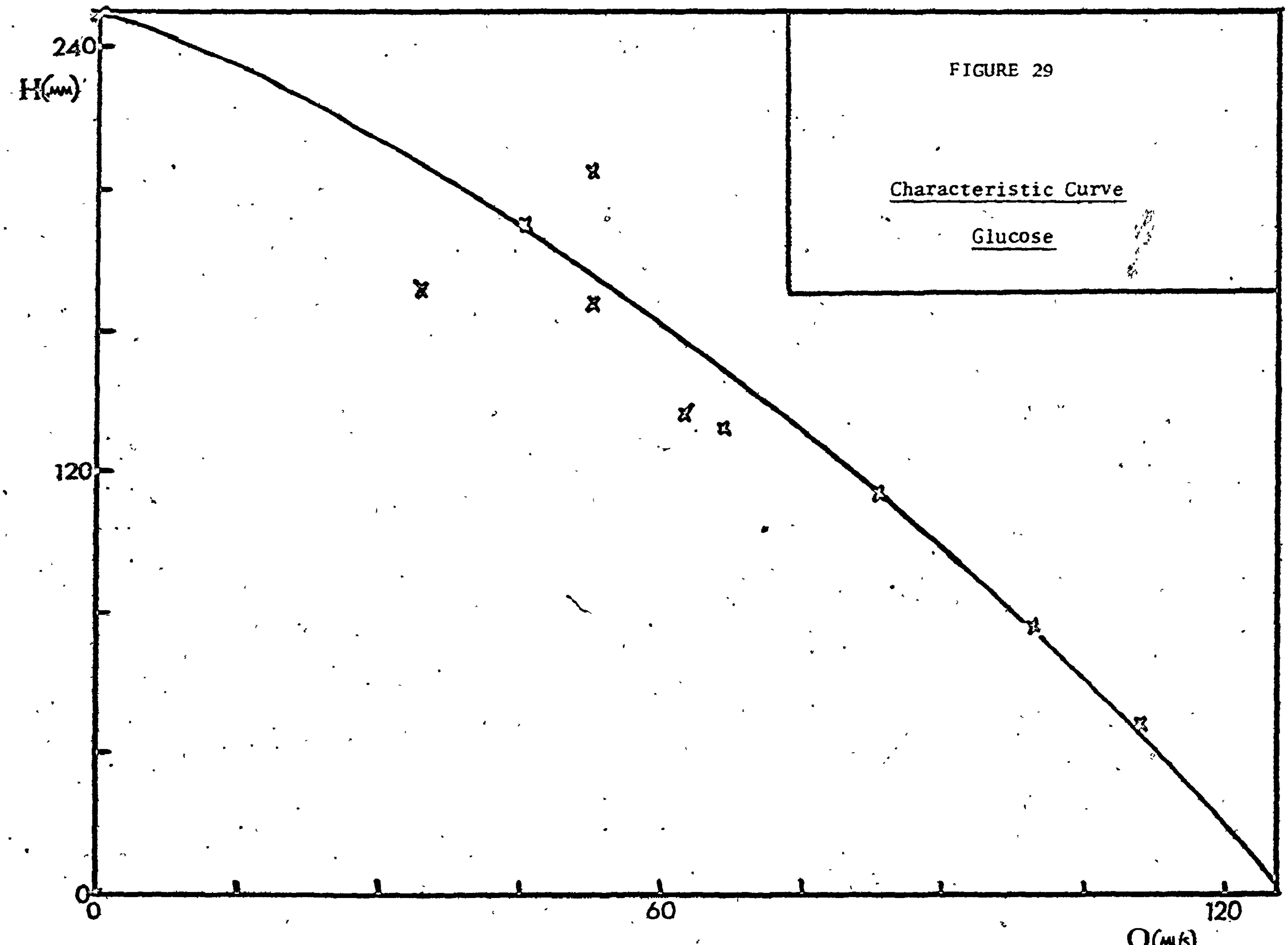


FIGURE 28

Characteristic Curve

Polyethylene Oxide


240
H(mm)
120
0
