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THE UNIVERSITY OF MICHIGAN
ANN ARBOR

SUMMARY REPORT ON CONTINUATION OF THE STUDY OF THE FLOW OF PASTE

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ABSTRACT

The experimental data on the flow of high-density pastes in vertical hairpins have been extended to include 8-ft lengths and angular as well as rounded particles. Sufficient data are not yet available to permit quantitative generalization. Study of the measurement of pressure drop required for fixed-bed expansion was continued and shows possibility for using the point of maximum pressure drop as a criterion of frictional effects.

An investigation of the use of electrical-conductivity measurement as a means of determining bed porosity showed it to be satisfactory. A partial literature search disclosed no useful information on this type of flow. Design concepts for continuous-flow loops are presented. The experimental exploration of one type of loop is described.

OBJECTIVE

The object of this period of study was to extend the data on the flow of high-density silica-water pastes in hairpin systems and to explore certain areas of interest to the overall problem of investigating paste flow for reactor systems.

INTRODUCTION

This report covers the findings of the study of the flow of high-density paste for the period from September 1 to December 31, 1955. This work was a continuation of the preliminary study which started on June 1, 1955, and which was described in _Summary Report on a Preliminary Study of the Flow of Paste_, September, 1955. It is to be followed by a one-year continuation over the period January 1 to December 31, 1956.

The general subject and object of the study were set forth in that summary report as follows:

"_Subject_.—The determination of the pressure-drop—flow-rate relationships for the flow of high-density pastes through tubes is required for the estimation of design requirements of a reactor. The system contemplated would have the following characteristics:

1. Paste is composed of uranium oxide or uranium powder suspended in molten sodium or sodium potassium.

    a. Density should be at least 40-50 volume-percent solids.
    b. Particle size may be varied to obtain optimum flow characteristics. A size range around 50-micron diameter is envisioned.

2. Tube diameter will be in the range of 1/4 to 1 in. Tube material will be stainless steel, probably 304.

3. Flow rate is anticipated to be in the range of 1/3 to 10 ft per day.

4. The orientation of the tube may range from horizontal to vertical.

"_Object_.—The object of this preliminary study is to obtain order-of-magnitude data on the pressure drop required to produce the desired flow rate and some insight into the mechanism of flow.

"For highly concentrated suspensions such as those of present interest, there are four general possibilities for the type of flow. If there is no appreciable attraction between the particles, there are two possibilities: the suspension will flow as a viscous fluid whose viscosity depends only on solids concentration and particle-size distribution, or the suspension may be so concentrated that it must increase in volume when sheared (i.e., it is dilatant). If there is attraction between particles, then the third possibility will occur and the behavior will be non-Newtonian and will exhibit a yield stress.

"The fourth possibility, which is dependent on the methods of feeding and withdrawal, is that the liquid could flow at a different linear velocity than the solid.

"Because of the range of possible modes of flow and the lack of generalized information which would enable the prediction of flow characteristics, it will be necessary to conduct an experimental study.

"The variables to be investigated as time permits are:

1. Flow rate
2. Paste density
3. Particle-size and size distribution
4. Tube material and wall finish
5. Tube geometry - turns and fittings
6. Vibration of the tube and/or pulsation of the pressure."

The scope of the work for the continued study was set forth in a letter from Mr. A. P. Donnell, October 3, 1955, which modified the original scope as follows:

ARTICLE I - SCOPE OF WORK

"Continue the study to obtain reliable data on the pressure drop required to produce flow of paste. The variables to be investigated are:

1. Flow rates
    (a) Paste - 0 to 30 ft/day
    (b) Liquid - as required to give desired paste flow rate.

2. Particle parameters
    (a) Size and size distribution - Concentrate on size distribution like that of the actual fuel particles. Mixtures will run from 44 to 200 microns with a 100 micron median size.
    (b) Density - Most work at 2.65 gm/cc (silica) and some at higher densities.
    (c) Shape - Rounded (Ottawa) sand and crushed quartz (angular).

3. Tube diameter and length - Diameters approximately 1/4", 1/2", and 1". Lengths 2 to 16 ft. (total).

4. Effect of geometries such as manifolds, contractions, and turns. Include a manifold with at least 25 tubes."

SUMMARY

The work performed during this four-month period was in five areas:

1. Construction of apparatus and obtaining data on paste flow in vertical hairpins up to 8 ft in length (16 ft of tube length). All the data, except one run on copper powder, are for rounded or angular silica particles. There are not yet sufficient data to permit any quantitative generalizations.

2. Construction of apparatus and obtaining data on the pressure drop required for fixed-bed expansion. The data show the inapplicability of the point of first expansion as a criterion of frictional effects. The points of maximum and equilibrium pressure drop seem promising as criteria.

3. Investigation of the applicability of electrical-conductivity measurement as a means of determining bed porosity. The method appears to be satisfactory and will be used in future work.

4. A literature search. No applicable information was found in the areas and time period covered.

5. Design conception and exploratory experimentation on continuous-flow loop systems. A system incorporating downward flow of dense paste inside a tube and low-density left for solids recycle was operated satisfactorily on sand and water. Examples of various conceivable system types are discussed.

FLOW THROUGH VERTICAL HAIRPINS

The experimental data on flow-rate—pressure-drop relationships were concentrated on the vertical-hairpin system because this seemed likely to be used in a reactor design. The range of variables was extended to include longer tube lengths, different particle sizes and shapes, and different tube diameters. While there are not sufficient data yet to determine adequately the effects of all variables, some conclusions can be drawn from these data. The solids used in most of the runs were round (Ottawa) sand and sharp (crushed) quartz. Copper powder was used in one run. Table I indicates the runs which were made.

TABLE I

EXPERIMENTAL RUNS IN VERTICAL HAIRPINS

Length of Hairpin (ft)	Tube ID	Material
2	10 mm	150/200 screened copper
1-1/2	10 mm	"Old" 100/150 Ottawa sand
8	10 mm	New 150/200 Ottawa sand
8	10 mm	150/200 synthetic quartz
4	10 mm	150/200 synthetic quartz
4	6 mm	New 150/200 Ottawa sand

APPARATUS

It was believed that much of the scatter obtained in the early data was due to measurements taken while the paste was accelerating or decelerating. To avoid this type of error, a new system was devised. This system contained a reservoir with a capacity of 2000 cc which would permit individual runs as long as sixteen to twenty-four hours, depending on the rate of flow. In addition, the tubing was fitted with pressure taps along the run as well as the inlet and exit points so that the pressure gradient along the tube could be determined. The system is shown in Fig. 3. In connecting the manometer, all the leads were elevated to a common level, thus canceling out the hydrostatic head. Thus, the net pressure may be determined from the manometer readings.

Flow rates were determined by first collecting the effluent paste and liquid for a measured time interval. The volume and weight were then determined and from these, knowing the density of the dry sand, the weight rates of flow of solid and liquid were computed. These data were then transformed into volume rates of flow of paste and liquid, using the average paste densities of 60.5 volume-percent solids for round sand and 51.0 volume-percent solids for rough quartz.

PROPERTIES OF PARTICLES

The solid particles used were a new supply of 150/200 Ottawa sand, a "synthetic 150/200-mesh" crushed quartz, 150/200-mesh copper powder, and the previously used ("old") 100/150-mesh Ottawa sand. It was found that the new sand supply differed in size from the old supply, even though they came from the same supplier and bore the same screen-size designation.

The size-distribution data for the various grades of sand and the crushed quartz are plotted in Fig. 11. Photomicrographs of both the new 150/200-mesh Ottawa sand and the 150/200-mesh crushed quartz are shown in Fig. 14. While both these have the same screen-size distribution, it can be seen that the longer particles of crushed quartz may be larger in volume than those of rounded sand.

EXPERIMENTAL DATA

The data for the runs described in Table I are presented in Figs. 1, 2, 4, 5, 6, 7, and 12 as plots of flow rate vs pressure drop. Figures 8, 9, and 10 show some of the same data replotted in terms of fraction overweight vs flow rate. Fraction overweight is the ratio of measured pressure drop to the pressure drop required to balance the weight of the solids. Figure 13 is a plot of pressure drop per foot of tube vs flow rate for the flow of 150/200-mesh Ottawa sand in each leg of a 10-mm-ID hairpin. Figure 15 is a plot of pressure vs tube length for an entire hairpin.

The effect of both tube length and particle diameter is indicated in Fig. 10. It can be seen that the overweight ratio for the 2-ft hairpins increases as particle diameter decreases. The fact that the copper-powder curve falls between those for the two sizes of sand is quite striking, but it is not possible to make too much of this on the basis of runs at only one tube length. Likewise, while the curves in Fig. 10 show an increase of overweight ratio with tube length, it is not possible to say how far this goes.

The effect of particle shape is shown in Figs. 10 and 12, where the data for both rounded and rough sand of the same size are presented. Figure 12 shows that rough sand flows at a lower pressure drop than round sand, while Fig. 10 shows that the overweight ratios for both are substantially the same. This relationship exists because the rough sand flows at a lower bed density (estimate 51%) than round sand (60.5%). It was found that the free-settled and vibrated densities of the rough sand were 47.9 and 53.9 volume percent, respectively.

CONCLUSIONS

Since not enough experimental runs have been made to show the effects of the several variables one by one, any conclusions from the presently available data must be considered to be tentative. We can make the following observations:

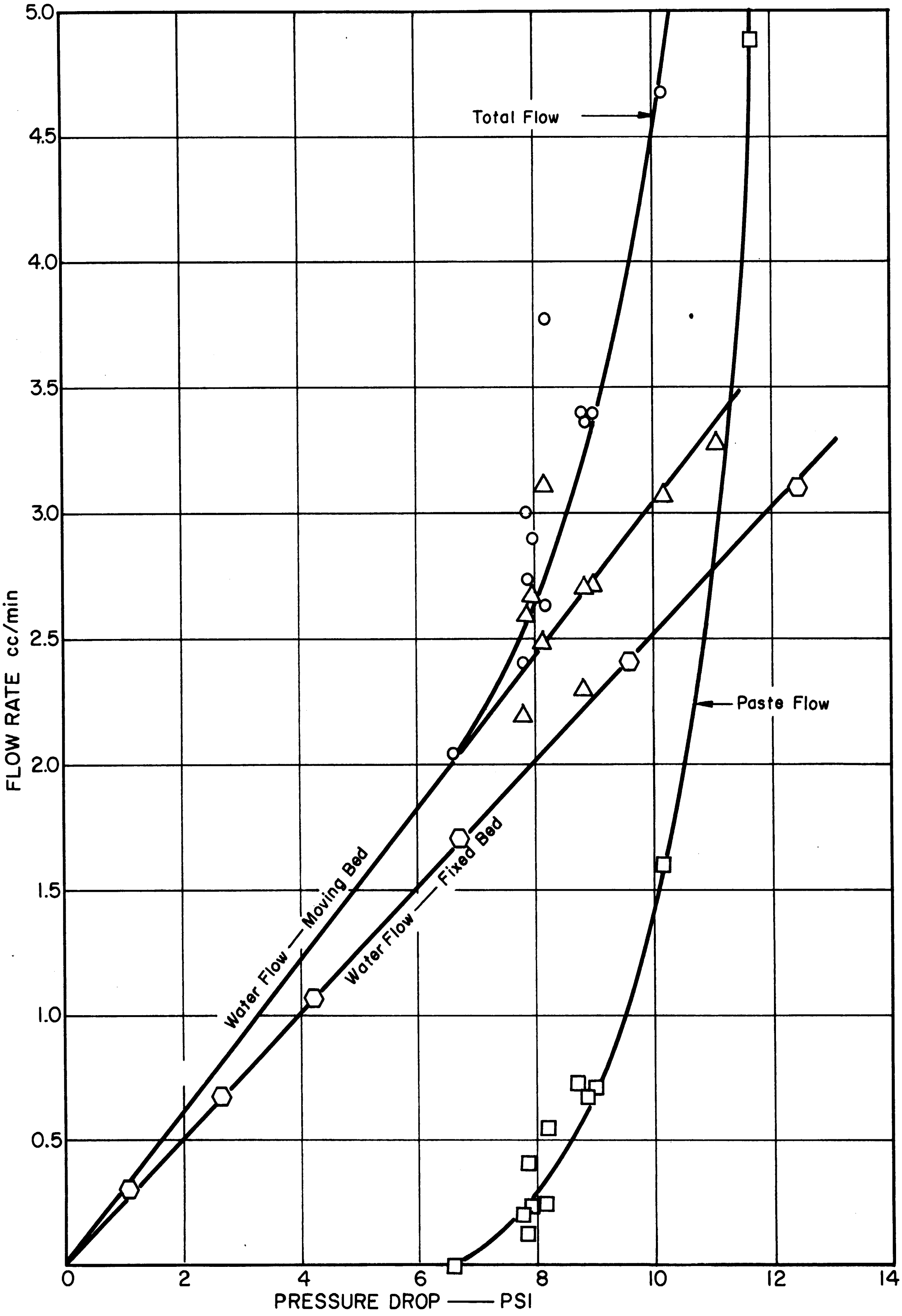


Fig. 1. Flow rate vs pressure drop for 150/200 screened copper flowing in a 2-ft hairpin of 10-mm-ID glass tubing; $D_{p_{avg}}$ = 89 microns.

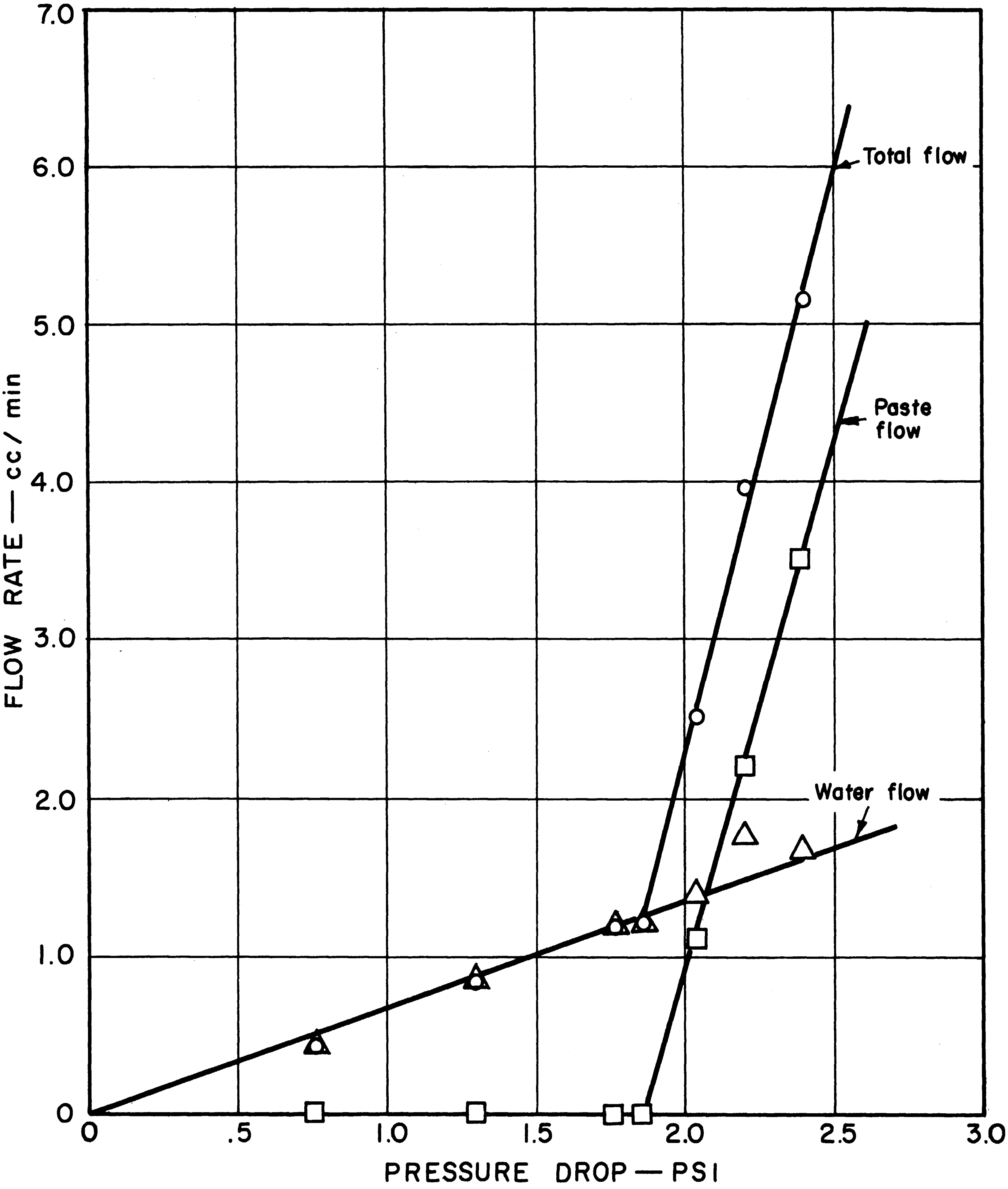
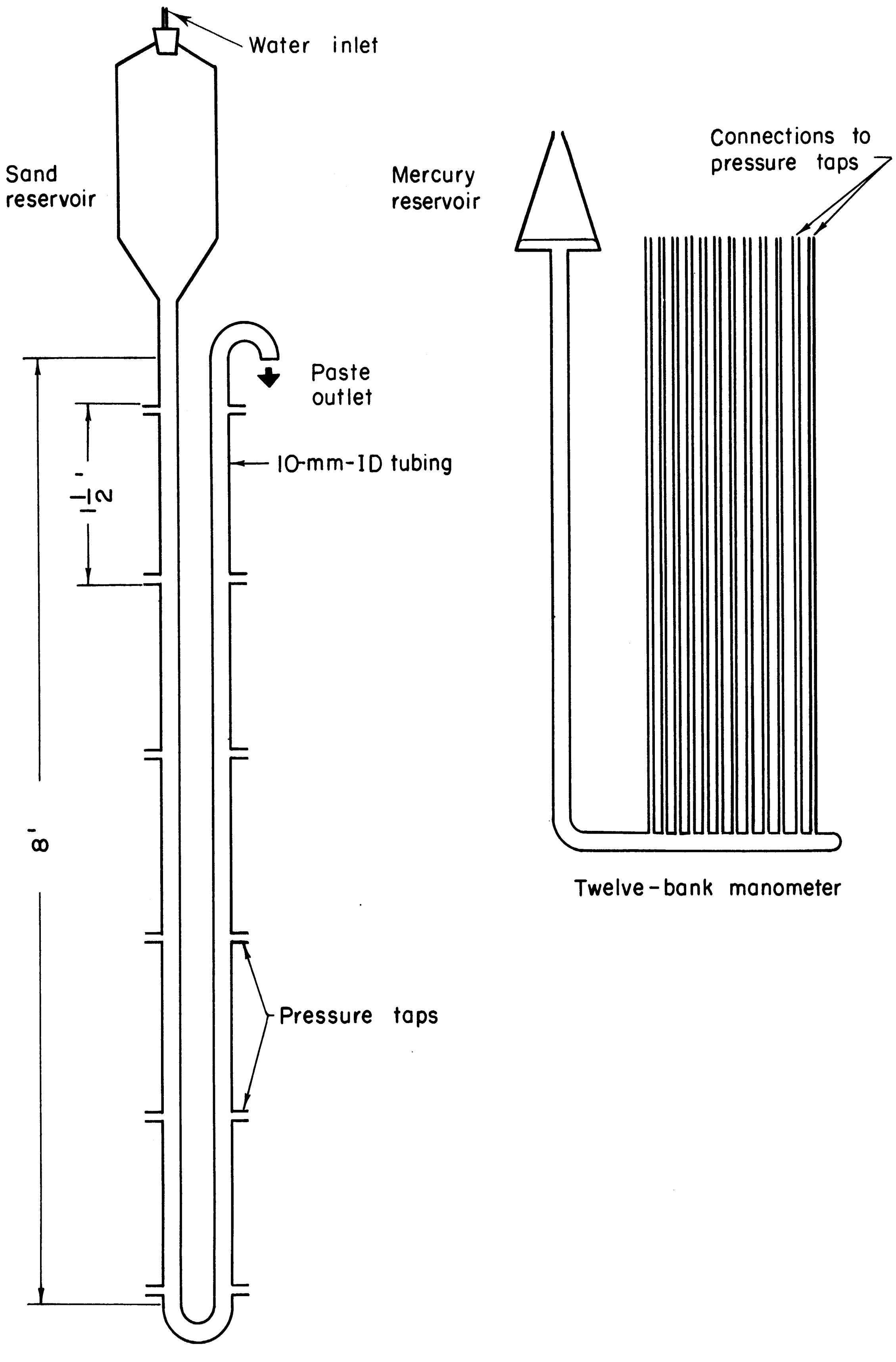


