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A FEASIBILITY STUDY OF A FIELD INSTRUMENT FOR THE
MEASUREMENT OF SUSPENDED SEDIMENT CONCENTRATION

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ABSTRACT

A flow-through instrument system for measuring the concentration of suspended sediments in natural streams is described. The sediment concentration is inferred from the change in electrical resistance of the water due to the presence of sediment. The system appears adaptable to either field or laboratory use. The potentialities of the system have been explored; however, no specific instrument design has been proposed. The range of particle sizes that can be handled in the laboratory instrument is from 9 to 300 microns in diameter at concentrations from 25 to 10,000 ppm by volume.

The system is unaffected by variations in temperature, salinity, and contaminants in the flow within practical limits. Conducting particles sometimes alter the calibration, but a separate calibration can be made for sediments containing known proportions of conducting particles.

PREFACE

This report describes an experimental feasibility study of a proposed system for determining the sediment concentration in a natural stream from a measurement of the electrical resistance of a sample of water containing the sediment in suspension. The study was carried out at the St. Anthony Falls Hydraulic Laboratory of the University of Minnesota in the period from March 31, 1968, to June 30, 1969. The Technical Committee, Committee on Sedimentation, Water Resources Council sponsored the work under U.S. Department of the Interior Contract No. 14-08-0001-11301.

The data were collected by Frank Tsai, Nazmi Sharabi, and John Almo. The report was reviewed by J. M. Wetzel, J. Beverage, and E. Silberman.

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LIST OF SYMBOLS

A	Area of tube
A'	Elemental area of tube
a	Cross-sectional area of particle normal to electric field
b	Particle area coefficient
c	Particle length coefficient
C	Volume concentration
D	Diameter of separator
d	Length of particle along electric field
e	Diameter of fine sediment and liquid outlet
f	Particle form factor
L	Axial length of separator chamber
l	Distance from top of separator chamber to fine sediment and liquid outlet
n	Number of particles in an elementary tube
n'	Number of elementary tubes
q	Radius of sediment separator rotor
r	Resistance of suspension
r_1	Resistance of conducting liquid without particles
Δr	Measured resistance change due to sediment
S	Salinity in grams/liter
T	Temperature in degrees Centigrade
β_T	Temperature coefficient of conductivity
β_S	Salinity coefficient of conductivity
ρ_w	Resistivity of water
ρ_p	Resistivity of sediment

A FEASIBILITY STUDY OF A FIELD INSTRUMENT FOR THE MEASUREMENT OF SUSPENDED SEDIMENT CONCENTRATION

I. INTRODUCTION

Investigation of the sediment transport properties of natural streams, and the study of the sediment transport mechanisms in general, have been hampered by the lack of convenient systems for the measurement of sediment particle size and concentration in the flow cross-section. A number of classic approaches are now in existence. The most highly developed are the many forms of visual and mechanical analysis. These visual and mechanical methods are frequently carried out in the laboratory and are preceded by various techniques of sampling a small quantity of the stream liquid and its suspended particles in the field. The field and laboratory procedures together usually constitute a tedious process which is difficult to automate.

A number of alternatives to visual or mechanical analysis have been proposed and investigated. These have usually been based on the scattering or absorption of electromagnetic or acoustical radiation. The various forms of turbidimeters and nuclear particle absorption devices are typical examples of devices employing electromagnetic radiation. The objective of the majority of these devices has been a more rapid means of measuring sediment concentration or particle size, in situ if possible.

The investigation reported here is an ad hoc effort to evaluate and develop an electrical impedance method of measuring sediment concentration for field use. Such a method would involve determination of sediment concentration in a container through measurement of the resistive component of electrical impedance, which is caused exclusively by the presence of suspended sediment. The sediment is assumed to be insoluble and non-agglomerating in natural ionized liquid which is conducting a small electrical current. Particle size is important only with respect to an upper and lower size limit that can be accommodated in the apparatus.

The investigation was carried out in the laboratory. The primary concern was with those factors which would be obvious constraints imposed by field conditions; thus the reference to "field use." The most obvious constraints are uncontrolled temperature, an unknown liquid conductivity and an

unknown sediment electrical conductivity, and no readily available means of calibration at the field site. Sampling techniques would be used in the field to draw quantities of sediment-laden water into the device; the sampling aspect of sediment measurement was excluded from consideration.

II. BACKGROUND

The manner in which insoluble particles in suspension influence the electrical conductivity of the liquid in which they are suspended is well known. Frick [1]* carried out a relatively complete study of biological cell and other organic suspensions. He cites an earlier study in which the conductivity of sand suspended in conductive gelatin was measured. Velick and Goren [2] extended Frick's theory to more irregular shapes in a study related to the conductivity of blood cells. Morgan and Pierson [3] have used impedance measurement techniques to determine the concentration of mineral suspension, and Lamb and Killen [4] have employed conductivity measurement to infer the concentration of suspended air bubbles in water.

Velick and Goren [2] give the following general relationship for the concentration of particles in a conducting liquid in terms of the electrical resistivity of the suspending liquid and the suspension:

$$C = \frac{\frac{r}{r_1} - 1}{\frac{r}{r_1} - 1 + f} \quad (1)$$

where

C = volume concentration of the particles

r = resistivity of the suspension

r_1 = resistivity of the conducting liquid without particles

f = form factor of the particles, which depends on the geometry of the particles and their orientation with respect to the electric field

Equation (1) assumes a parallel electric field of infinite extent where the particles have infinite resistance and do not appreciably disturb

* Numbers in brackets refer to the List of References on page 16.

the original field. Non-conducting particles are a special case of Velick's and Goren's original development.

Table I from Ref. [2] gives values of f for some common geometries and random orientations. (The reference gives a more extensive tabulation than is reproduced here.)

TABLE I

<u>Axial Ratio</u>	<u>f for Random Orientation</u>	<u>Model</u>
1:1:1	1.500	sphere
2:1:1	1.539	rod
3:1:1	1.577	rod
2:2:1	1.589	oblate spheroid
3:2:1	1.643	ellipsoid
3:3:1	1.718	oblate spheroid
7:1:1	1.633	rod
5:5:1	2.183	ellipsoid

The techniques of electrical impedance measurement in electrolytes are fundamental to the determination of suspended particle concentration. The literature on this topic is much too extensive to adequately review here; reference is made to a comprehensive review by Higgins [5].