0
60
120
Q(ml/s)
FIGURE 29
Characteristic Curve
Glucose

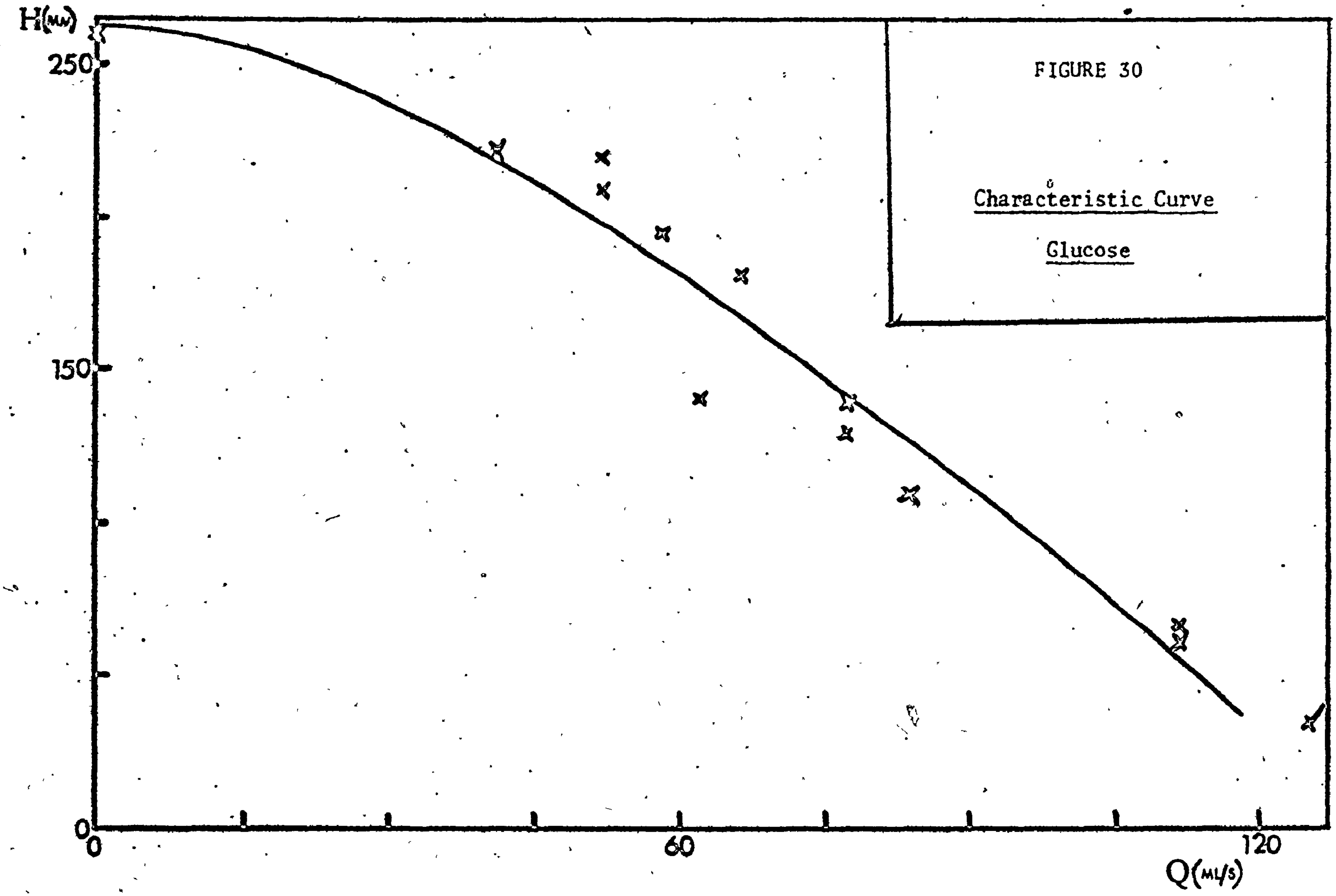


FIGURE 30