Fig. 2. Flow rate vs pressure drop for 100/150 Ottawa sand flowing in an 18-in. hairpin of 10-mm-ID glass tubing; $D_{p_{avg}}$ = 120 microns.



Twelve-bank manometer

Flow apparatus

Fig. 3. Diagram of flow system.

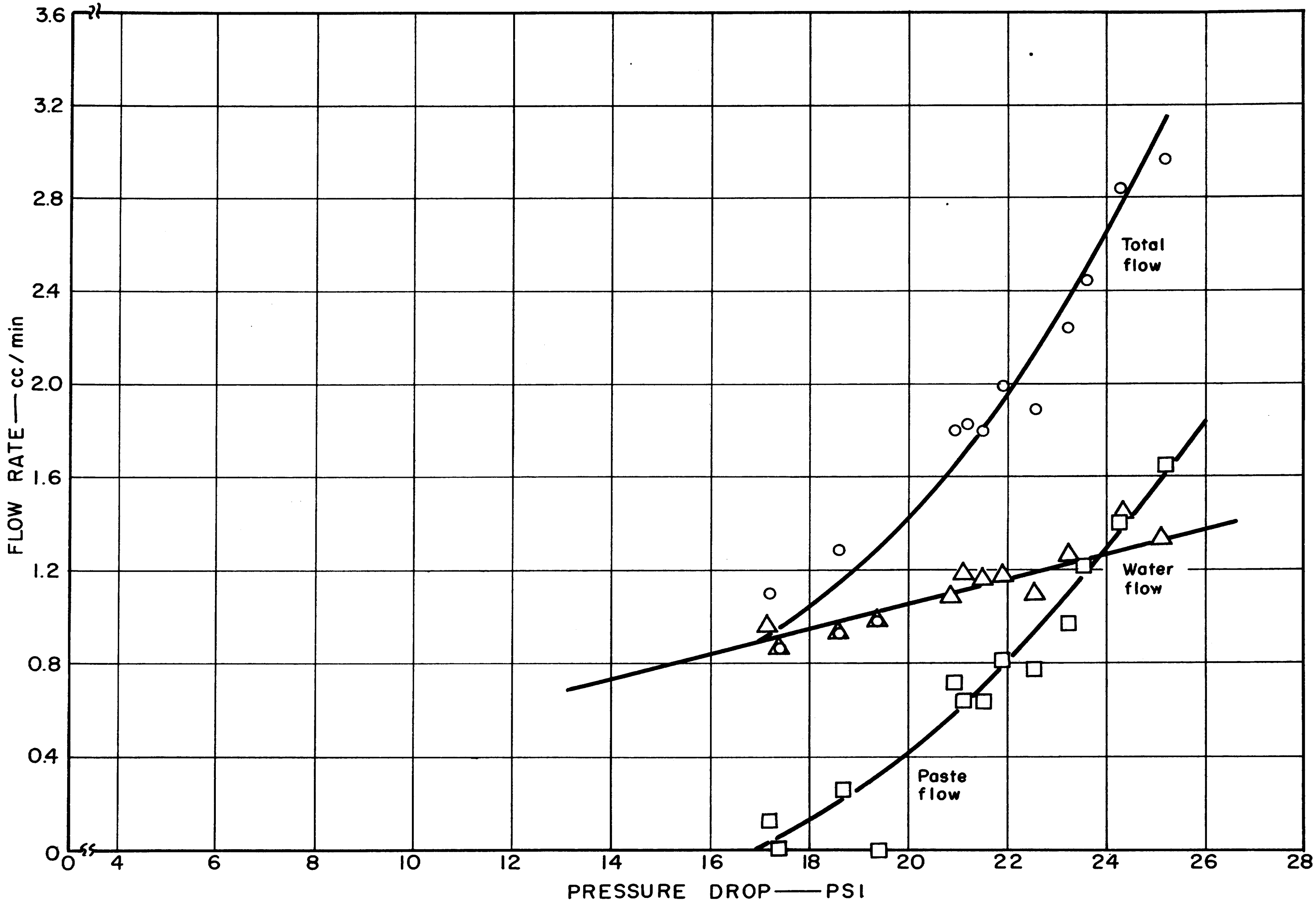


Fig. 4. Flow rate vs pressure drop for 150/200 Ottawa sand flowing in an 8-ft hairpin of 10-mm-ID glass tubing; $D_{p_{avg}} = 98$ microns.

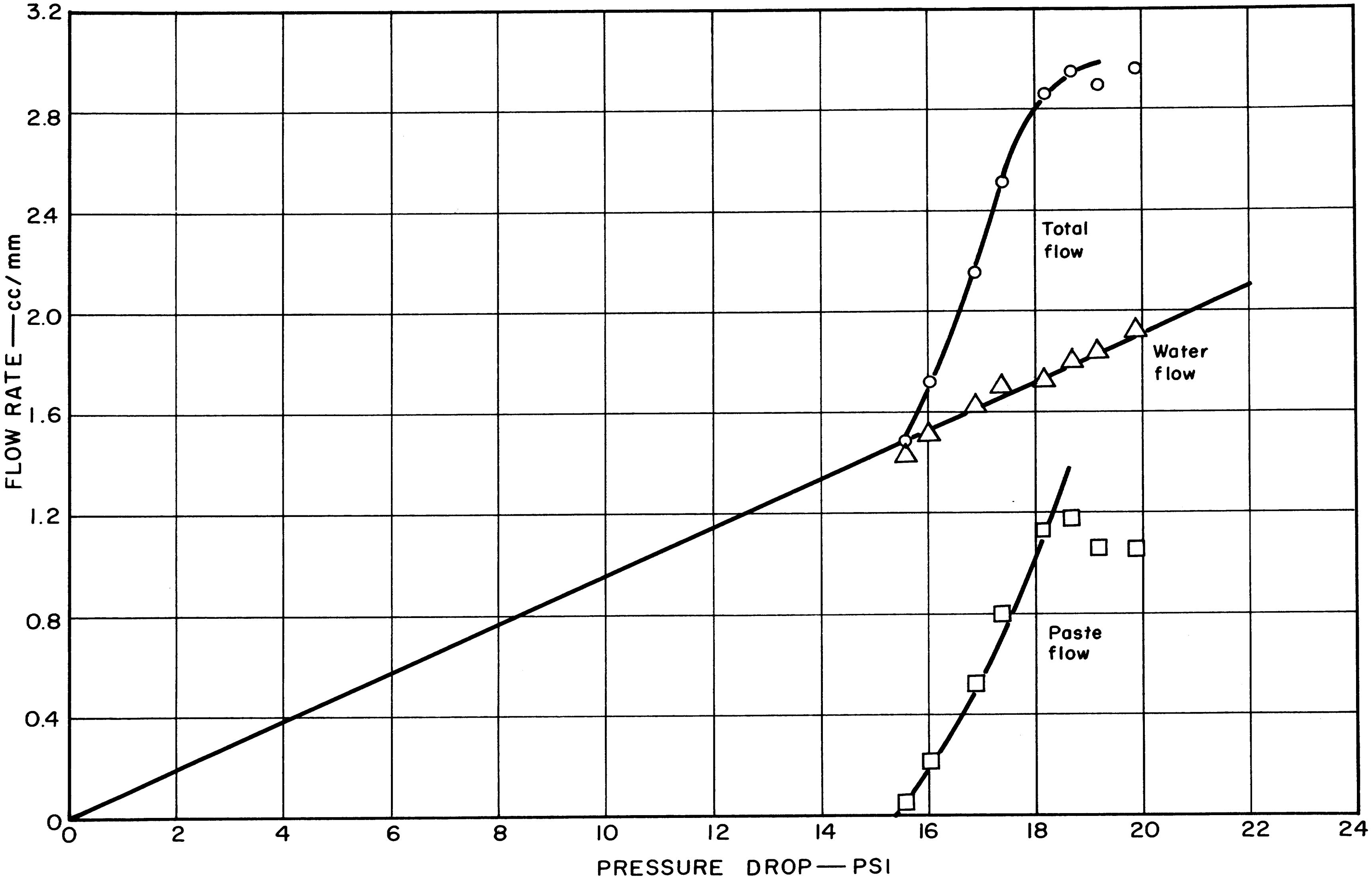


Fig. 5. Flow rate vs pressure drop for a synthetic 150/200 quartz flowing in an 8-ft hairpin of 10-mm-ID glass tubing; $D_{p_{avg}}$ = 98 microns.

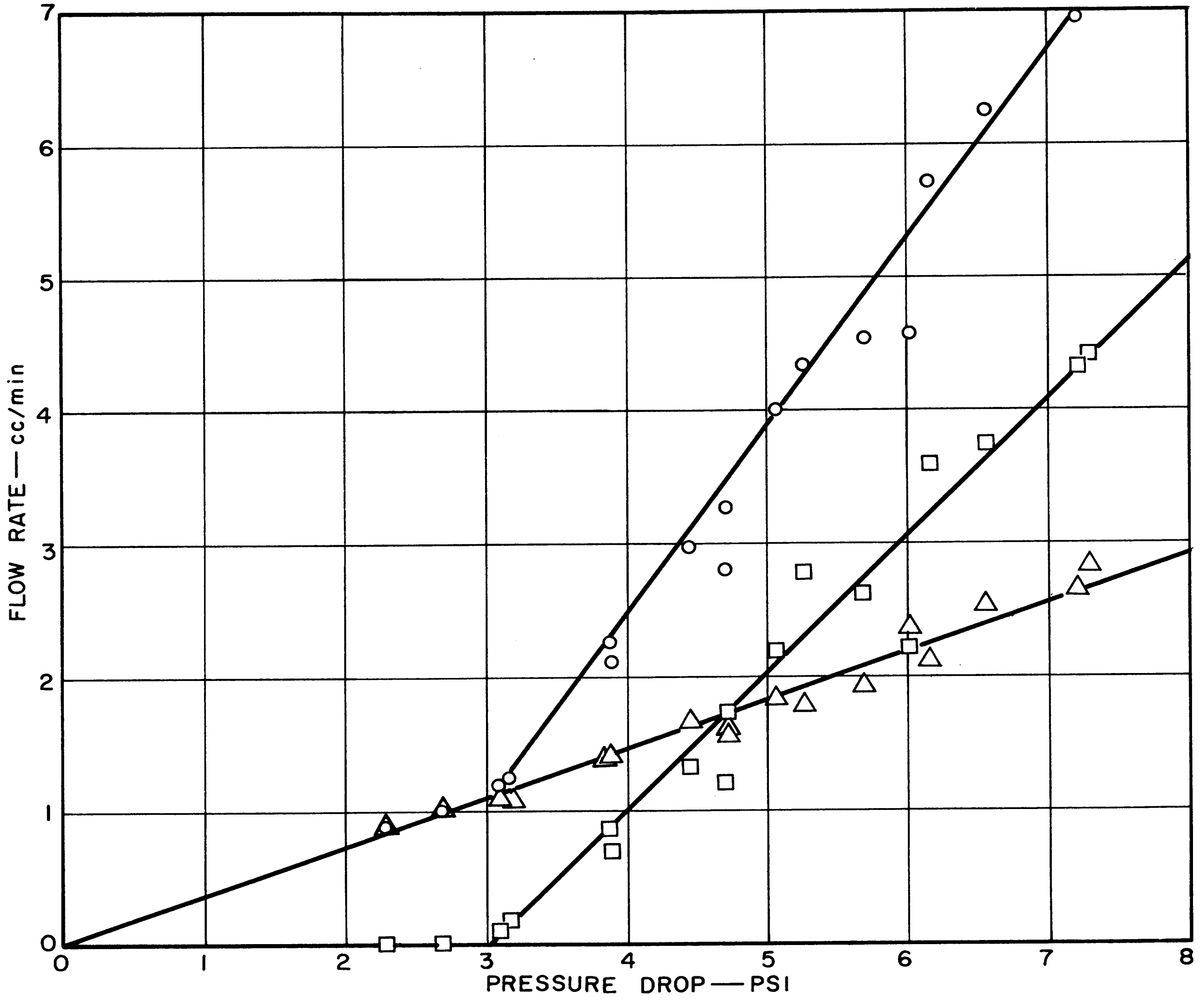


Fig. 6. Flow rate vs pressure drop for a synthetic 150/200 quartz flowing in a 4-ft hairpin of 10-mm-ID glass tubing; $D_{p_{avg}}$ = 89 microns.