Measurement of the electrical impedance of the electrolyte is usually made by causing an electric current to flow in the solution and coupling the current flow either conductively, inductively, or capacitively with an auxiliary electrical network in which the measurement of impedance is made. This measured impedance can be related to the actual impedance of the electrolyte.

The conduction method involves placing a pair of electrodes in the solution and connecting the electrodes in turn in one of the arms of an electrical impedance bridge. The voltage-current relationships in the bridge network make it possible to infer the equivalent impedance between the electrodes.

Unfortunately, the chemical and physical interaction of the electrode with the electrolyte gives rise to a complex electrical impedance at the

electrode interfaces. This interface impedance has no simple relationship to the impedance of the liquid, and generally serves to mask the liquid impedance which is to be related in turn to the sediment concentration.

In the present investigation, an electrical bridge system was devised with a similar liquid element and electrodes in each of two arms. The same interface impedance can be made to occur in each of the liquid elements, and its effect can then be canceled by the bridge network.

Variations in temperature and salinity give rise also to considerable resistance variation. Higgins [5] gives the following equation for small variations in temperature and salinity:

$$\frac{\Delta r}{R} = -\beta_T(T - T_0) - \beta_S(S - S_0) \quad (2)$$

where

R = resistance at a given concentration and temperature

Δr = change in resistance

T_0 = reference temperature

S_0 = salinity at T_0 and R

β_T = temperature coefficient 2.1 per cent per degree C

β_S = salinity coefficient = 2.5 per cent per gram in 1000 grams of water

The coefficients β_T and β_S are not constants, but vary with both salinity and temperature. The coefficients given with Eq. (2) must therefore be restricted to a limited range of temperature and salinity about an appropriate mean value.

III. LABORATORY SYSTEM

A feasibility study of a field instrument for the measurement of suspended sediment in a flowing stream was judged to be most profitably carried out in the laboratory, where the effects of known field constraints could be more easily evaluated. The laboratory system devised for this study is shown in a diagram in Fig. 1 and in a photograph in Fig. 2. The four main parts of the system are (1) the sediment mixing chamber, (2) the sediment separator, (3) the measuring chamber, and (4) the electrical system.

A special sampling nozzle would replace the sediment mixing chamber in field use. It is assumed that an adequate nozzle will be available when required. The design of a sediment sampling nozzle was excluded from this investigation under terms of the contract. No special design effort was necessary on a sampling nozzle for the laboratory system, since measurement of the sediment content of the sample was made after it had passed through the test system.

The overall laboratory system in general can be described with reference to the four main parts shown in Fig. 1. Detailed descriptions of individual elements will be given later. The mixing chamber (1) was used to hold a prepared concentration of water and sediment in suspension. The mixture was constantly recirculated by a pump through the heat exchanger and mixing chamber via a nozzle at the top. A variable speed pump was used to draw a sample of fluid from the mixing chamber and to discharge it into the centrifugal separator (2). The sampling rate of flow was found to be of minor importance to the measuring system. The dominant requirement was a sufficient flow velocity to keep the sediment in suspension. A flow rate capable of change would be a distinct advantage in field application, where an adjustable flow rate might be required in order to obtain a representative sample.

The separator serves a two-fold purpose: It provides the sediment-free sample required as a reference liquid for temperature and salinity compensation and it increases the concentration and electrical resistance of the remainder of the sample into a range more easily measured. There are two outputs from the separator, one for the reference liquid and one for the concentrated mixture. The two outputs discharge through a 4-way valve and then proceed to a chamber (3) in which electrical resistance, which can be correlated with sediment concentration, is measured. The electrical system (4) is part of the measuring chamber and is shown in Figs. 3 and 13. The discharge from the measuring chamber returns to the mixing chamber through a heat exchanger for the purpose of temperature control.

A. Measuring Chamber

Several considerations arose in the choice of measuring chambers. An electrical current can be induced to flow through a liquid by means of

electrostatic or electromagnetic induction or through direct contact with electrodes immersed in the fluid. Each of these methods carries with it additional factors dependent on geometry, electrical properties of the fluid and the particles, and polarization of electrodes.

For this instrument, conduction (direct contact between electrodes and liquid) was chosen. This method suffers from the complication of an elusive interface impedance in the measuring system. However, a three-electrode system can be devised which eliminates the effect of the stray electrical pathways to ground which are of necessity present in a field system.

Figure 3 is a sketch of the measuring chambers with electrical connections indicated symbolically. The suspension passed through either the right tube or the left tube (right or left bridge arm) while the reference liquid passed through the alternate tube. Each tube had three electrodes and formed two cylindrical chambers between the electrodes. The chambers were connected electrically in parallel pairs, 1 with 3 and 2 with 4. This avoided having unknown parallel paths grounding across the measuring chambers. The entire unit was mounted in a lucite block to provide a rigid geometry.

The previously mentioned liquid-electrode interface resistance has been found to vary with the chemical composition of the electrodes and of the liquid, with the rates of electric current flow and liquid flow, with the amount of debris accumulated on the electrode surface, with variations in the abrasive action of the sediment on the electrode, and with the temperature. The use of electromagnetic or electrostatic induction to introduce an electric current into the system would effectively eliminate interface effects. However, all attempts during the test program failed to produce an inductive system which could effectively compensate for temperature and chemical composition and yet have sufficient sensitivity to detect small sediment concentrations. The double-arm liquid bridge reduced the effect of interface impedance to a small value. The use of alternating current on the bridge further reduced this effect.

Two electrode materials were used, stainless steel and carbon. No significant difference between these two materials could be found in the measurements.

The abrasion and accumulation of debris on each of the electrodes were equalized by use of a 4-way valve between the separator and the measuring chamber. The valve reversed the role of each chamber with each measurement. The passage through each electrode (Fig. 3) must have a small convergence of two to three degrees in the direction of liquid flow so that firm adherence of the liquid to the electrodes will occur at all times and the impact of sediment on the electrode will produce a cleansing action. The effect of liquid flow rate on the resistance measurement was found to disappear after a minimum flow rate had been exceeded.

With these precautions, reasonably reproducible results were obtained. The space between electrodes was one inch; 1/8-inch- and 1/16-inch-diameter tubes were used. It appears that physical size is important only in allowing a sufficiently large sample of suspension to give a good average to pass between the electrodes; a 3/16-inch-diameter tube would probably be most satisfactory.