Characteristic Curve

Glucose

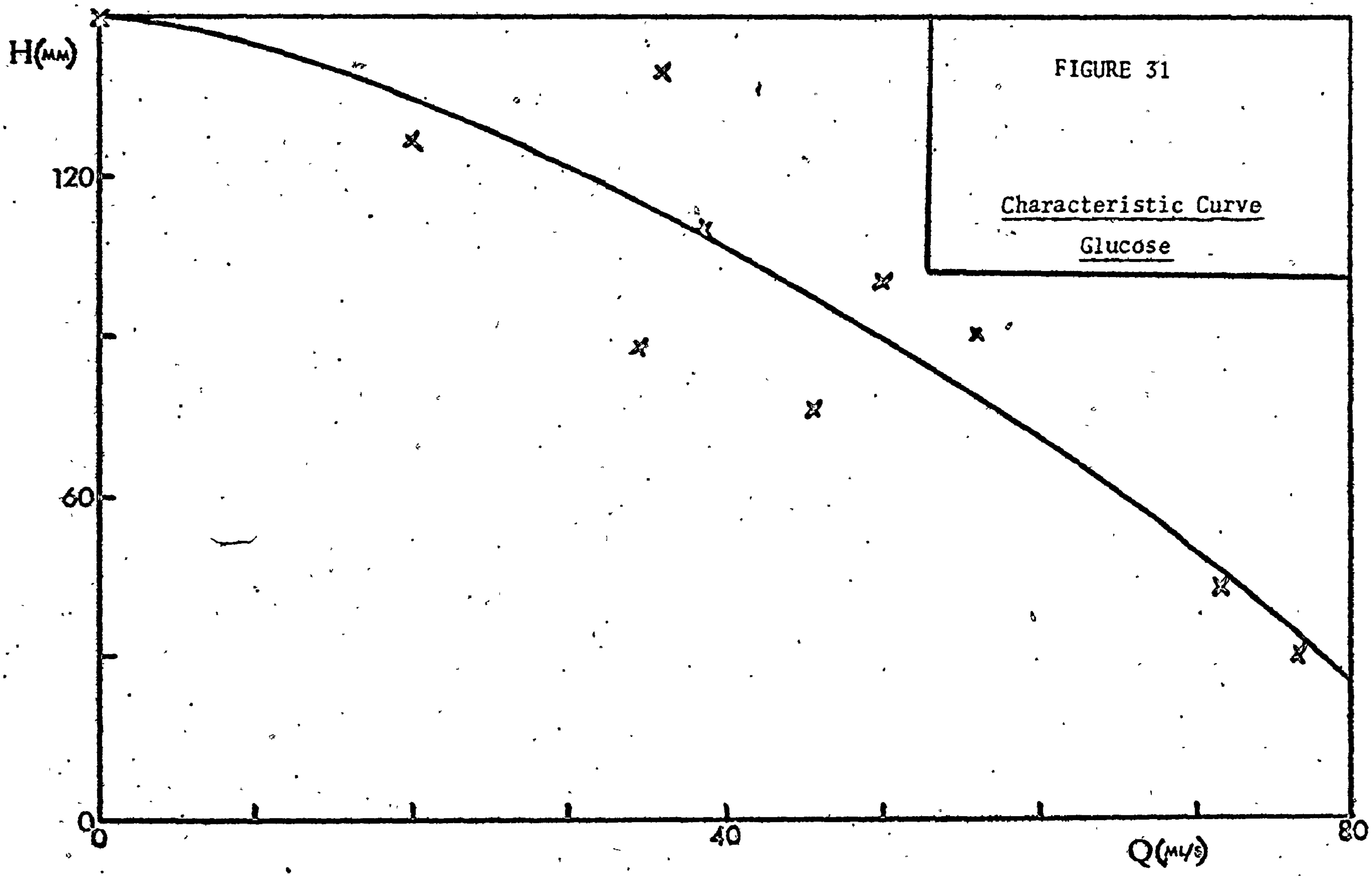


FIGURE 31

Characteristic Curve

Glucose