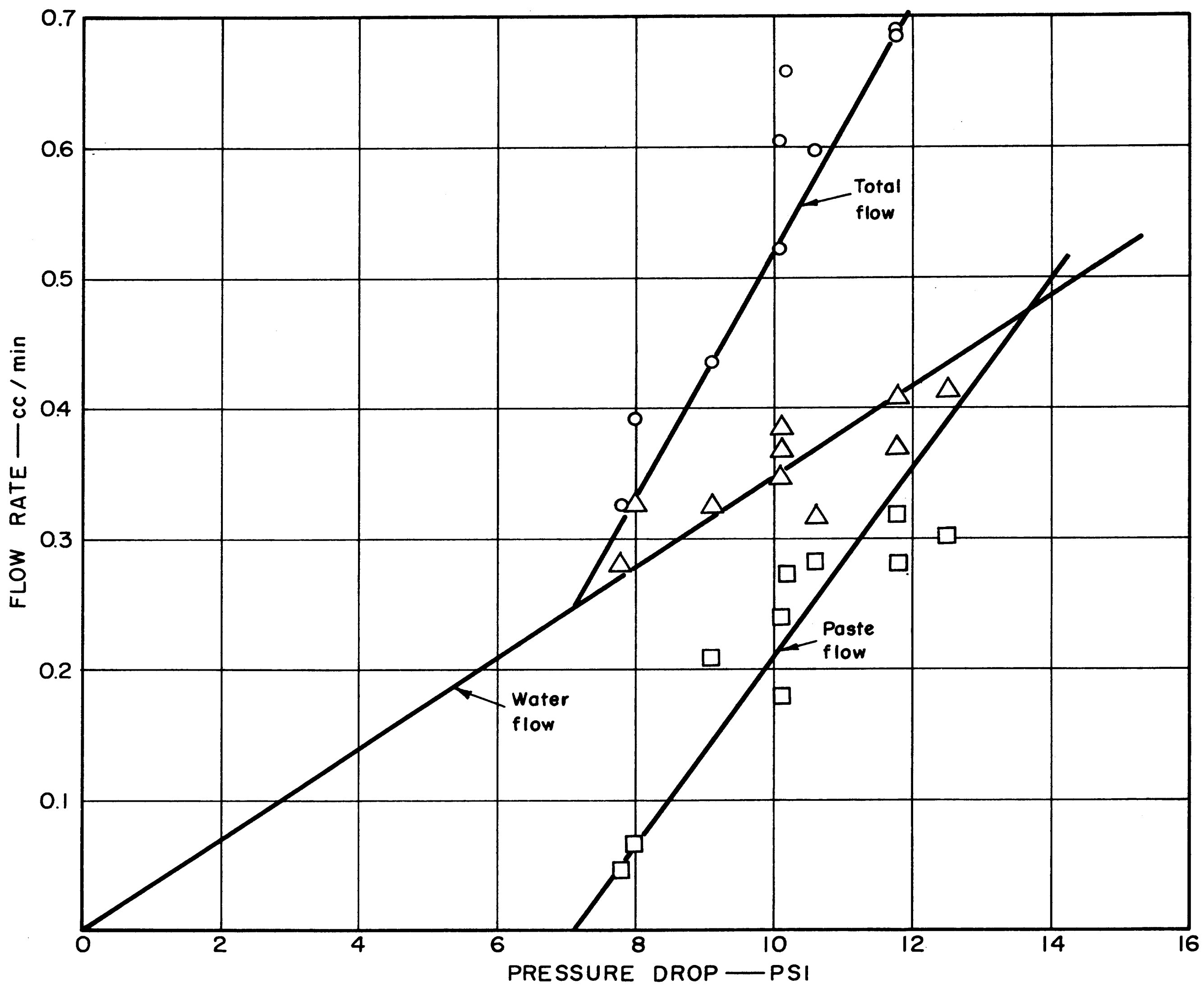


Fig. 7. Flow rate vs pressure drop for 150/200 Ottawa sand flowing in a 4-ft hairpin of 6-mm-ID glass tubing; $D_{p_{avg}} = 98$ microns.

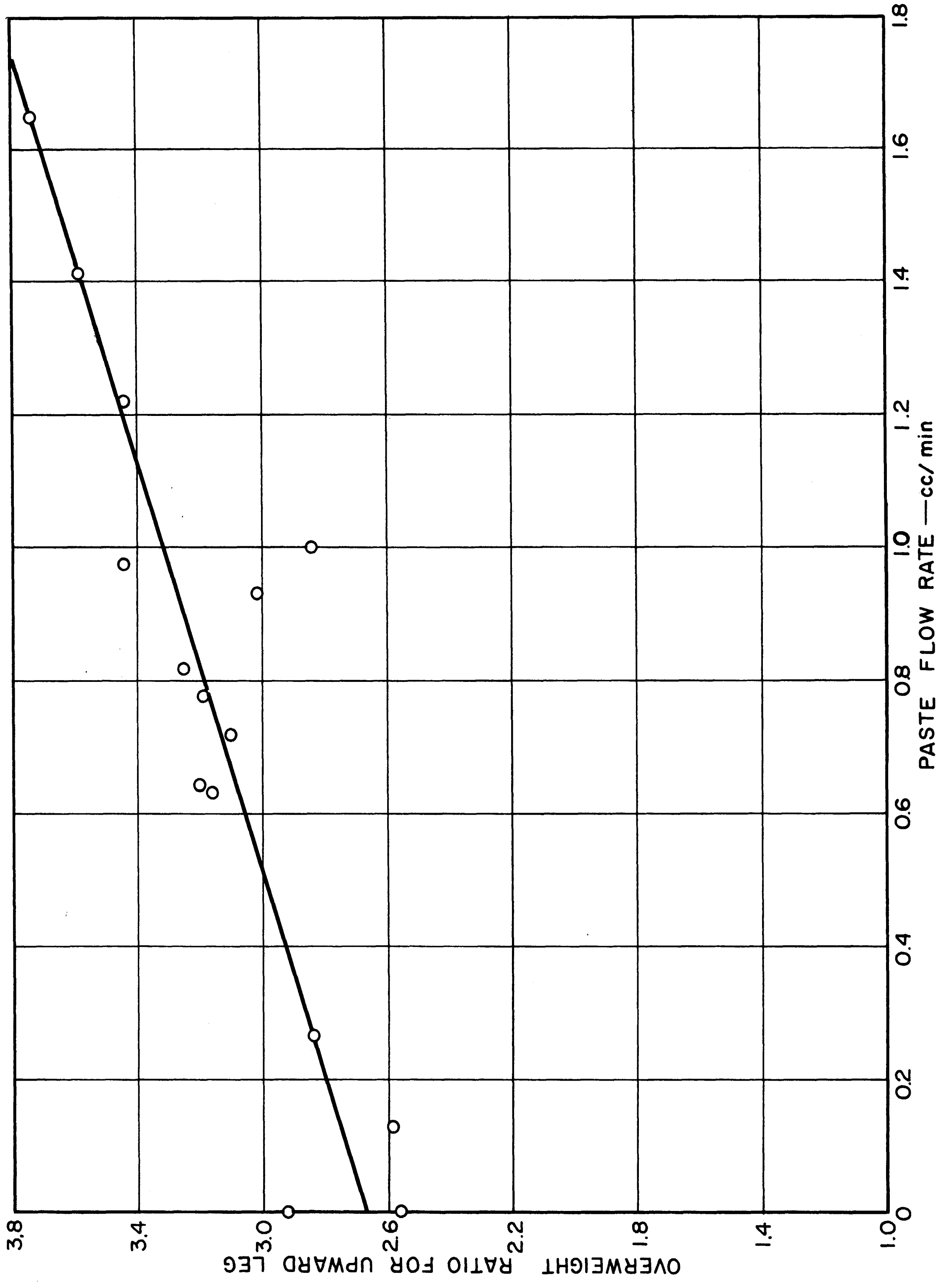


Fig. 8. Overweight ratio vs flow rate for 150/200 Ottawa sand flowing in the upward leg of an 8-ft hairpin of 10-mm-ID glass tubing; $D_{p_{avg}}$ = 98 microns; paste density, 60.5% by volume.

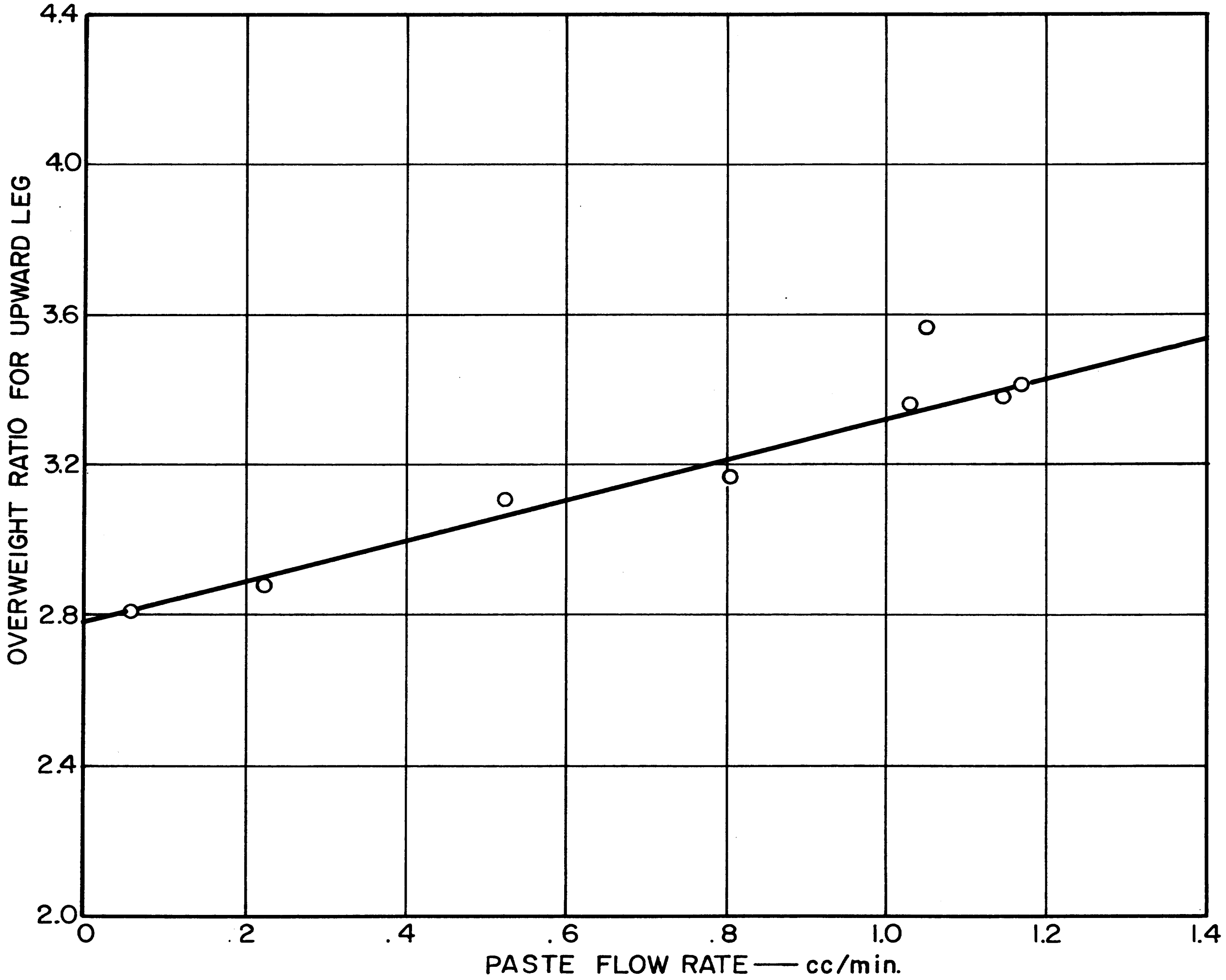


Fig. 9. Overweight ratio vs flow rate for synthetic 150/200 quartz flowing in the upward leg of an 8-ft hairpin of 10-mm-ID tubing; Dp_{avg} = 98 microns; paste density, 51% solids by volume.

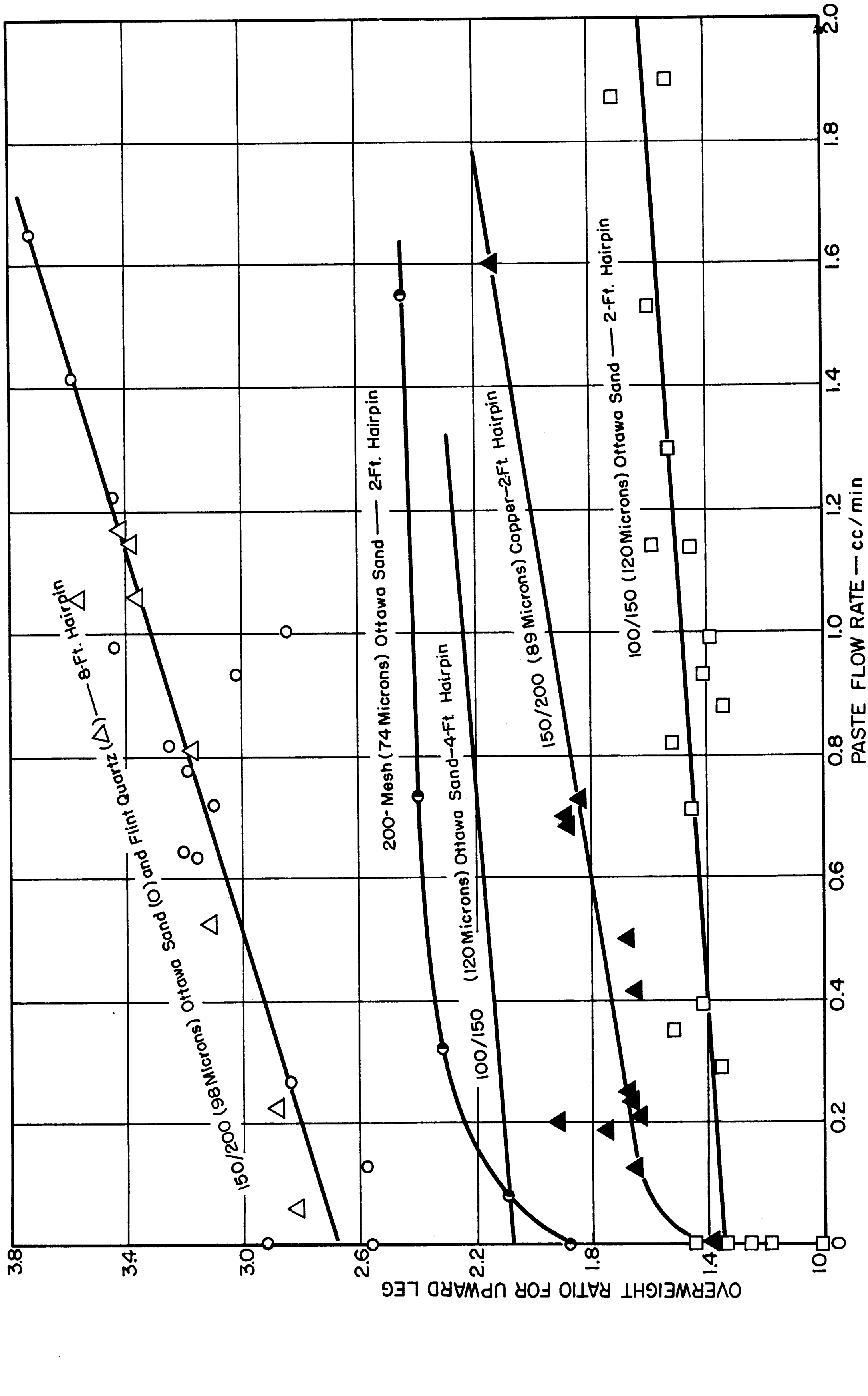


Fig. 10. Overweight ratio vs flow rate in the upward leg of hairpins of 10-mm-ID glass tubing.

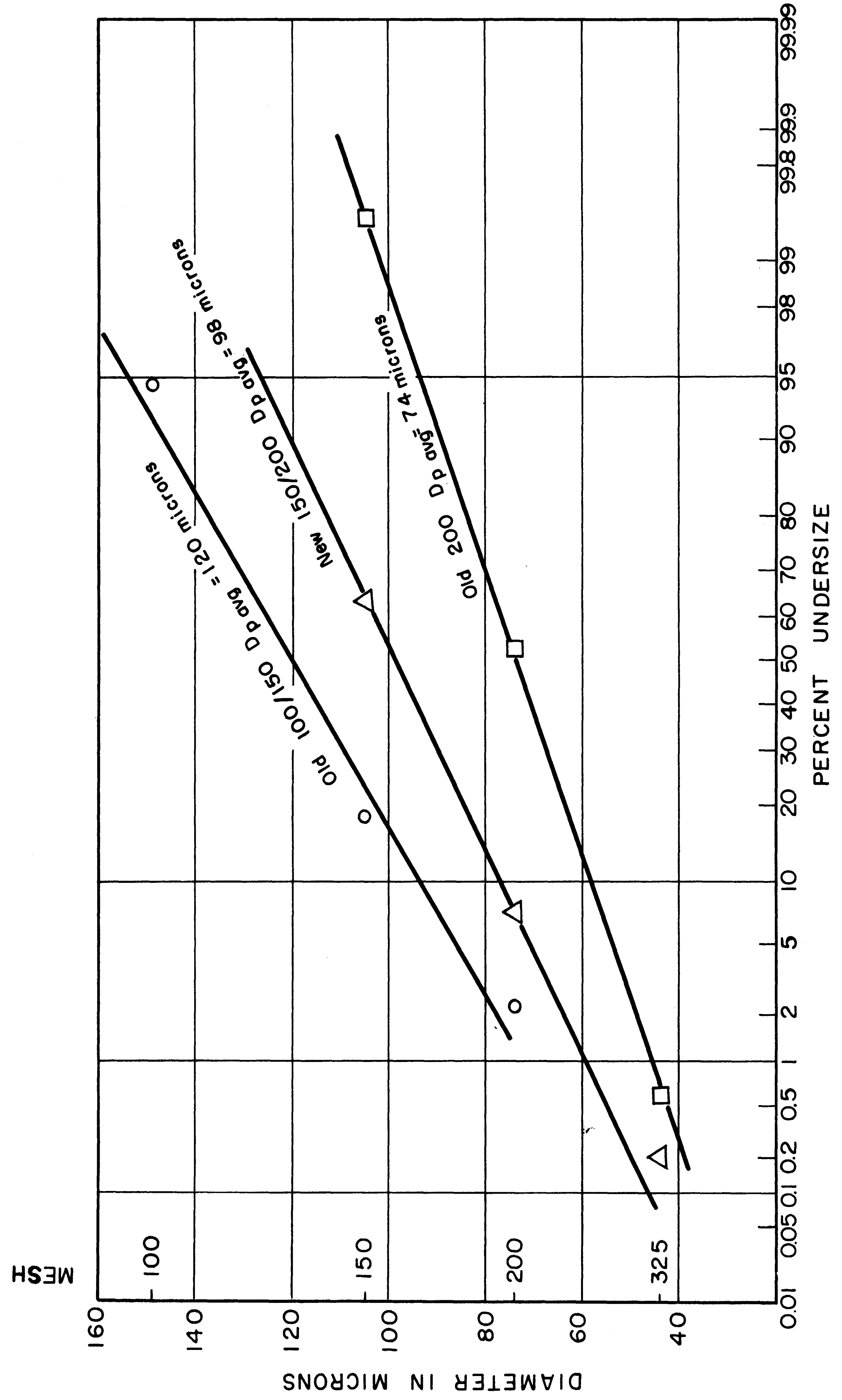


Fig. 11. Hazen plot for Ottawa sand used in flow experiments.