B. Electrical System

The bridge circuit employed is shown in Figs. 3 and 13. (The requirements for the system are discussed in Appendix II.) An oscillator which delivered 15 rms volts at 600 to 1000 cycles to the bridge system was used as a source. A precise value of frequency did not seem important so long as the frequency remained constant. A phase-sensitive detector was employed as a bridge balance indicator.

The variation in concentration with time makes the conventional bridge-balancing procedure difficult. The phase-sensitive detector can be given a long time constant which greatly aids in averaging out the fluctuations of the balance point due to the fluctuation in sediment concentration. This effect is most evident with coarse sediments.

C. Separator

The measurement of resistance requires compensation for temperature and dissolved chemicals. Compensation may be accomplished by mechanically separating the sample into two parts, one containing liquid with only very fine sediment, to be used as a reference liquid, and the other containing

coarse sediment in suspension at a higher concentration than in the original sample. Both parts would contain the original liquid at a common temperature and chemical composition.

Early in the program a hydrocyclone was employed to accomplish separation after filters and elutriators were judged to be too cumbersome or too impractical in requiring the constant attention of an operator. The hydrocyclone was effective; however, it required a high supply pressure and consequently a high flow rate for effective action.

Figure 4 shows a separator which behaves essentially as a hydrocyclone but in which high rotational velocity is imparted to the liquid by a motor-driven rotor. Information in Ref. [6] relative to the design of hydrocyclones applies to this device. A recommended optimum design which has been taken in part from Ref. [6] is described below.

A relatively high rate of flow of the reference liquid was desired, and this called for as large an outlet as possible. The possibility of clogging made the alternative of a small concentrated sediment outlet impractical. Optimum separation (division of sediments between the reference outlet and the sediment outlet at the smallest mean particle size) is obtained with these dimensions given in Ref. [6]: $L/D = 5$, $b/D = 0.28$, $e/D = 0.34$, and $l/D = 0.4$. Definitions of the letters are given in Fig. 4. Optimum classification (smallest deviation in range of particle sizes separated) is given in Ref. [6] as follows: $L/D = 2.5$, $b/D = 0.14$, $e/D = 0.14$, and $l/D = 0.4$.

The discharge from the sediment outlet can be controlled by a pinch clamp. A maximum ratio of 4:1 was maintained between the reference liquid discharge and that from the sediment outlet. The concentration in the sediment-laden flow is proportional to the flow rate of each discharge. It was found that the electrical resistance change Δr increased in proportion to the ratio of flow of the two discharges for the same initial concentration of sediment.

The flow from each discharge outlet can be measured with a flow meter, or, as was done in the present effort, the discharge from each outlet can be collected in graduated containers for a short period of time. The ratio of the elevations of the liquid in each graduated tube then gives the ratio of the flow rates.

The usefulness of the separator in sizing the sediment is immediately apparent. It should be possible to adjust the coarse-fine division point of the sediment flowing through the separator by changing the speed of the rotor. This feature has not been investigated. The performance of the separator could be improved by the use of a hollow shaft motor to provide a passage for the reference liquid. The turbulence would be reduced by removing the reference liquid outlet from its present position (see Fig. 4).

IV. EXPERIMENTAL PROCEDURE

Laboratory experiments were conducted to evaluate the specific configuration of electrical and mechanical systems formed from the elements described in the previous paragraphs as to sensitivity and reproducibility. Also, an effort was made to evaluate the effects of various secondary factors, such as temperature, salinity, contaminants, and particle characteristics within the practical limits established by field conditions. Not all these objectives were accomplished in a comprehensive manner; however, sufficient information was obtained to enable prediction of the potentialities of the system.

Test suspensions were prepared by adding a measured quantity of test material to tap water in the mixing chamber. Glass beads, a number of sands, and silicon carbide abrasive served as test materials. The recirculating pump served to keep the sediment in nearly uniform suspension.

The concentration of the sediment in the measuring arm of the bridge was determined by collecting a known volume of the suspension as it was discharged from the return tube (Fig. 1). The sediment in the sample was allowed to settle. The liquid was carefully poured off and the remaining sediment dried and weighed. This procedure measured the sediment concentration independently of the original concentration in the mixing chamber and independently of the characteristics of the sampling nozzle.

A heat exchanger was installed in the return line to the mixing chamber to offset rises in the temperature of the liquid as it was pumped through the system. A refrigeration unit was connected to this unit for taking data at low temperatures.

Concentration was measured as follows: The system was filled with liquid and run for a short time to remove air. A measured quantity of

sediment was added to the mixing chamber. The separator motor was started and the sampling pump speed was increased until sediment was moving in suspension throughout the system.

First the bridge was balanced with R_1 and R_2 for a minimum and then the phase-sensitive detector was set to zero with R_1 . The 4-way valve was then used to interchange the flow in the two legs of the bridge, and the bridge balanced with R_3 (zero phase detector reading). The change in R_3 as the flow was interchanged was twice the true change due to the presence of sediment. The sediment leg of the bridge was then replaced with a resistor R_4 and the bridge balanced again. The ratio $\Delta R_3 = \Delta r/R$ is the desired measurement. The value $\Delta r/R$ was then plotted against concentration in the measuring arm (see Appendix I).

V. RESULTS

Results which were reported in monthly progress reports between March 1968 and the present are summarized here along with data from the final report under the previous contract. Since the two contracts had the same objective, the two sources of data are necessary for completeness.

Fig. 5 shows the effect of temperature on measurements of a test sediment. The test material was 177 micron mean diameter glass beads (Minnesota Mining and Manufacturing Co.). A variation of 74 Kohms in the resistance of the liquid in the cell occurred for a temperature change of 40° to 97°F. The effect of temperature was completely compensated by the ratio $\Delta r/R$. The temperature variation was produced by controlling the temperature of the liquid in the heat exchanger of Fig. 1. The temperature range chosen was that of ordinary field conditions, and the liquid used was tap water.

The report written under the preceding contract showed a variation of results with a change in salinity. The tests were repeated under this contract, and the results are shown in Fig. 6. Three concentrations of sodium chloride in tap water--0.05, 0.1, and 0.5 grams per liter--and two types of electrode materials were used to check the possibility of salt electrode reaction. This range of salinity should correspond to the range of tap water in the U.S. [5], and a close correlation in salinity should exist between tap water and natural stream water. Sand was used for the particles.