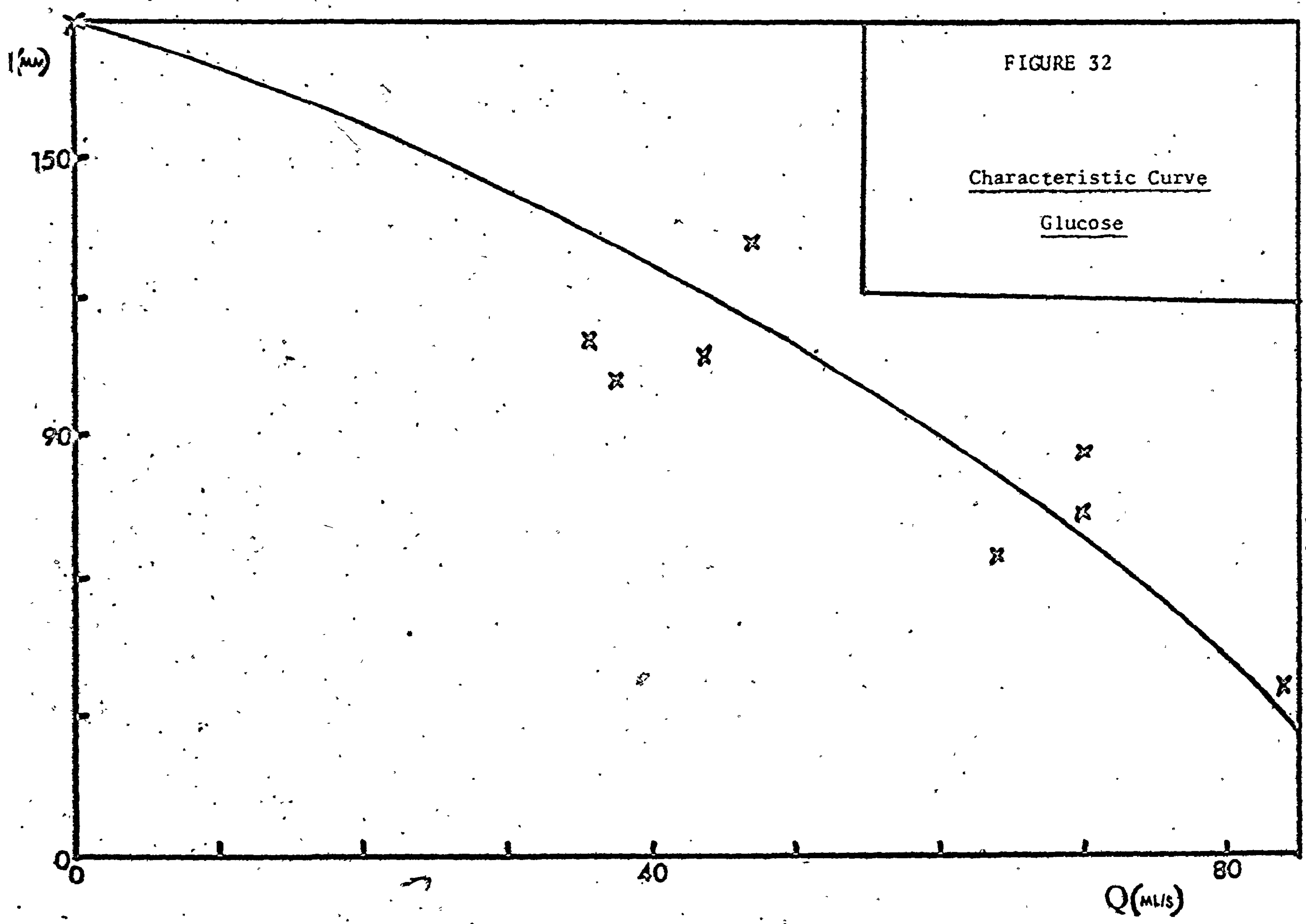


FIGURE 32
Characteristic Curve
Glucose
I(μw)
150
90
0
0
40
80
Q(ML/S)