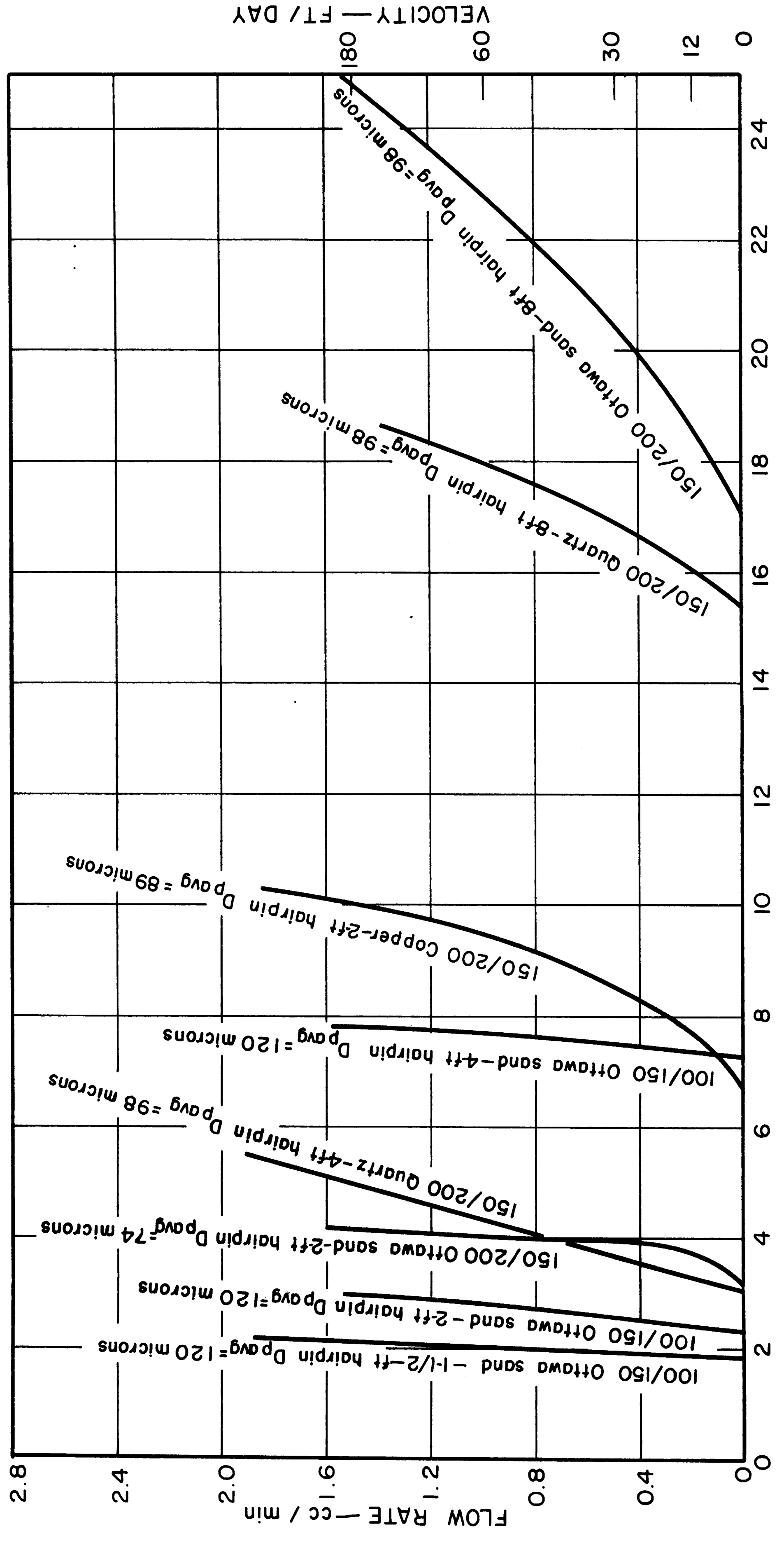


Fig. 12. Flow rate vs pressure drop in hairpins of 10-mm-ID glass tubing.

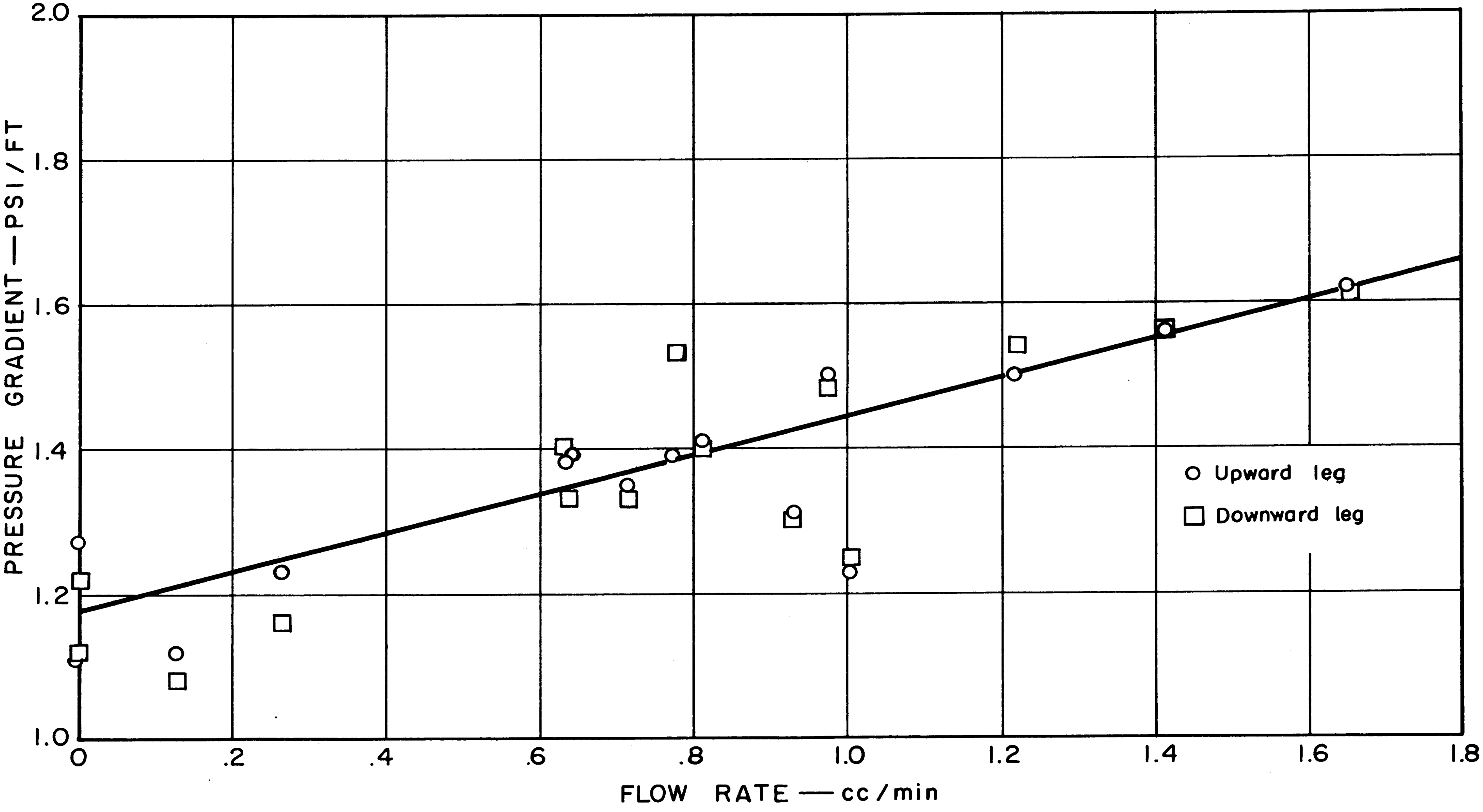
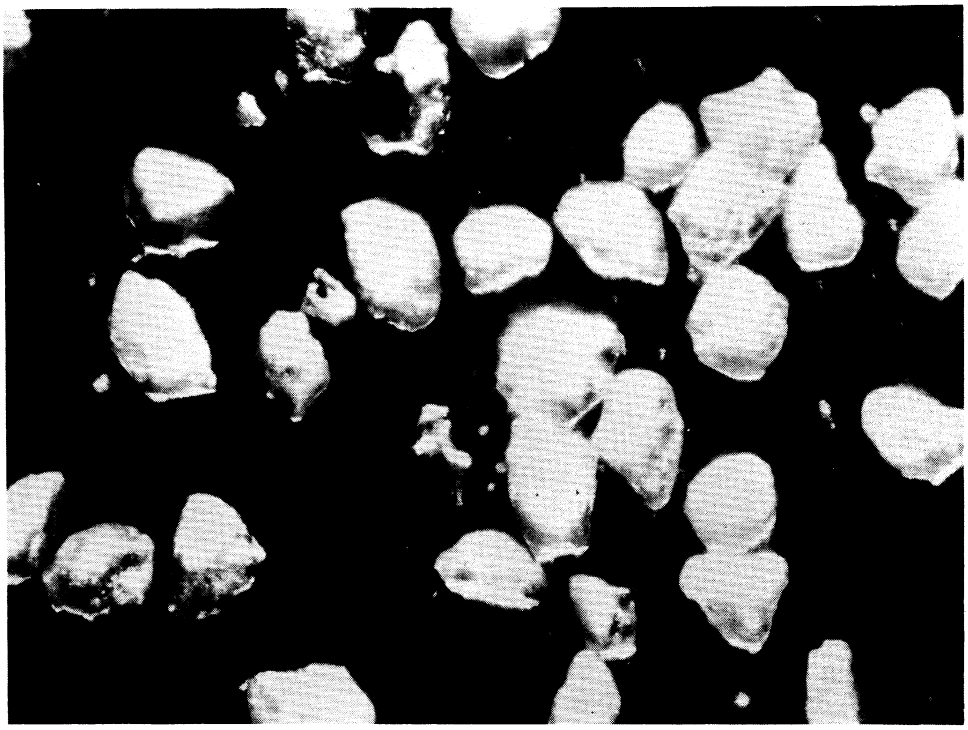
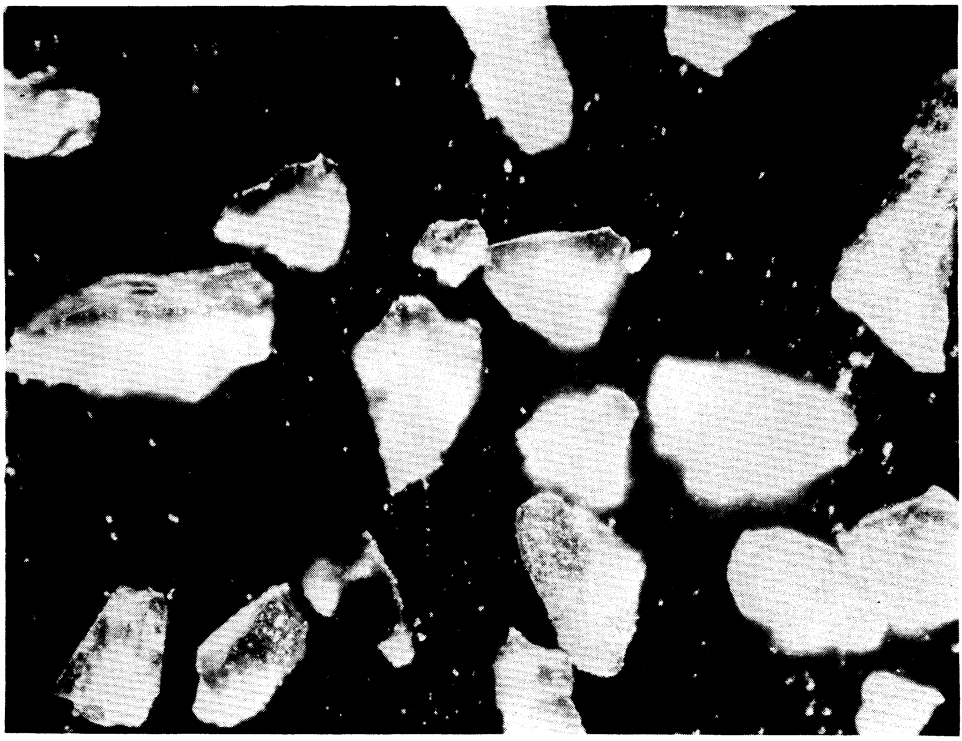


Fig. 13. Pressure gradient vs flow rate for 150/200 Ottawa sand flowing in an 8-ft hairpin of 10-mm-ID glass tubing.



150/200 Ottawa sand; $D_{p_{avg}}$ = 98 microns



150/200 synthetic quartz; $D_{p_{avg}}$ = 98 microns

Fig. 14. Photomicrographs of the new 150/200 Ottawa sand and 150/200 synthetic quartz.

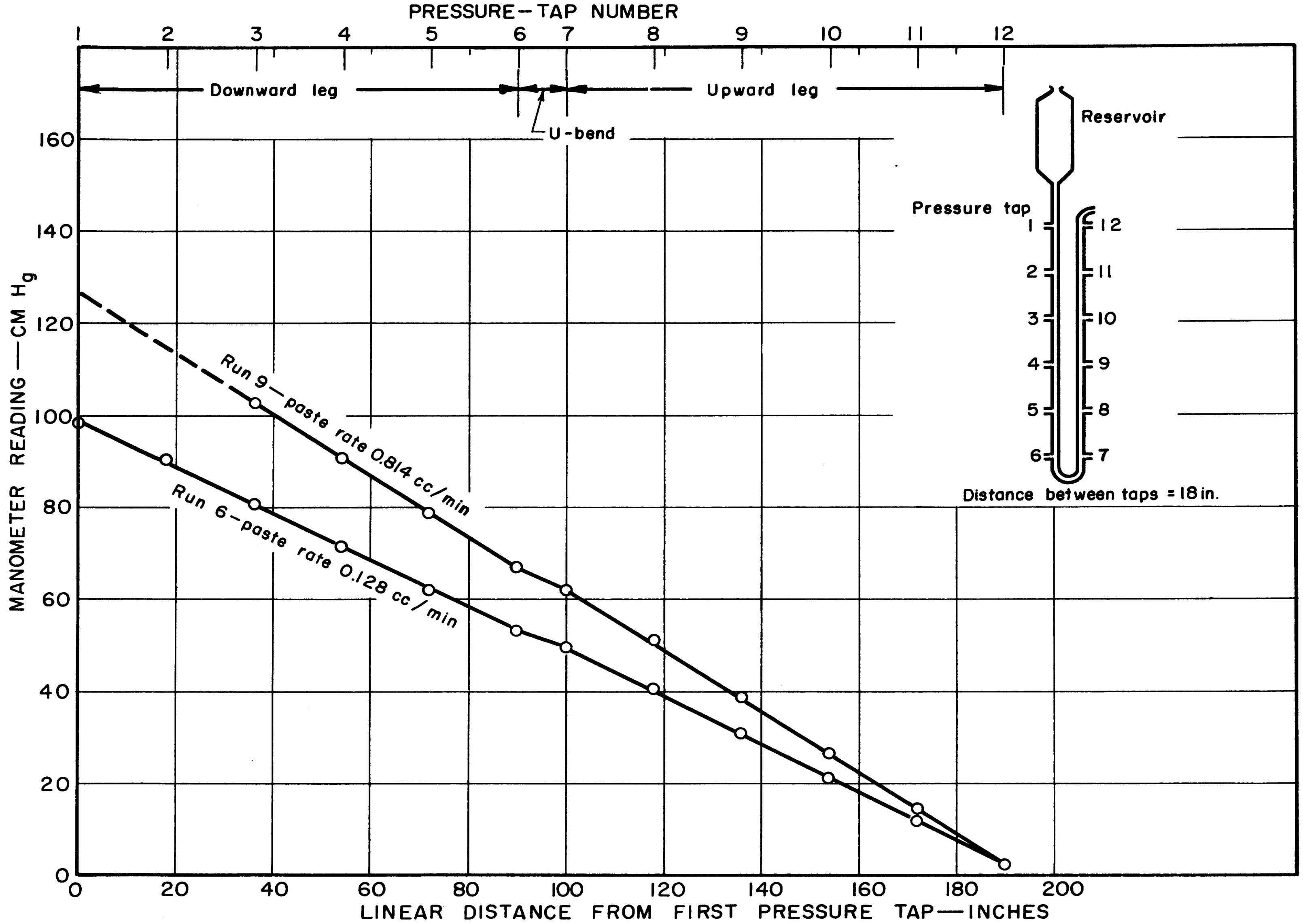


Fig. 15. Typical pressure distribution during flow of 150/200 Ottawa sand in 8-ft hairpin of 10-mm-ID glass tubing; $D_{p_{avg}}$ = 98 microns.

1. Data on 8-ft-long hairpins show a continuation of the tendency of pressure drop per unit length (or overweight ratio) to increase with tube length.