The tests were conducted at room temperature with room-temperature liquid. No significant variations were found among the combinations of electrodes and salt concentrations which were used. The slight variation noted is thought to be due principally to the difficulty of averaging the bridge balance when using coarse materials.

Some common contaminants, such as detergents, oils, and sulfates, were added to the test water. The results are shown in Fig. 7. Tap water at room temperature was again used as the suspending liquid, and the 114 micron glass beads were used as the test particles. Dreft was used as the representative detergent which might be encountered in natural streams. Sulfuric acid was added to the test water to produce the pH values shown in Fig. 7 as a test of the effect of sulfates in the solution. Only a slight effect, if any, was noted. Water-soluble oil (cutting oil) was added to the test liquid without any apparent effect.

An important element in the system is the separator, which was necessary to provide an incremental change in sediment concentration which can be measured. A major objective of the second contract was the development of the impeller-driven hydrocyclone which is sketched in Fig. 4. The design parameters for the final design used in this test program are $L/D = 4.6$, $e/D = 0.1$, $b/D = 0.35$, and $l/D = 0.6$. These can be compared to the parameters given earlier from Ref. [6]. The drive unit was taken from a Sears, Roebuck Co. centrifugal pump. Its speed was approximately 12,000 rpm and it had a 1-3/4 in. diameter rotor.

The ability of the final unit tested to separate sediment is shown in Fig. 8. Tap water at room temperature was used as the test liquid. Silicon carbide particles (Carborundum brand) of 400, 500, 600, 800, and 1200 grit size were used as test particles, since these were readily available commercially in carefully graded sizes.

The results of Fig. 8, plotted in a different way, are shown superimposed on the size distribution of 400, 700, and 1000 grit Carborundum particles (taken from Ref. [7]) in Fig. 9. In Fig. 8, the ordinate shows the ratio of the fine sediment in the reference arm to the total sediment. In Fig. 9 the same data are plotted as vertical lines, but the lines are placed to represent the difference in the per cent of fine material with and

without the rotor running, and this amounts to twice the value shown on the ordinate in Fig. 8. When extreme fines were passing through the system they were split in proportion to the flow rate. If a coarser component was then added, a part of this was removed from the fine leg and transferred to the coarse leg in proportion to its probability of transfer, which depends on the separator and the particle size. The intersection of the separation line with the distribution curve gives an estimate of 8 microns for the average separation size using the pick-up distance, $l = 1-1/2$ inches.

The bridge system used for concentration measurement ignored sediments which were distributed evenly between both arms. The separator divided the fines uniformly between both arms. As a result, measurement was made of sediment concentration in sizes above 8 microns in diameter only.

The size of the sediment in the fine discharge from the separator was also estimated from the fall velocity. A value of 9 microns was obtained. The division of the sediment as to size appeared to be independent of the flow rate from each outlet. It therefore seemed advantageous to increase the flow as much as possible from the reference outlet. The resulting increase in concentration of sediment in the sediment outlet decreased the lower concentration limit of the instrument. A ratio of one to four between the reference and sediment discharges seemed practical. The data referred to in the figures thus far have been for an equal division of flow. Figure 10 shows concentration measurements for the same total concentration for two different flow divisions between the outlets. The increase in sensitivity with the greater ratio is apparent.

Figure 11 shows measurements made with composite mixtures of both sand and glass beads. All particles with the exception of the Missouri River sand fall within a narrow band.

The Missouri River sand was observed to contain about ten per cent magnetic particles. The magnetic particles were separated from the sample until sufficient magnetic particles were obtained to make a sample of reasonable concentration of magnetic particles only. When an attempt was made to measure the concentration of this sample electrically, no influence on the resistivity of the water could be noted. This indicates that the material has a resistivity near that of water in spite of the fact that the

resistivity of a metal would be expected to be lower than that of water and that polarization would be expected to increase the surface resistance. This possibility for error must be considered in some applications.

A number of valve designs were tried for reversing the coarse sediment and the fine sediment outlets between the separator and the measuring chamber. The four-way plug valve with a stainless steel plug and Teflon liner (Conant BR4TSL 1/8 in.) proved to be quite satisfactory. The hand-operated model was used. Magnetic actuators are available for this valve.

VI. DISCUSSION

The experimental work has shown the feasibility of the electrical impedance method of measuring sediment concentration for concentrations of approximately 25 through 10,000 ppm by volume for sediment sizes between nine and 300 microns. (Although the figures used herein show lesser maximum concentrations, the experiments extended to the upper limit quoted.) The instrument can be readily compensated for temperature changes of 40° to 90°F and salinity changes of 0.05 through 0.5 grams per liter. It is also unaffected by contaminants such as soluble oil, sulfates, and detergents.

The apparatus needed to make field measurements is shown in Fig. 1. The basic components are

1. A pump and sampling tube to transport representative samples from the stream to the instrument system.
2. A separator to provide an essentially sediment-free reference for compensation of temperature and salinity.
3. An electrical measuring chamber composed of two parallel tubes in a non-conducting material 1/8 inch in diameter or larger with three stainless steel electrodes along the wall at one-inch intervals. Each electrode tube should converge to assure uniform mechanical action of the sediment on the electrodes.
4. An electronic system consisting of an oscillator, bridge, and phase-sensitive averaging detector.

The results of such a system in a laboratory set-up can be summarized as follows:

1. The electrical resistance changes due to the presence of sediment are of the same order of magnitude as the percentage concentration of the particles by volume. The results are within an unknown particle shape factor of the theoretical results.
2. The use of a liquid reference chamber in a bridge arrangement with the measuring chamber stabilizes the system so that measurement can be made of a highly fluctuating concentration between 200 and 10,000 ppm by volume. The sensitivity can be increased so that readings down to 25 ppm by volume can be made when a differential flow rate is used in the chambers.
3. Division of the resistance change due to the presence of sediment by the value of absolute resistance obtained from a nearly concurrent measurement in the reference arm effectively eliminates the need for correction due to changes in resistance and salinity in most ordinary situations. Tests were conducted over a temperature range of 40° to 90°F and a salinity range of 0.05 to 0.5 grams of NaCl per liter.
4. Resistance measurements are independent of flow velocity and of the ratio of the velocities in the sediment and reference chamber after sufficient velocity is reached to hold the temperature constant and the sediment in suspension.
5. A flow reversal valve which interchanges the sediment flow and the reference flow from the separator with each reading doubles the sensitivity of the system, reduces drift error, and assures equal wear in both chambers.
6. The size of the measuring tube has little effect so long as clogging does not occur and the size of the tube does not approach the particle diameter (see Appendix I). Only two sizes of tubes were tested, 1/8 in. and 1/16 in., and the 1/8 in. size was found generally most convenient.