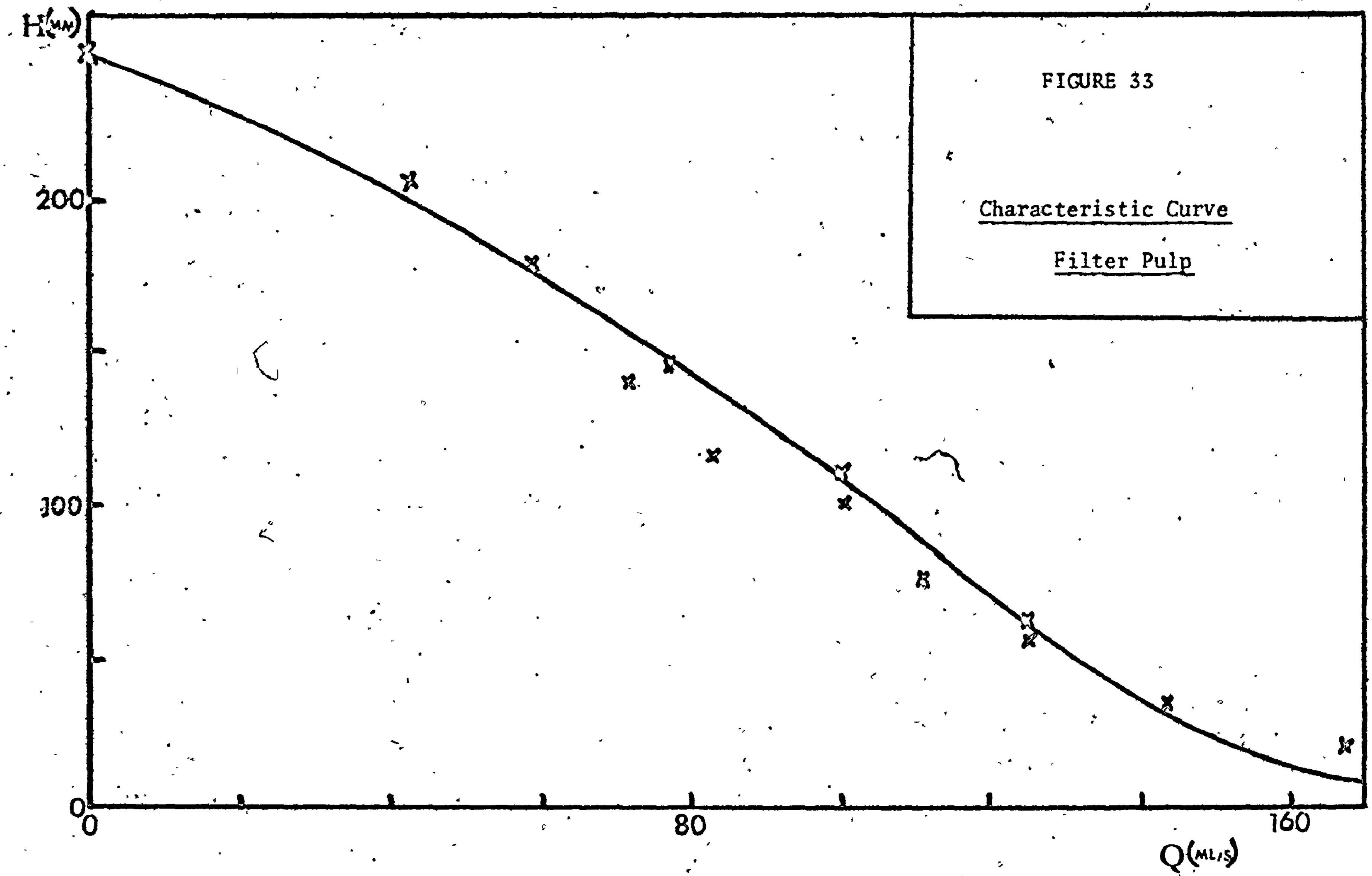


FIGURE 33
Characteristic Curve
Filter Pulp
H(MM)
200
100
0
0
80
160
Q(ML/S)