2. The pressure gradients in the upward and downward legs of a hairpin are practically equal.

3. The pressure gradient in the return bend of a hairpin is less than that for an equal length of straight, vertical tubing because of the stratified flow which occurs in the horizontal section of the bend.

4. Pressure drop increases as particle diameter decreases in the range of diameters studied.

5. Particle shape has no significant effect on overweight ratio but does affect flowing bed density and pressure drop.

EXPANSION OF FIXED BEDS

Exploratory experiments, which were described in the summary report on the preliminary phase of this study, indicated the possibility of correlating data on the pressure drop for the expansion of fixed beds with data on pressure drop for flow through tubes. In these experiments, water was forced upward through a tube packed with sand and the pressure drop across the sand bed was observed at the point where the liquid flow was just high enough to cause expansion of the bed. It was observed that the fraction overweight computed from this pressure drop increased linearly with bed length.

The results of further experiments on fixed-bed expansion are presented in this report. The data cover a range of tube lengths up to 220 cm for 10-mm-ID and 5-mm-ID glass tubing and up to 136 cm for 1/2-in.-ID Lucite tubing. Three different liquids were used: water, carbon tetrachloride, and mineral oil. The same solids, 150/200-mesh (average diameter = 98 microns) Ottawa sand, were used in all runs except one where 150/200-mesh (screen fraction) crushed quartz was used.

EXPERIMENTAL DATA

The data for fixed-bed expansion are presented in graphical form as plots of overweight ratio vs tube length in Figs. 16 through 22.

Figure 16 shows the points of first expansion for free-settled sand and for tapped sand. The free-settled density was between 60.9 and 63.8 volume-percent solids, while tapped settling produced densities around 69 volume percent.

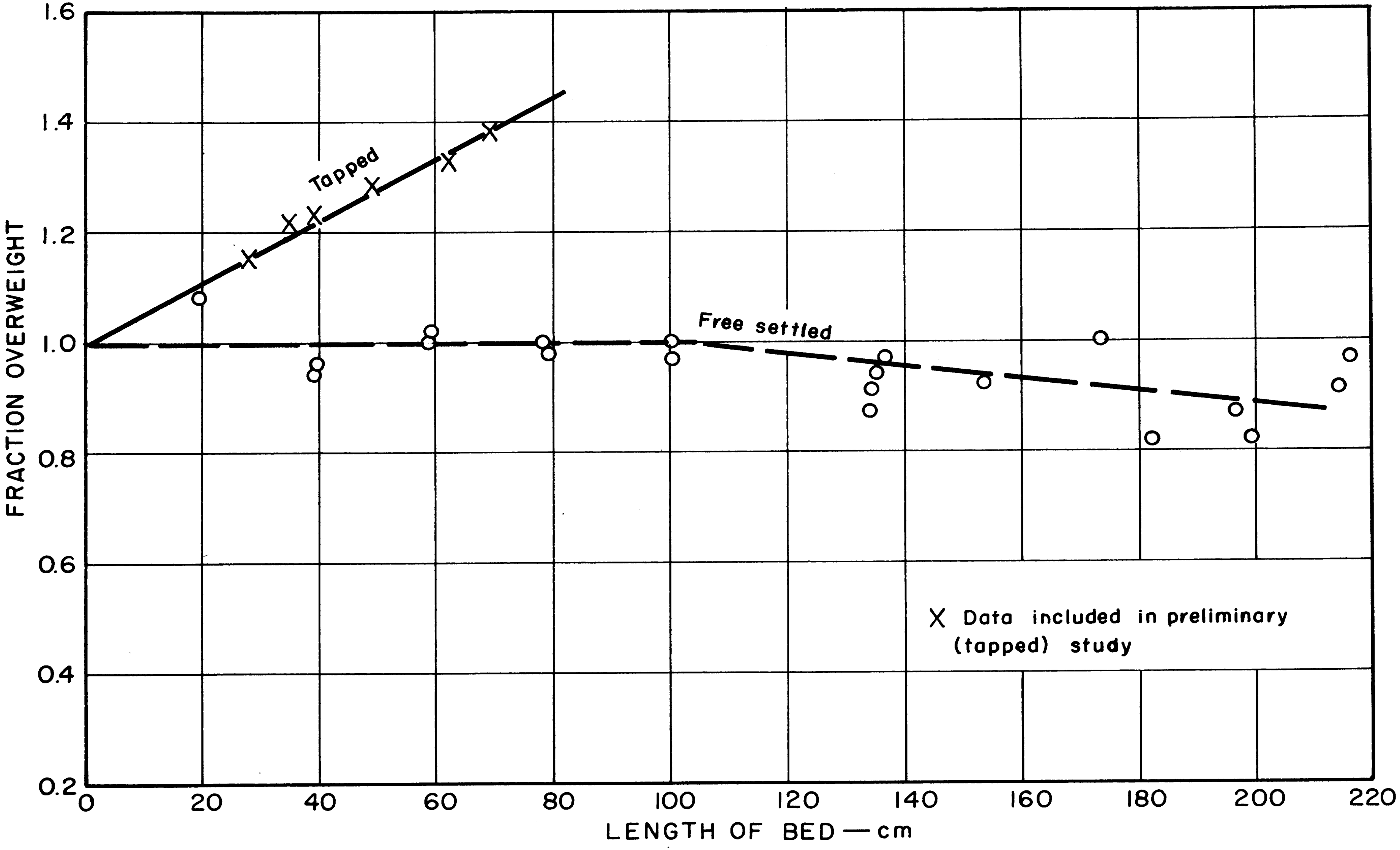


Fig. 16. Fraction-overweight data, 150/200 Ottawa sand in water, 10-mm-ID glass tubing; $60.9 \leq (1-x) \leq 63.8$.

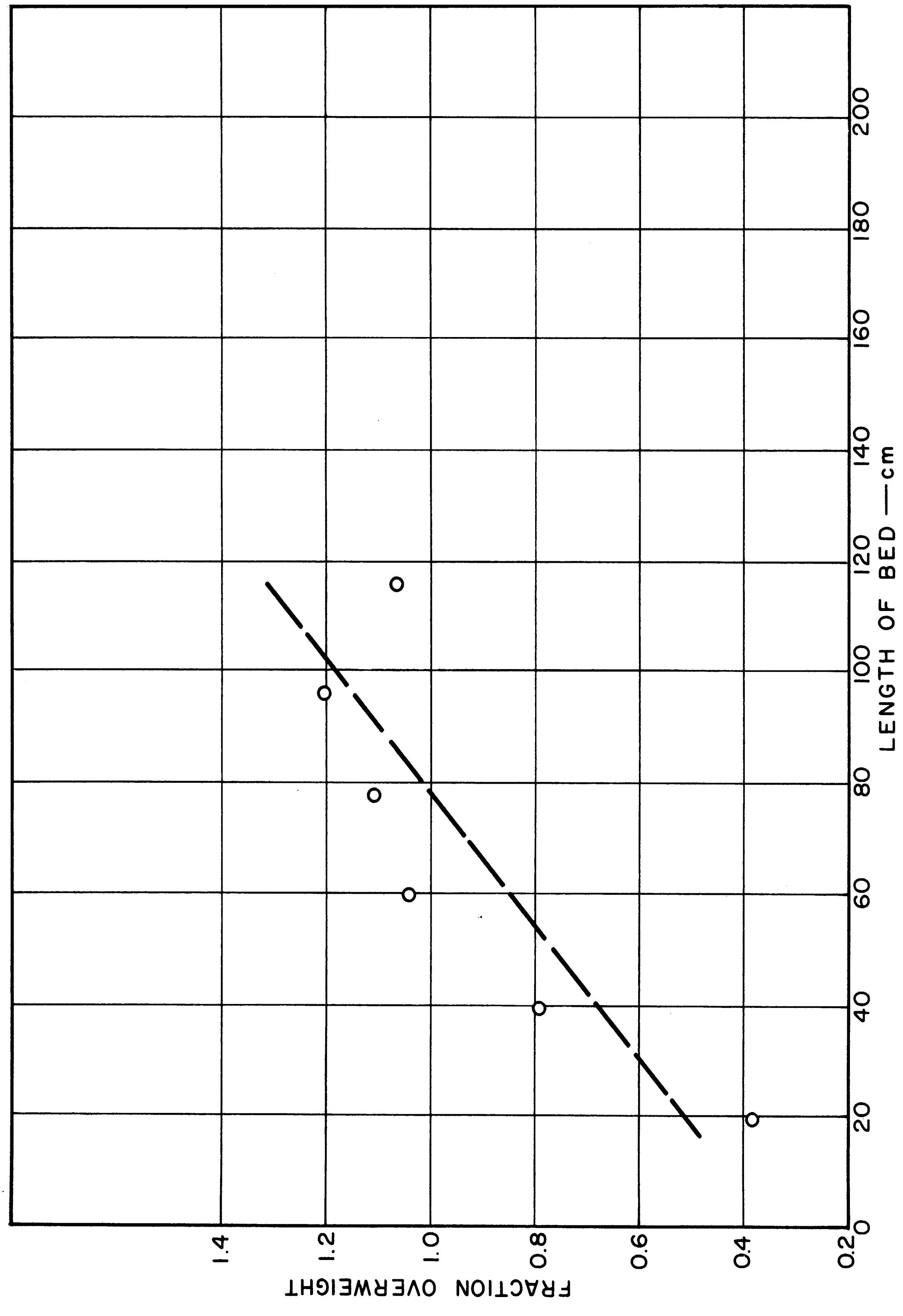


Fig. 17. Fraction-overwieght data, 150/200 Ottawa sand in CCl$_4$, 10-mm-ID glass tubing; $61.8 \leq (1-x) \leq 63.9$.

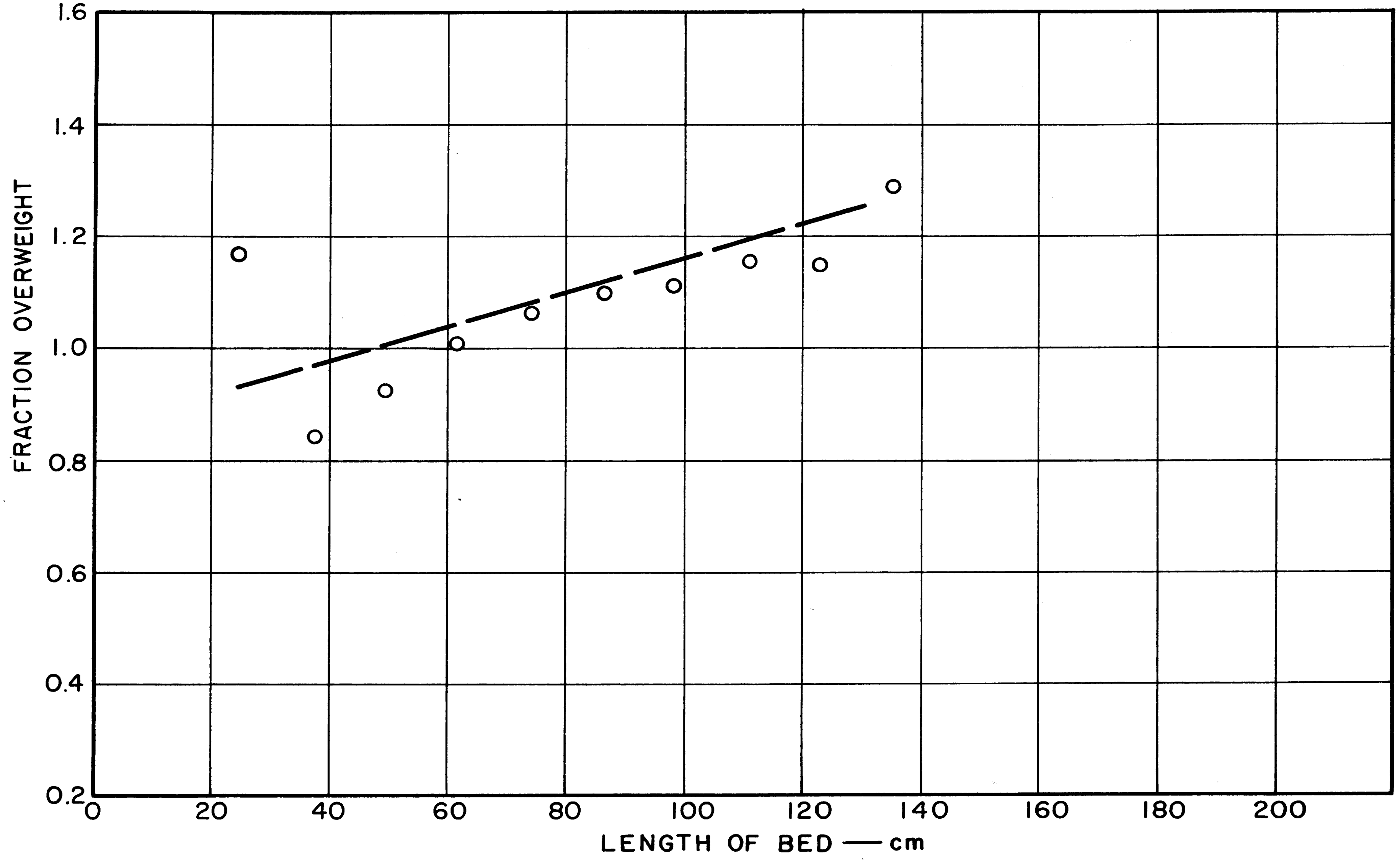


Fig. 18. Fraction-overweight data, 150/200 Ottawa sand in CCl_4, 1/2-in.-ID Lucite tubing; $61.8 \leq (1-x) \leq 62.3$.

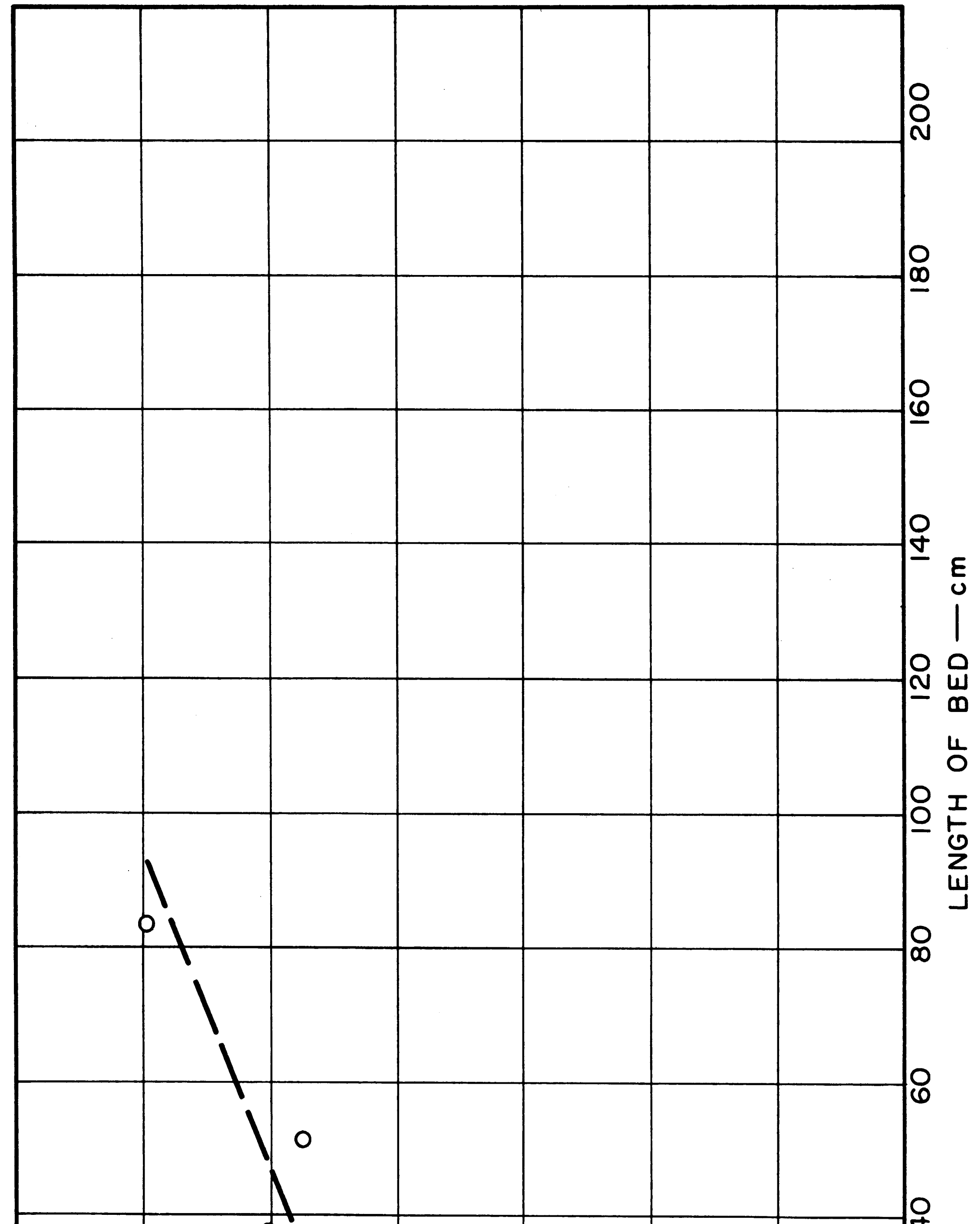


Fig. 19. Fraction-overweight data, 150/200 Ottawa sand in mineral oil, 1/2-in.-ID Lucite tubing; $59.8 \leq (1-x) \leq 61.1$.