7. Measurements were made with sediments whose minimum size was approximately 3 microns. The separator divided the flow at approximately 8 microns. The use of multiple separators would carry the system to smaller sizes. The presence of sediment below 8 microns is ignored in this system.
8. An uncertainty of 20 per cent occurred in calibrations with Missouri River sand as compared to other sands or glass beads. This was found to be due to the presence of 10 per cent magnetic particles in the flow. These particles had an apparent resistivity near to that of water, and were consequently ignored by the instrument. This demonstrates the necessity of establishing the insulating quality of the sediment in any particular application or accounting for the presence of conducting particles.
9. The presence of small quantities of industrial contaminants such as oils, detergents, and sulfates did not appear to have any noticeable effects on the results. This was possibly due to the cleaning of the electrodes by the flowing liquid and sediment.

The system was developed having in mind measurements in natural streams using a continuous sampling technique where a very large sample is available. However, this system can also be used to analyze samples in the laboratory by employing a recirculating system such as the one described in this report. A much smaller mixing chamber would, no doubt, be desirable. Possibly the mixing chamber could be eliminated by returning the discharge to the sampling pump inlet directly.

A 10 to 15 per cent variation in concentration reading occurs among the various sediments used in this investigation (glass beads, Bay City sand, St. Peter sand, Missouri River sand, Blast sand, Chickasha clay, and Carborundum). The variation could be reduced to about one-third of this value by calibration on any one sample.

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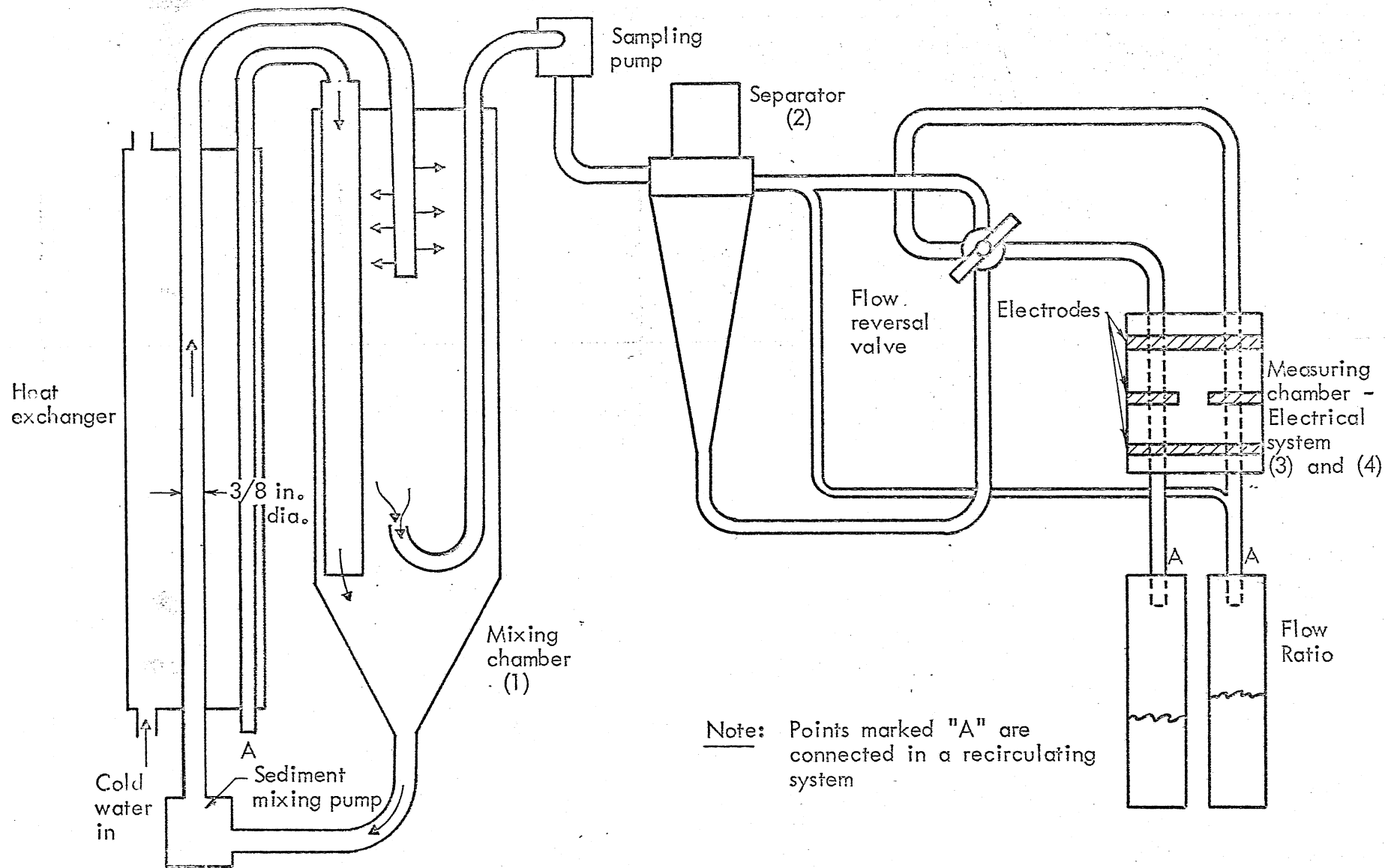