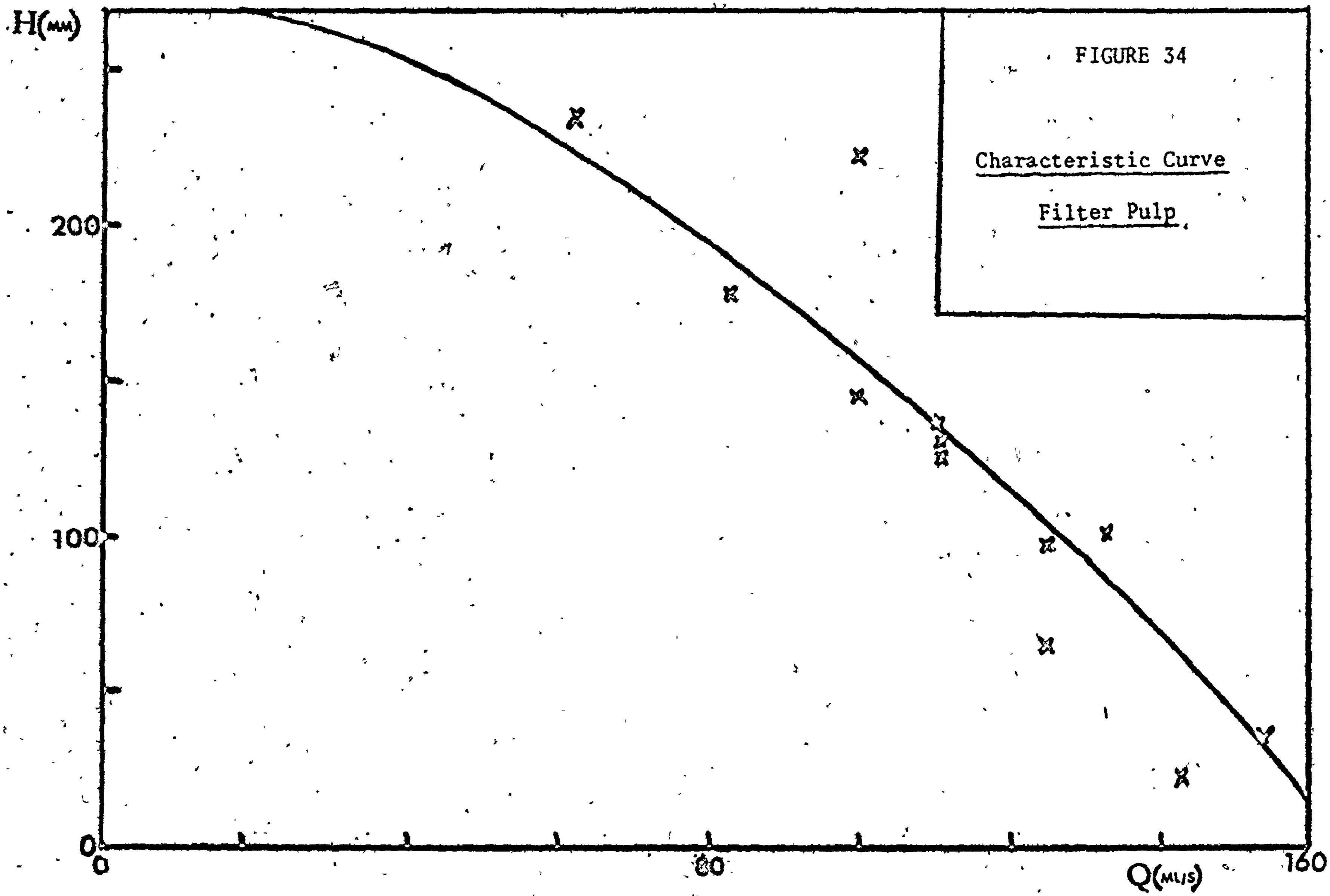


FIGURE 34

Characteristic Curve

Filter Pulp

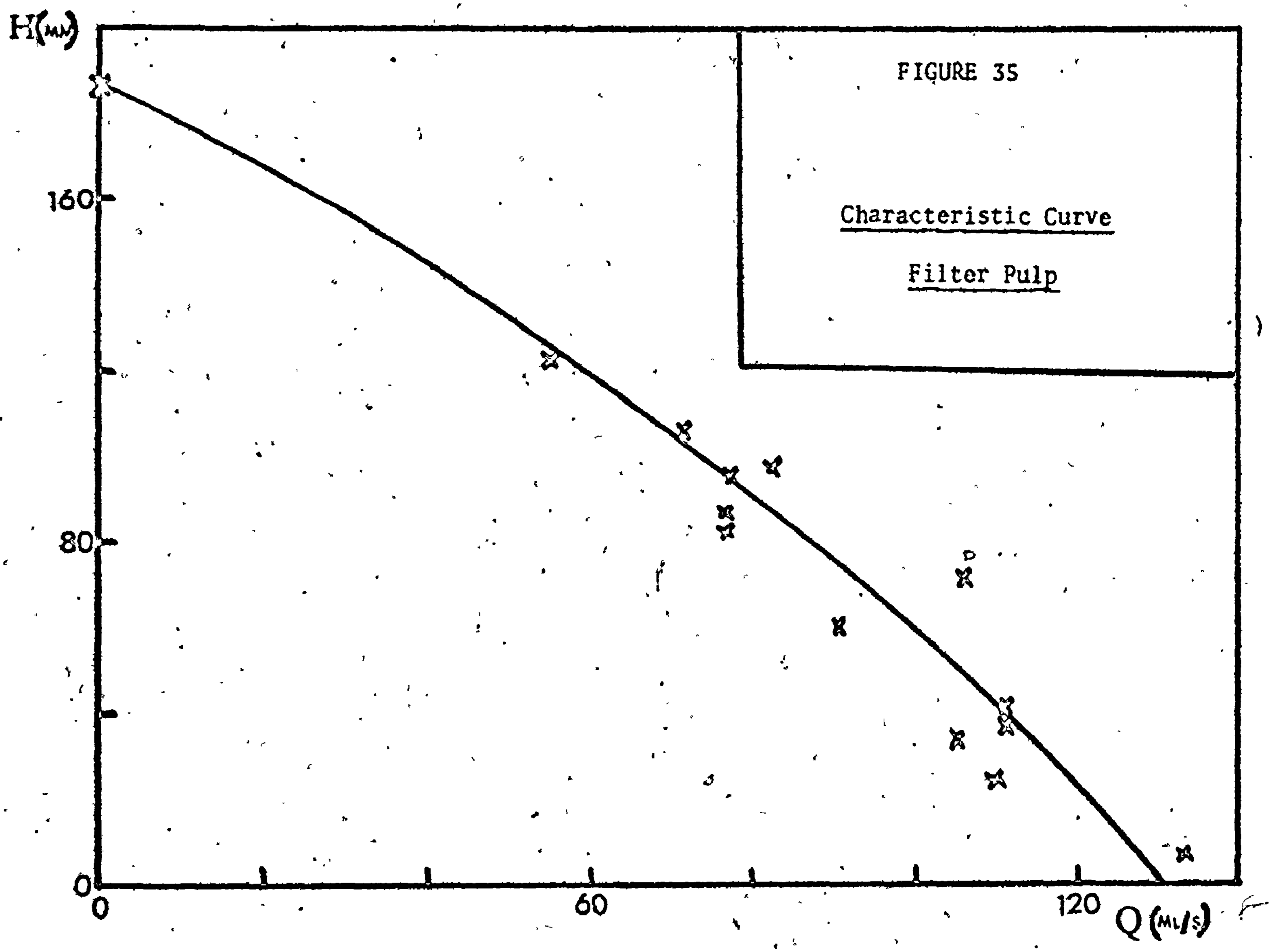


FIGURE 35
Characteristic Curve
Filter Pulp
H(mm)
160
80
0
0
60
120
Q (ml/s)

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