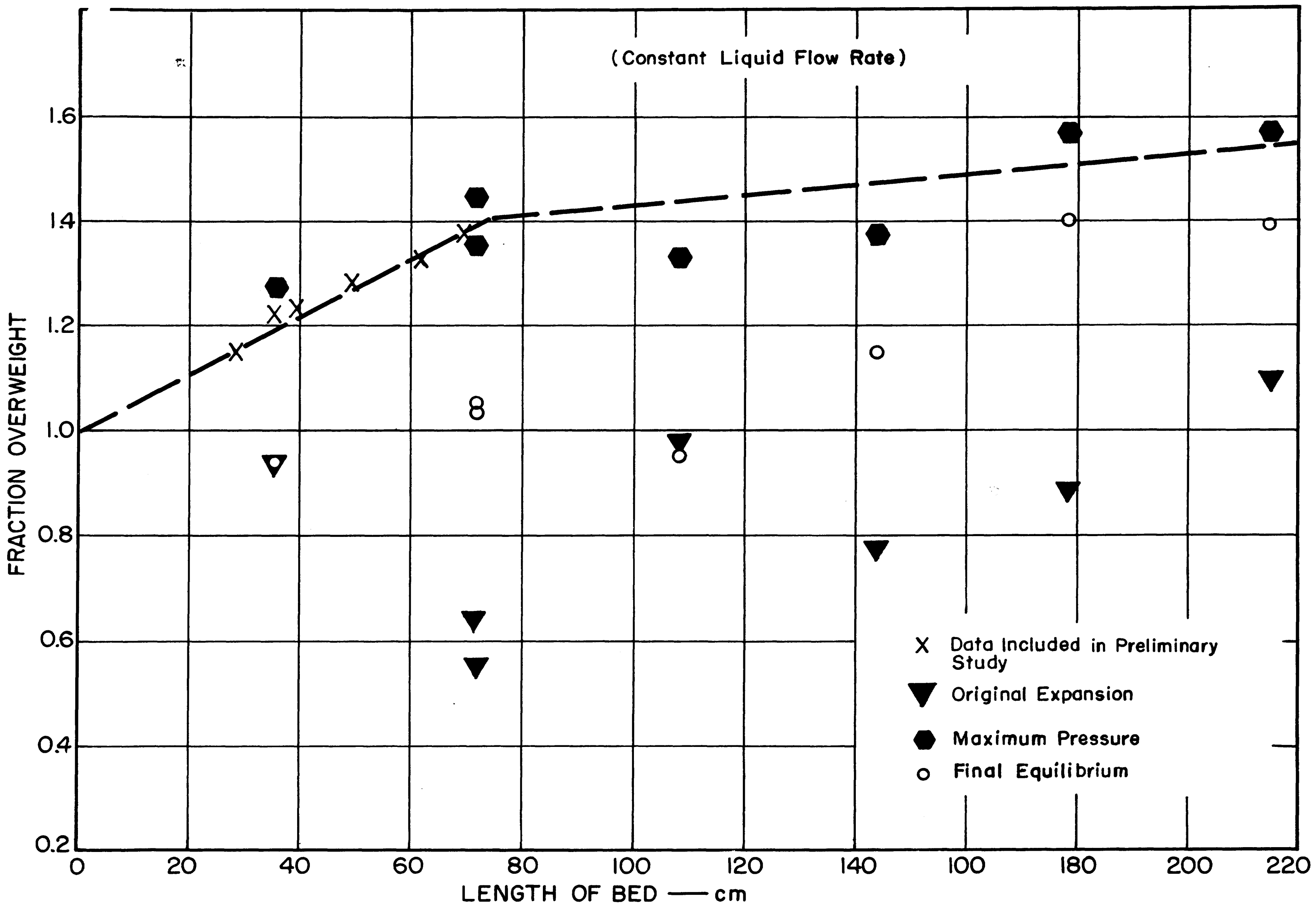


Fig. 20. Fraction-overweight data, 150/200 Ottawa sand in water, 10-mm-ID glass tubing (tapped)

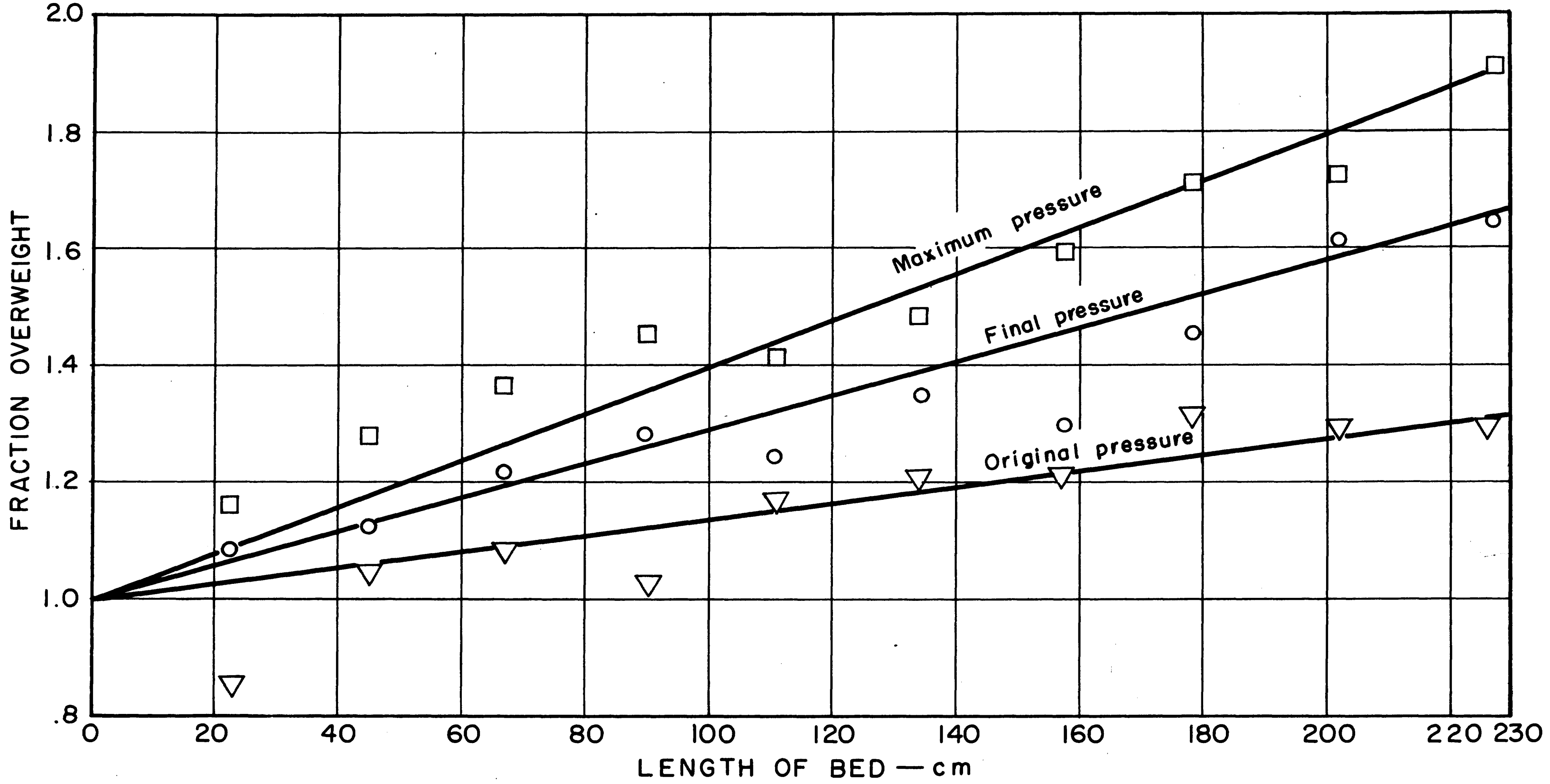


Fig. 21. Fraction-overweight data, 150/200 quartz in water, 10-mm-ID glass tubing; $55.3 \leq (1-x) \leq 56.3$ (tapped).

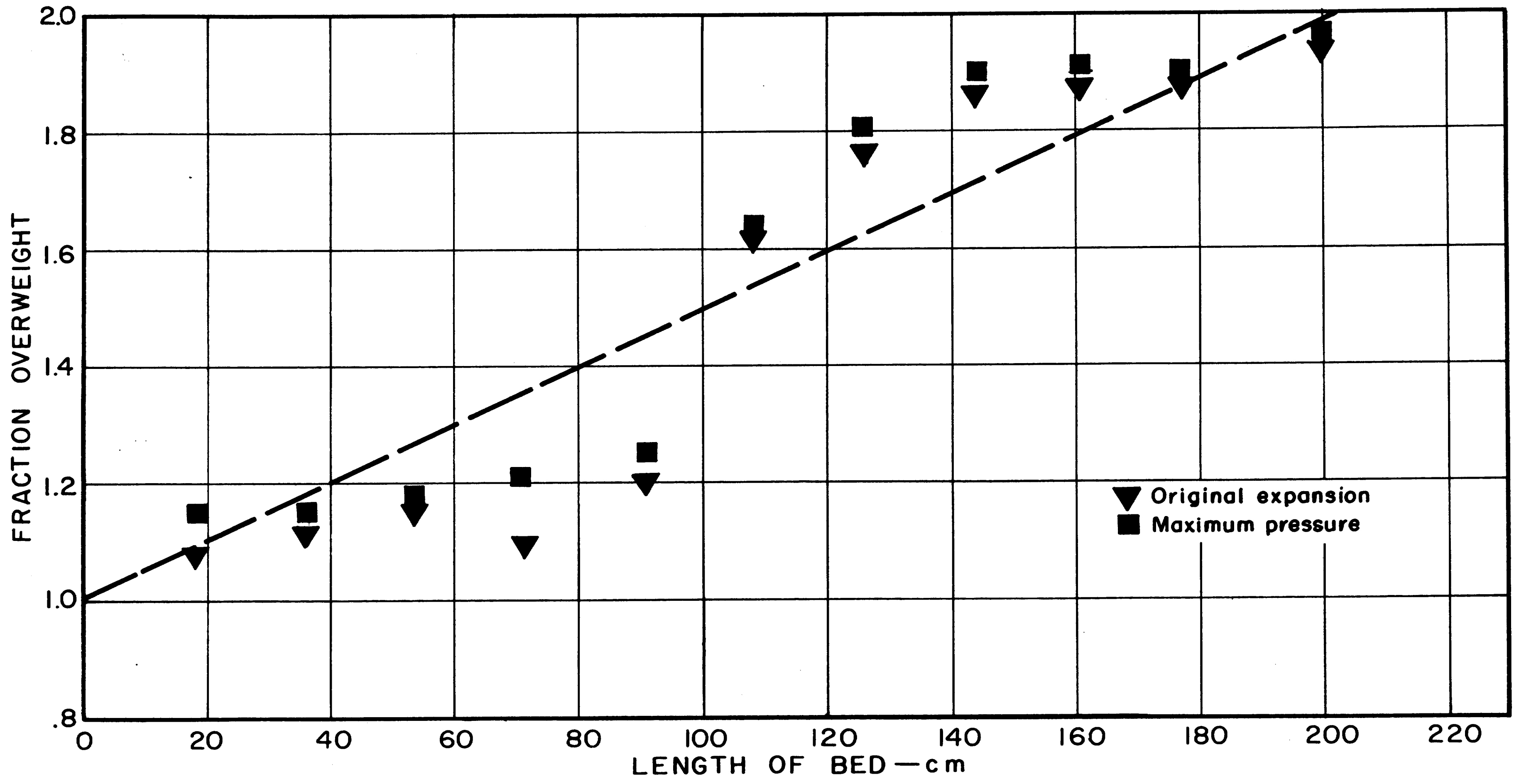


Fig. 22. Fraction-overweight data, 150/200 Ottawa sand in water, 5-mm-ID glass tubing; $67.6 \leq (1-x) \leq 69.2$ (tapped).

Figure 17 is the same sort of plot for sand in carbon tetrachloride in a 10-mm-ID glass tube, while Fig. 18 is for the same system in a 1/2-in.-ID Lucite tube. Both plots are for the free-settled sand. Figure 19 is the plot for free-settled sand in mineral oil in a 1/2-in.-ID Lucite tube.

Since the data up to this point showed no relationship to either the preliminary findings or the actual flow case, the usefulness of the point of first expansion obviously was doubtful. It had been observed that if the liquid flow rate was increased beyond this point, the pressure drop would reach a maximum and then subside to a final value. In the following runs, the pressure drops at these points were recorded.

Figure 20 shows the three characteristic points for tapped Ottawa sand in water in a 10-mm-ID glass tube. Figure 21 is the same for tapped crushed quartz in water in a 10-mm-ID tube, and Fig. 22 is for tapped Ottawa sand in water in a 5-mm-ID glass tube.

DISCUSSION

The point of first expansion obviously is not a satisfactory criterion of frictional effects. The most logical reason why the bed can expand at pressure drops less than the equivalent of an overweight fraction equal to one is that irregularities in bed density may cause higher pressure drops over short lengths of the bed. These short lengths would then expand until the bed density becomes uniform.

The two higher pressure points look more promising as indicators of the magnitude of frictional effects. The data for the point of maximum pressure drop shown in Figs. 20 and 21 are fairly close to the overweight ratios observed in flow through tubes (see Fig. 10).

ELECTRICAL CONDUCTIVITY AS A MEASURE OF PACKED-BED DENSITY

The possibility of using the electrical conductivity of a packed bed as a measure of its density or porosity was discussed in the preliminary report and we proposed to investigate its practicality during this phase of the study. This section of the report deals with experiments involving the measurement of the electrical conductivity of salt water in beds of sand at various porosities and the relation of conductivity to porosity.

The test apparatus used is shown in Fig. 23. A known weight of solids was loaded into a 10-mm-ID glass tube which was fitted with platinum electrodes, as shown. A conducting solution (sodium chloride in singly distilled water) was circulated through the bed and conductance readings were taken on a standard 60-cycle a-c conductivity bridge. The solids concentration was determined by the relation

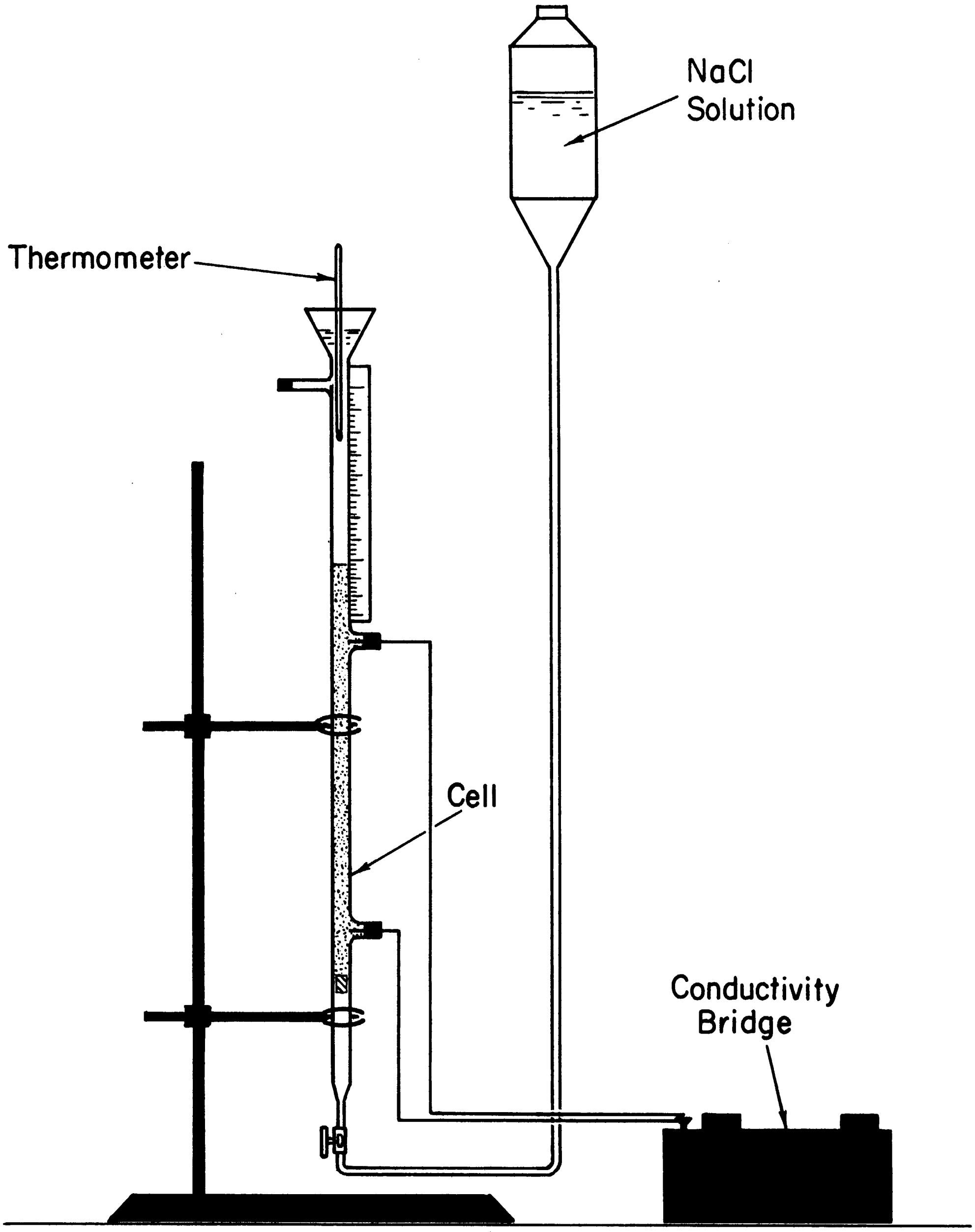


Fig. 23. Apparatus for measuring specific conductance in a bed of granular solids.

$$(1 - x) = \frac{W_S/\rho_S}{V_B} ,$$

where

x = porosity (volume fraction),
$(1-x)$ = fraction solids by volume,
W_S = weight of solids,
ρ_S = weight density of solids, and
V_B = volume of bed.