Fig. 1 - Schematic of Laboratory Sediment-Measuring System

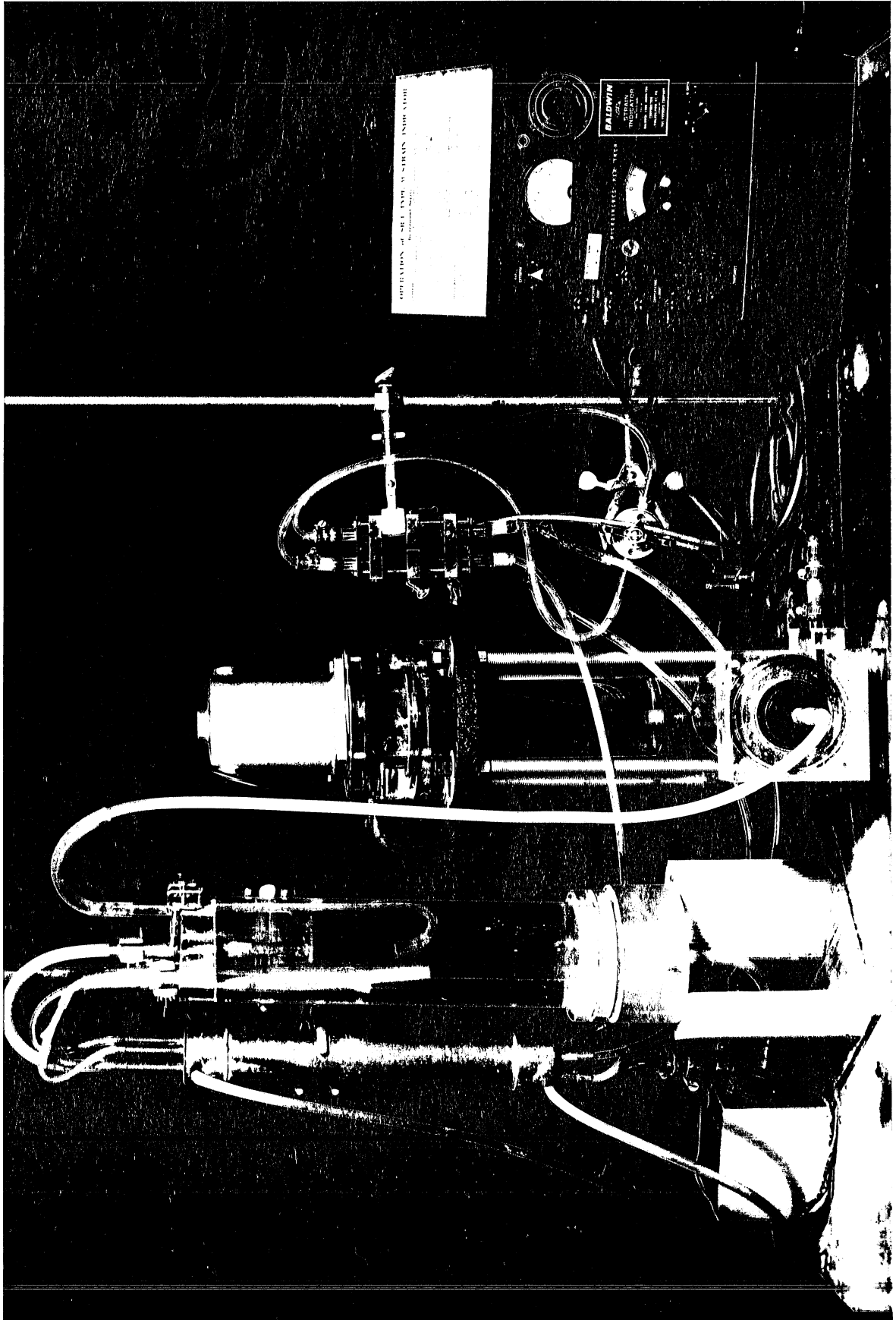


Fig. 2 - Photograph of Laboratory Sediment-Measuring System