The volume conductivity, or specific conductance, of an electrolyte is given as

$$k = \frac{K}{R} ,$$

where

k = specific conductance,
K = cell constant, and
R = measured resistance.

The cell constant was determined by using a solution of known conductance.

The results obtained in a first series of runs have been plotted in Figs. 24 to 26. These results are of a relative nature only, as there was some error in determining the cell constant.

It can be seen from the graphs that in the range of solids concentrations between 40 and 65% by volume, there is a definite relationship between specific conductance and concentration of solids for each material. The curves are almost linear and the average deviation of test points is well below 2%. The existence of a reproducible correspondence between the two quantities establishes, in principle, the applicability of the method.

Additional reliable data will have to be obtained in order to determine accurately the effect of particle shape and size, cell geometry, and the properties of the original solution.

This technique is considered to have sufficient merit to be included in our future studies on flowing systems.

LITERATURE SURVEY

A brief search of the material published on two-phase fluid-solid systems was conducted in order to determine what information was available on the flow properties of such systems and especially on high-density sediments.

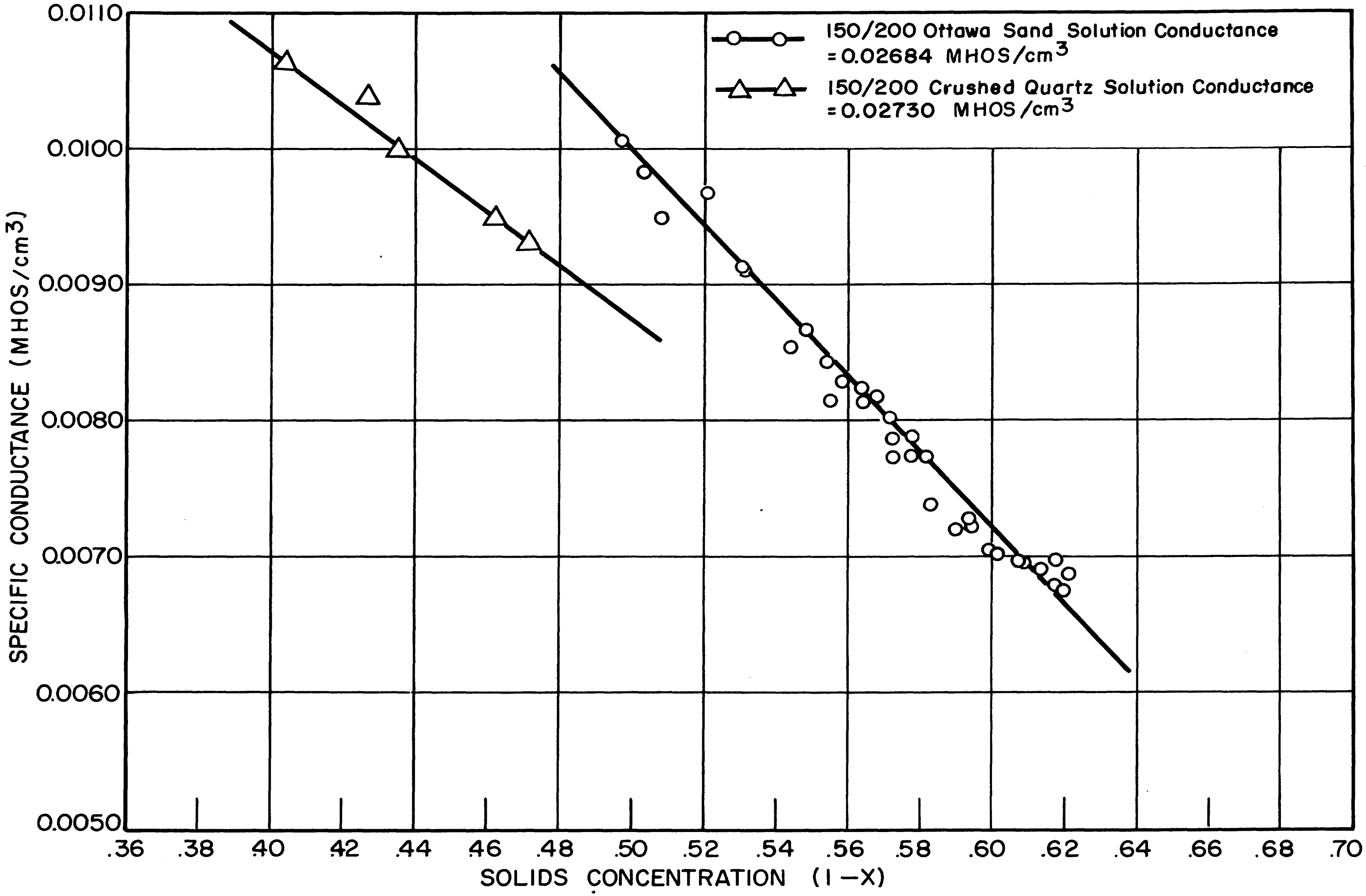


Fig. 24. Specific conductance of porous bed vs solids concentration; sand and quartz.

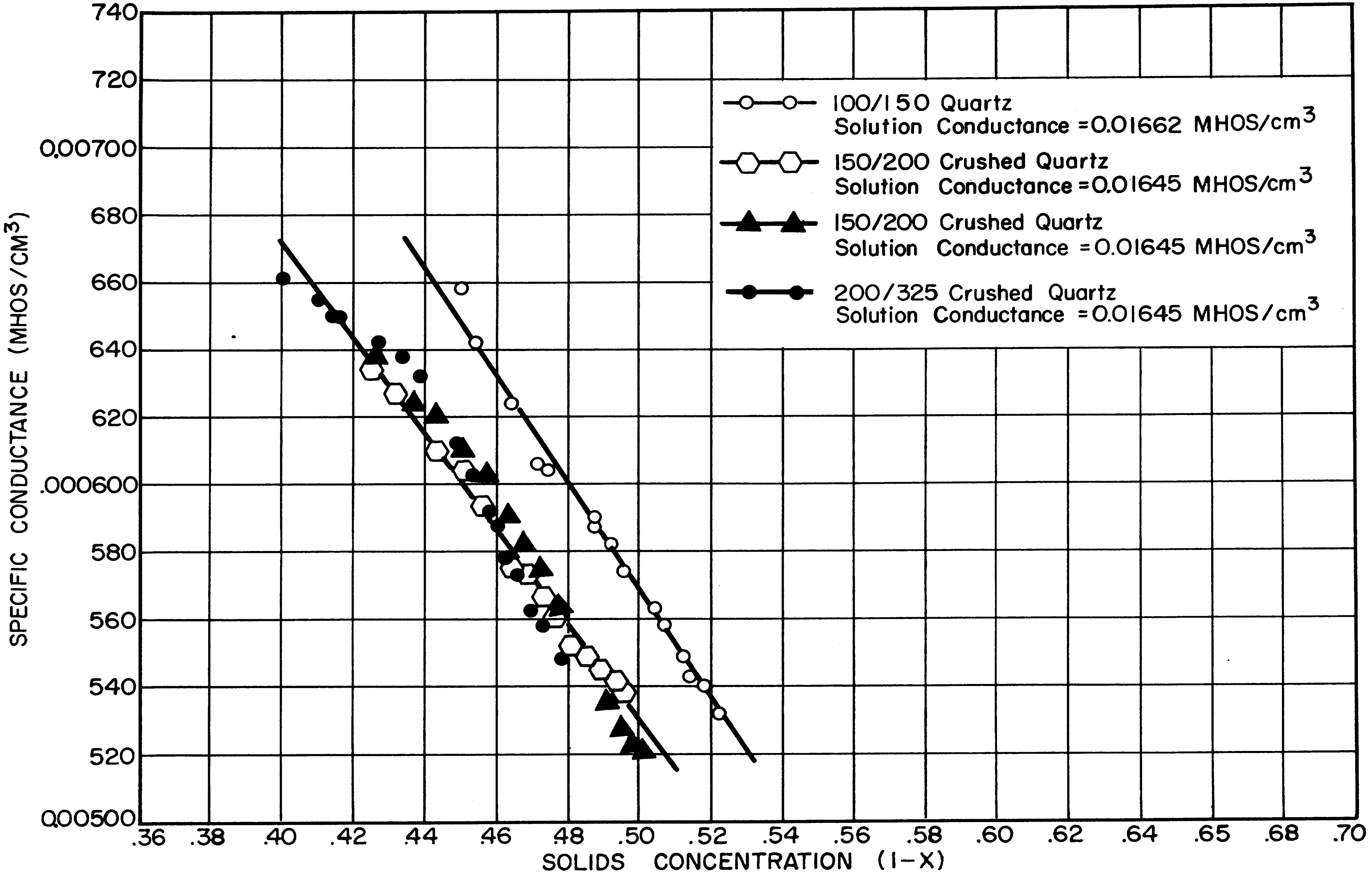


Fig. 25. Specific conductance of porous bed vs solids concentration; quartz.

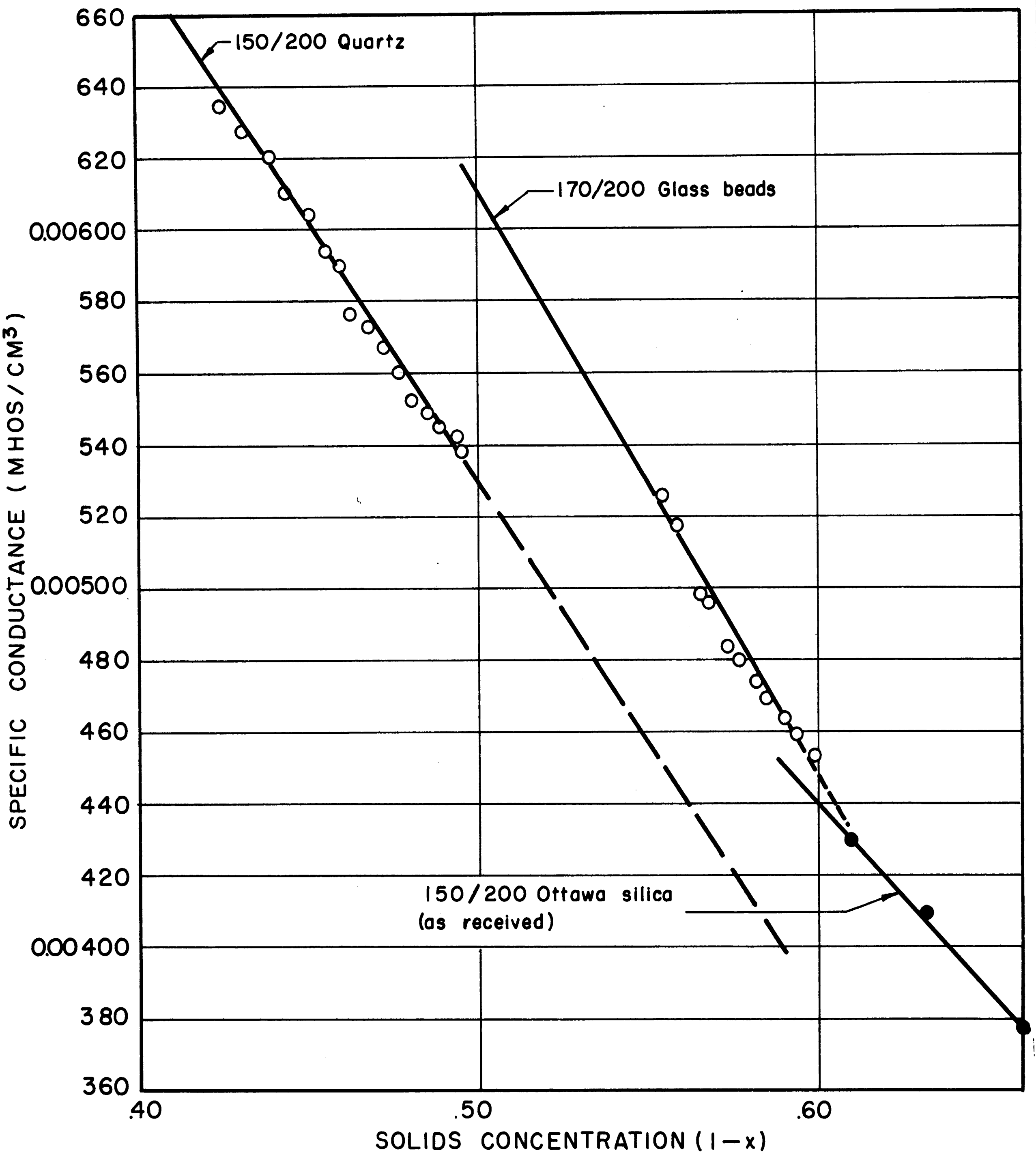


Fig. 26. Specific conductance of porous bed vs solids concentration; sand, quartz, and glass beads.

The sources used were the Engineering Index (1950-54) and Chemical Abstracts (1938-54)

The survey revealed that the majority of studies published on the subject are concerned with the problems involved in some specific application. Most of the work has been carried out in the fields of catalytic cracking (fluidization of solids by gases), the transportation of bulk solids, and the movement of sediments in river beds.

The most important result of the survey, although a negative one, is that no reference was found dealing specifically with the flow of sediments through pipes in the range of solids concentrations around 60% by volume.

Some general studies have been made on the flow of comparatively-low-concentration suspensions, slurries, and sludges in vertical and horizontal tubes (References 2, 4, 6, 7, 8, 9, 10, 11, 12, and 13). The results obtained vary widely with different materials and flow conditions. The methods of correlation presented are just as varied and no general conclusion could be drawn as to the flow characteristics of the systems involved.

It appears, however, that low-concentration suspensions (below 40-50%) behave as Newtonian fluids in the absence of interparticulate forces (References 1, 17, and 21). They are identified by a linear stress rate-of-shear relationship, and flow in this case can be treated as a single phase problem. The larger part of the experimental work conducted with such systems has centered around viscometer measurements, and several formulae have been developed expressing the viscosity of suspension.

Newtonian behavior, on the other hand, is not the norm, even at fairly low concentrations. Several materials, such as clay slurries and sewage sludges, exhibit a yield stress and have been termed "plastic," although there is no general agreement on the exact usage of the term. Plastic materials were investigated mostly from a rheological standpoint, and efforts were directed at determining properties such as their yield point, apparent viscosity, fluidity, etc. (References 17, 18, 21, 22, and 26). A discussion and data pertaining to the flow of plastic sludges through tubes can be found in References 4 and 13.

Granular materials exhibit a host of other different rheological properties and no general classification can be found covering the entire field. Some powders have been shown to be dilatant; they possess the property of dilating when sheared. Others, in the presence of electrostatic forces acting between particles, become thixotropic; that is, their viscosity decreases with shear and is regained when they are brought back to rest (References 1, 20, 21, and 22). These characteristics are not altogether clearly understood and few or no data are available on the flow of such systems through circular conduits.

The methods of correlation most frequently encountered for fluid-solid flow through circular pipes are in the majority of cases entirely empirical. Data are presented in terms of dimensionless groups, usually identified as friction factors and Reynolds number. Tables and graphs are usually included, showing the relative effect of the system variables (References 7, 8, 9, 10, 12, and 20).

A number of semi-analytic methods have been developed. These tend to approach the problem from two different aspects. On the one hand, the extension of hydrodynamic results obtained for a single particle to multiparticle systems (References 2, 11, 14, 15, and 16); on the other, a consideration of bulk effects rather than single particle behavior (Reference 4). In both cases, the applicability of the relations obtained is, for the most part, limited to the specific systems considered.

In view of the negative result of this preliminary survey, it was decided to postpone a more extensive literature search to a date when additional time would be available for its completion.

Topics such as the movement of sediments in river beds and soil mechanics were not covered in the preliminary search. It is believed that they should be included in any future survey.

A list of selected references follows this section. Abstracts have been compiled for the most pertinent among them.

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CONTINUOUS-FLOW LOOPS

A small amount of effort has been devoted to the design and experimental exploration of continuous-flow loops. By continuous-flow loops we mean systems in which both solids and liquids are recycled so that they flow in closed circuits. The establishment of the feasibility of loop systems is of obvious importance in the consideration of overall reactor systems.

The most promising systems conceived "at first glance" are those involving downward flow of the high-density paste and upward flow of solids in a low-density lift leg. The other major class of systems would involve hairpin (single or multiple) flow with its combined downward and upward flow of high-density paste. The major difference between the two classes of systems is that the pressure drop required would be much higher for the hairpin systems.

A high-density down flow plus low-density lift system was constructed and operated to demonstrate, qualitatively, its feasibility. A schematic drawing of this system is shown in Fig. 27. Several types of paste tube ends and lift injectors were tried and worked; so the design shown is not necessarily the optimum.

There was difficulty in obtaining relatively smooth paste flow when air was present in the paste and the ejector geometry was a simple "Tee." In this instance, tap water was being used and the dissolved air came out of solution and formed small bubbles in the paste column. The paste flowed as before, carrying the gas bubbles at apparently the same rate as the sand grains, but the gas bubbles accumulated at the lower end of the paste tube (the branch of the "Tee"). This gas was not removed by the injector fluid, so it accumulated until it stopped the flow of paste, acting just like a solid piston.

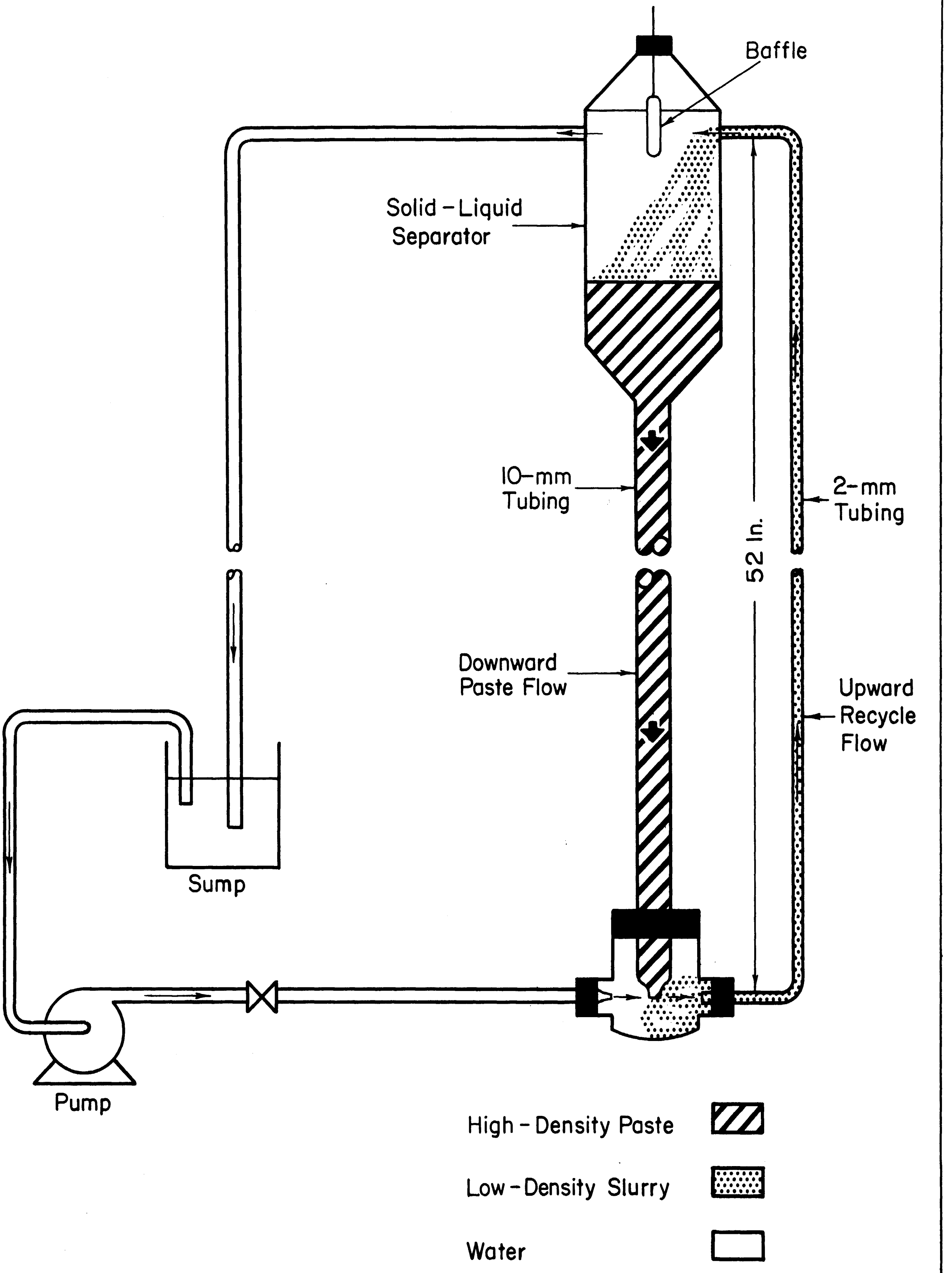

Fig. 27. Continuous-flow system.

For this reason, the subsequent designs made provisions for sweeping the gas away from the tube end. This is one reason for using the constriction on the tube end. The other, and perhaps more important reason, was to explore the use of constrictions as a means of controlling paste flow rate. Qualitative observations indicated the possibility of obtaining smoother flow in this way and point to the need for a careful study of the effect of contractions, baffles, etc.

A possible means of application of paste-flow-down-inside tubes—low-density-lift system is shown in Fig. 28. Here the geometry is similar to a shell-and-tube-bundle heat exchanger. The separation zone and paste-distribution header are combined at the top of the exchanger. Quite possibly this zone would have to be poisoned in order to keep down the local power generation. The sodium stream is motivated by an electromagnetic pump, another of which could be used as a booster pump on the low-density leg, if it proves desirable.

Figure 29 shows a schematic drawing of a variant on the dense-paste-down, low-density-lift system. Here the paste flows outside the coolant tubes on the shell side of the reactor-heat exchanger. The possible advantages of this are as follows:

1. A simple flow path for the paste. One entrance tube, one exit tube. No headers or manifolds.

2. No need for an external settling zone. The separation among solids, liquid, and gas takes place at the top of the reactor core.

3. Lower fuel inventory results from 1 and 2.

4. The tube bundle can be pulled out from the top. The whole works could be designed for top servicing.

A hairpin-type system is shown in Fig. 30. The principal difference between this and the previously discussed systems is that a high-pressure difference between tube entrance and exit must be provided. Aside from this, the system does not differ much from the paste-flow-down-inside-tubes system shown in Fig. 28. It has the advantage of fewer tube-end connections.

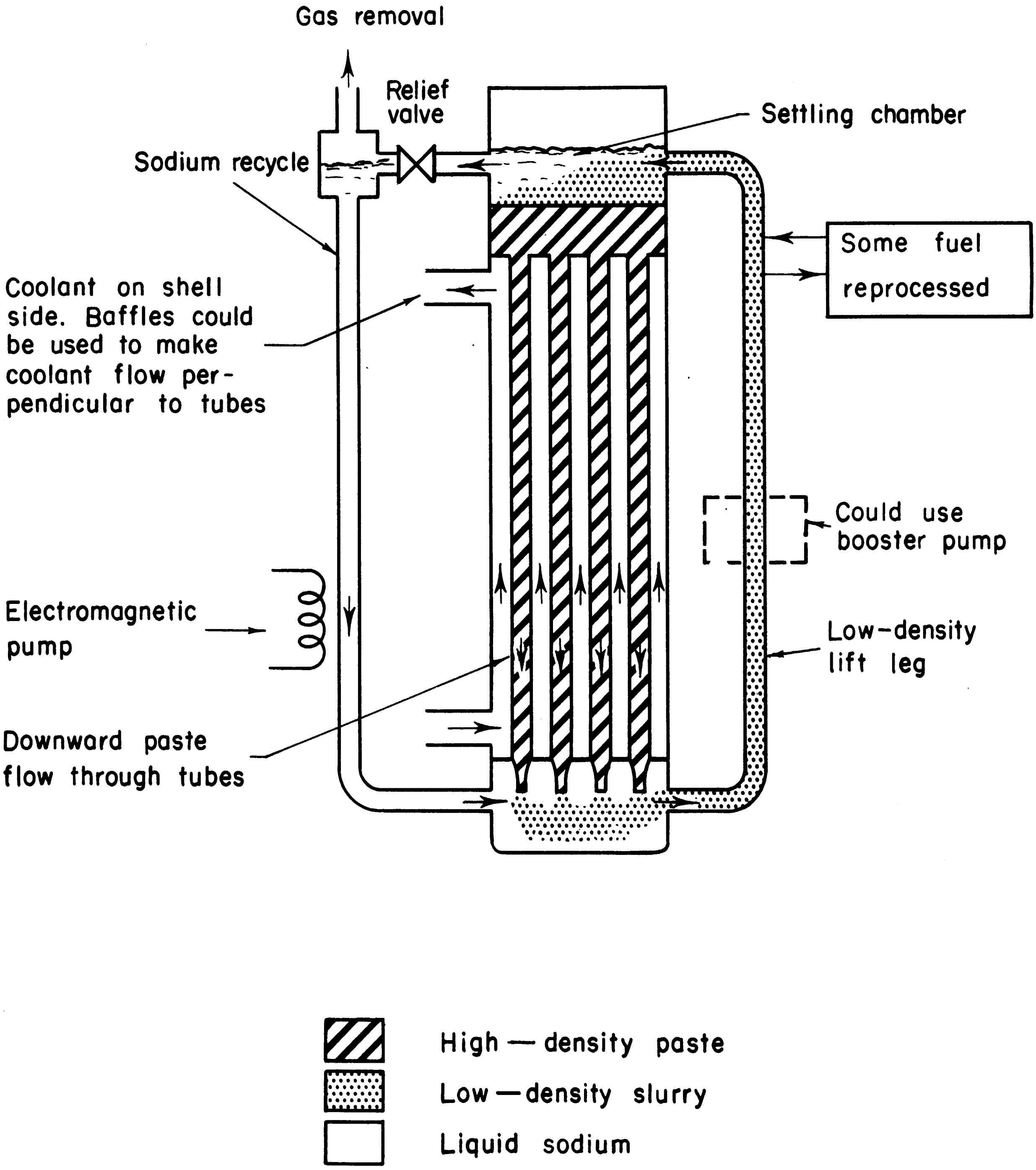

Fig. 28. Multiple paste downflow.

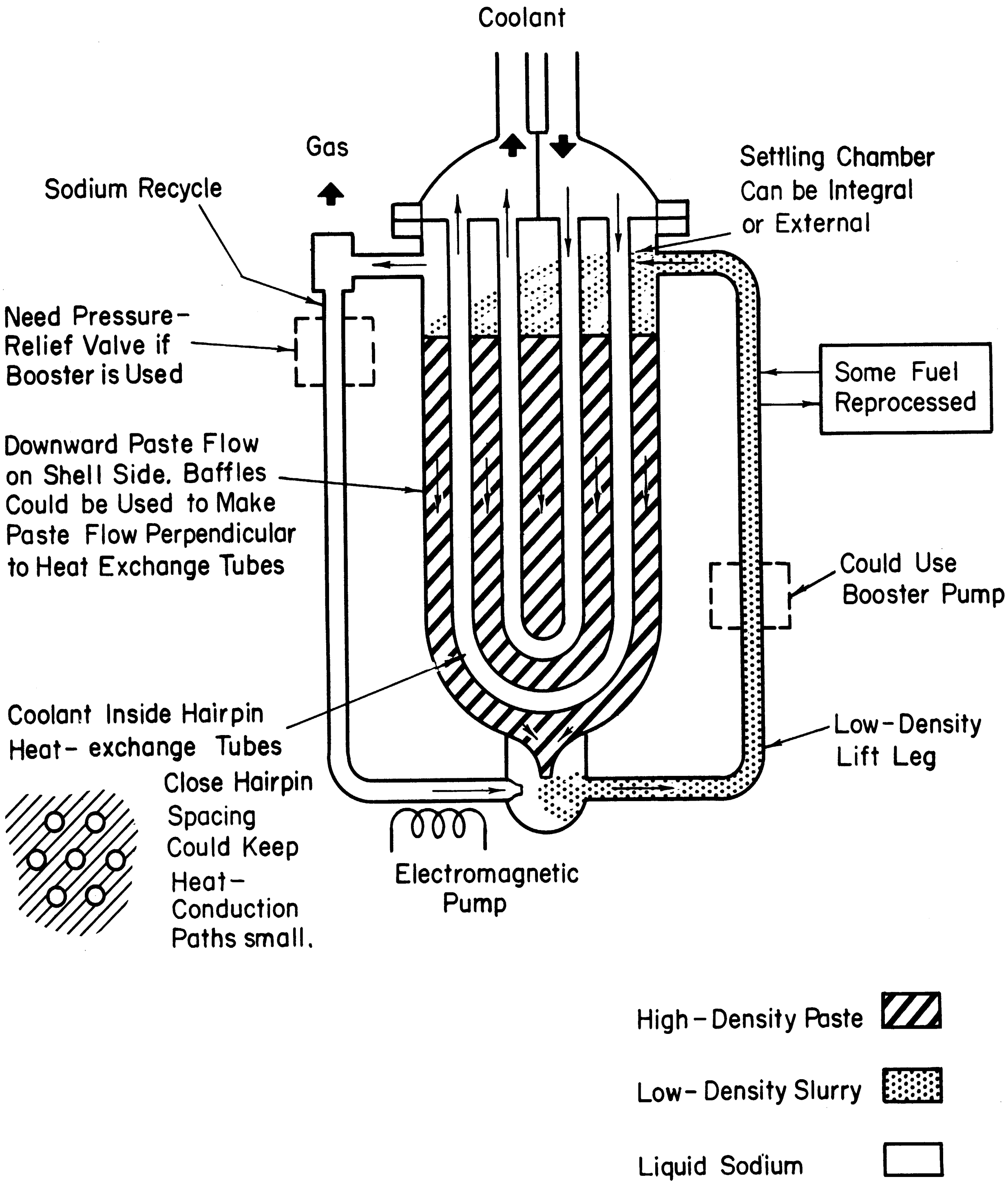

Fig. 29. Paste flow through shell.

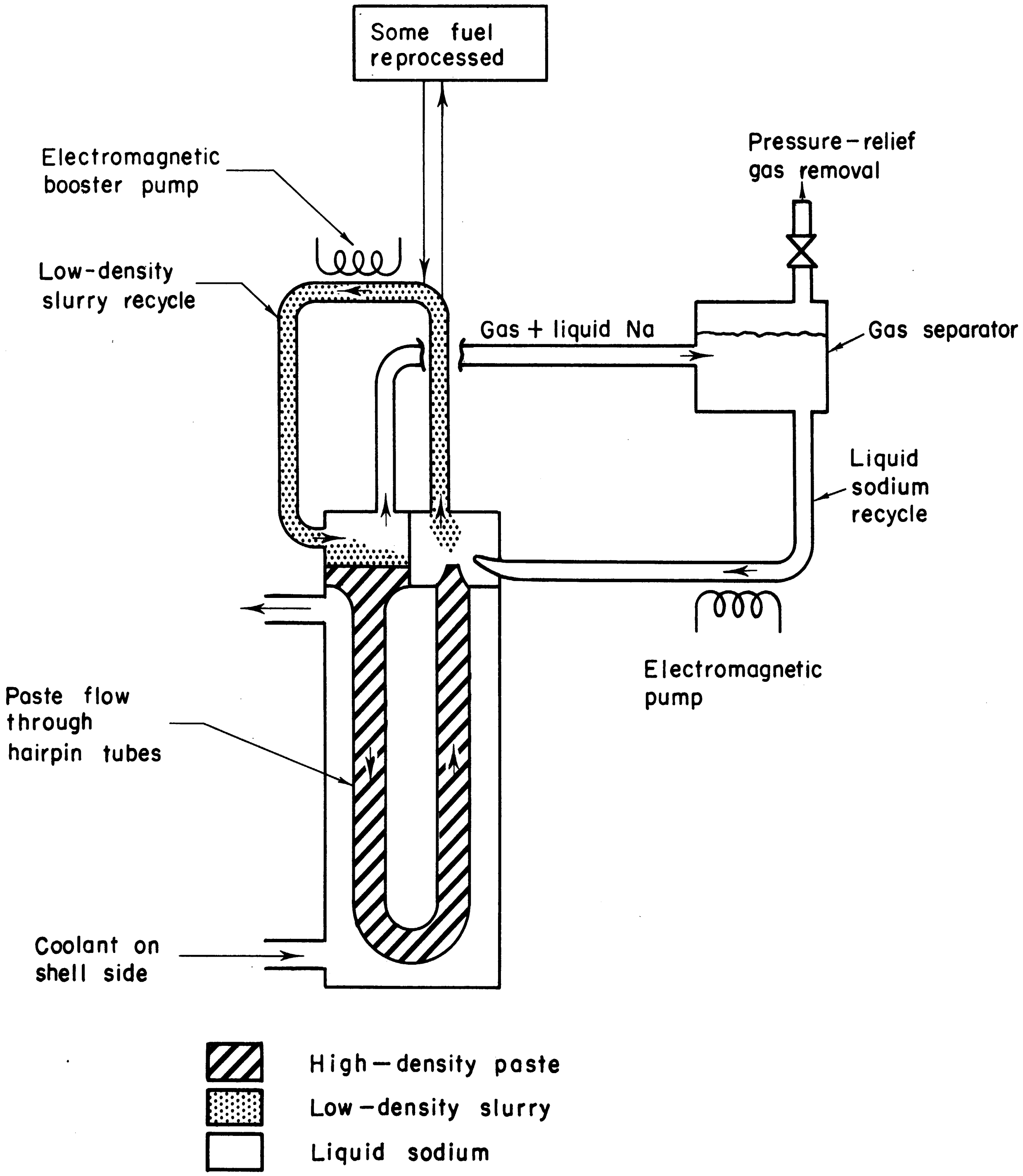

Fig. 30. Paste flow through hairpin tubes.