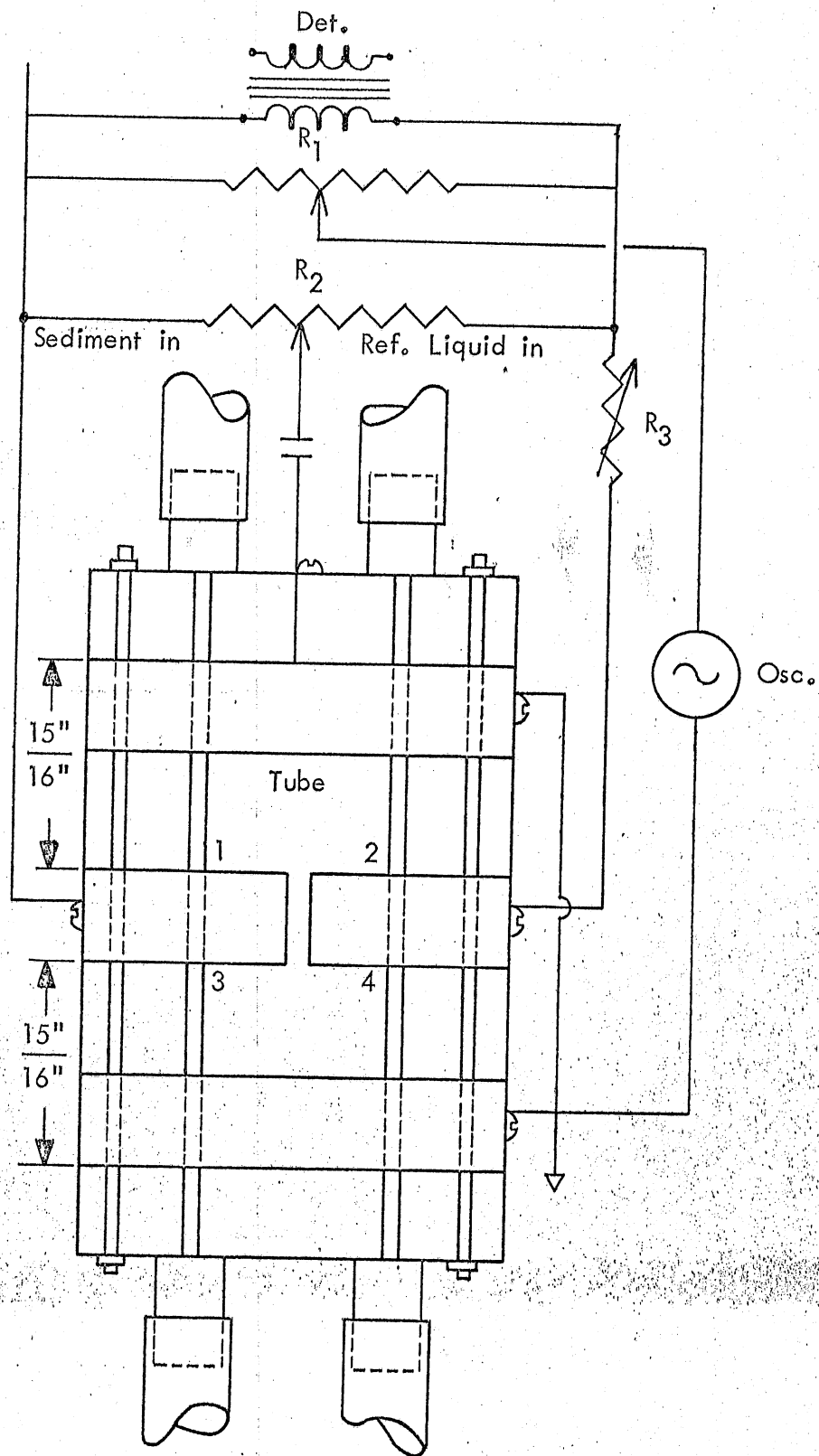


Fig. 3 - Schematic of Measuring Chamber

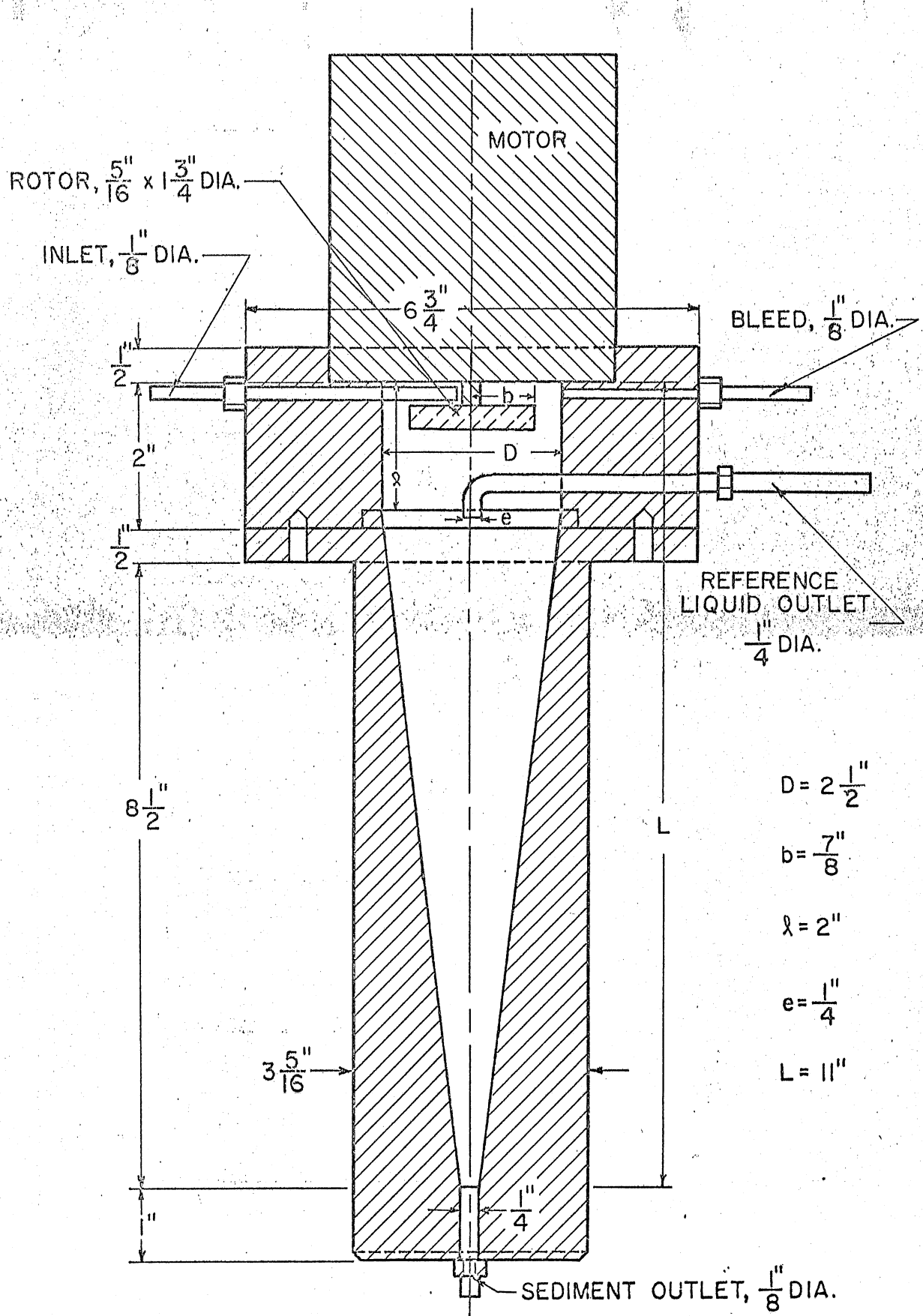


Fig. 4 - Schematic of Sediment Separator

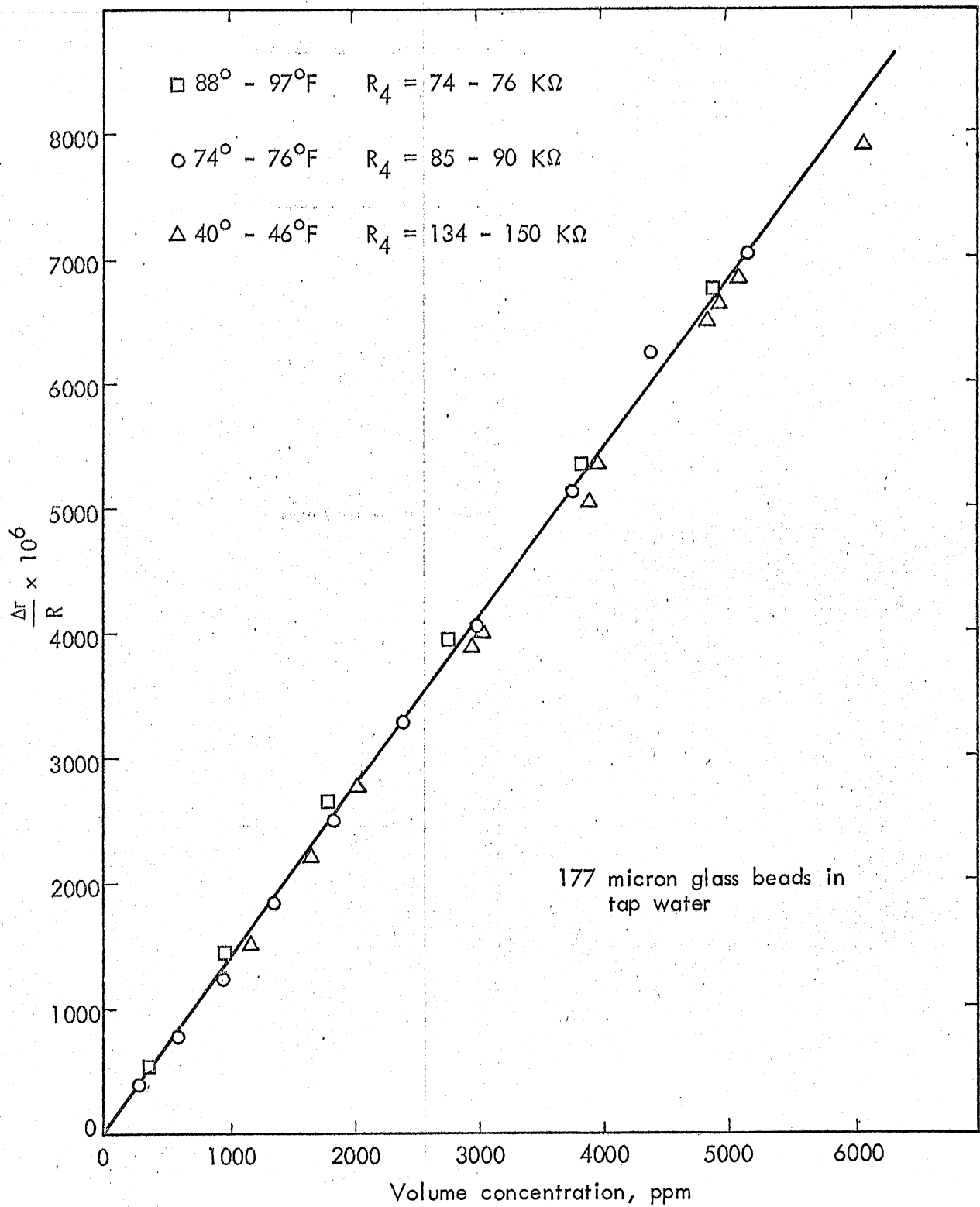


Fig. 5 - Effect of Temperature on Concentration Measurements

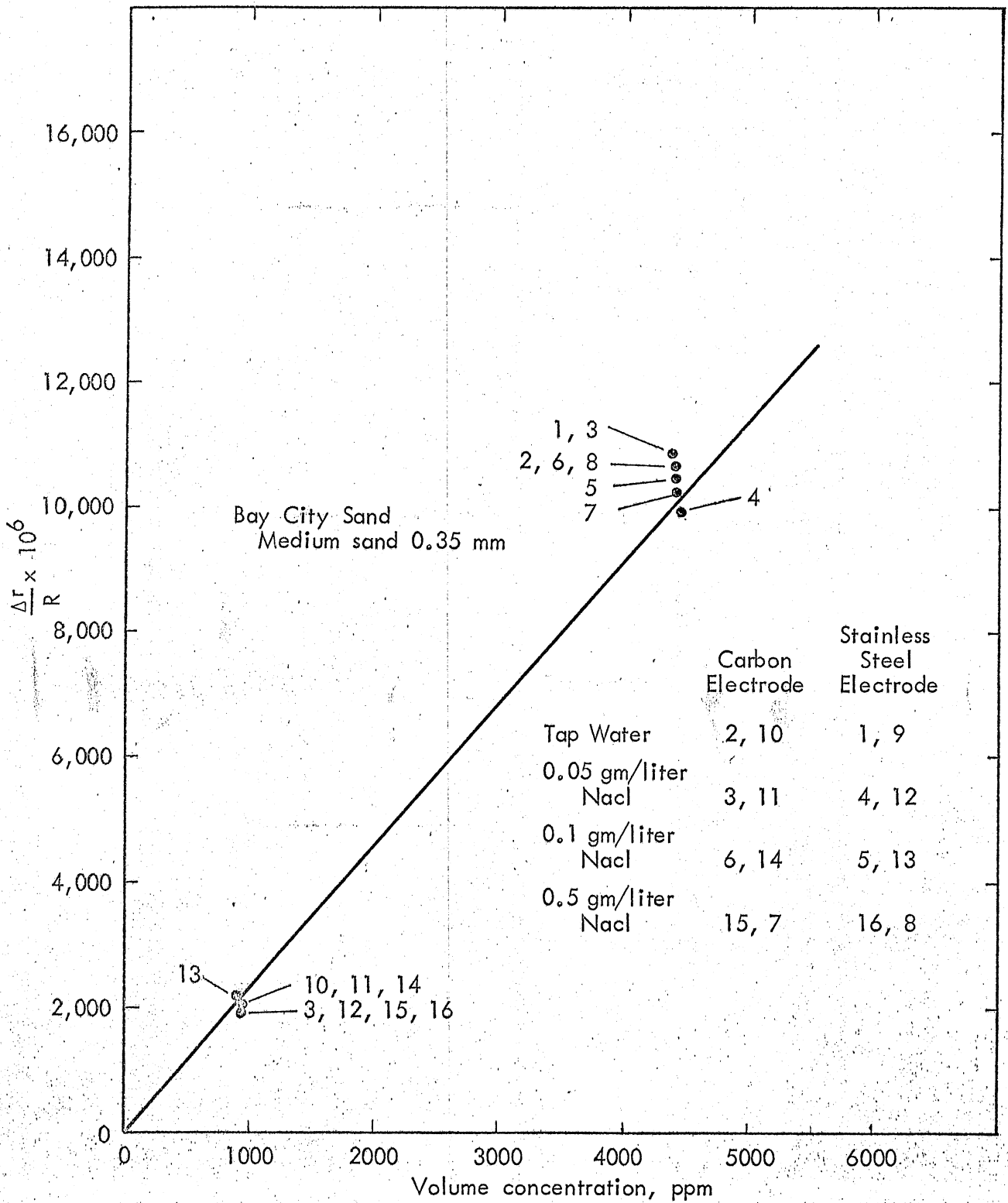


Fig. 6 - Effect of Salinity on Concentration Measurements

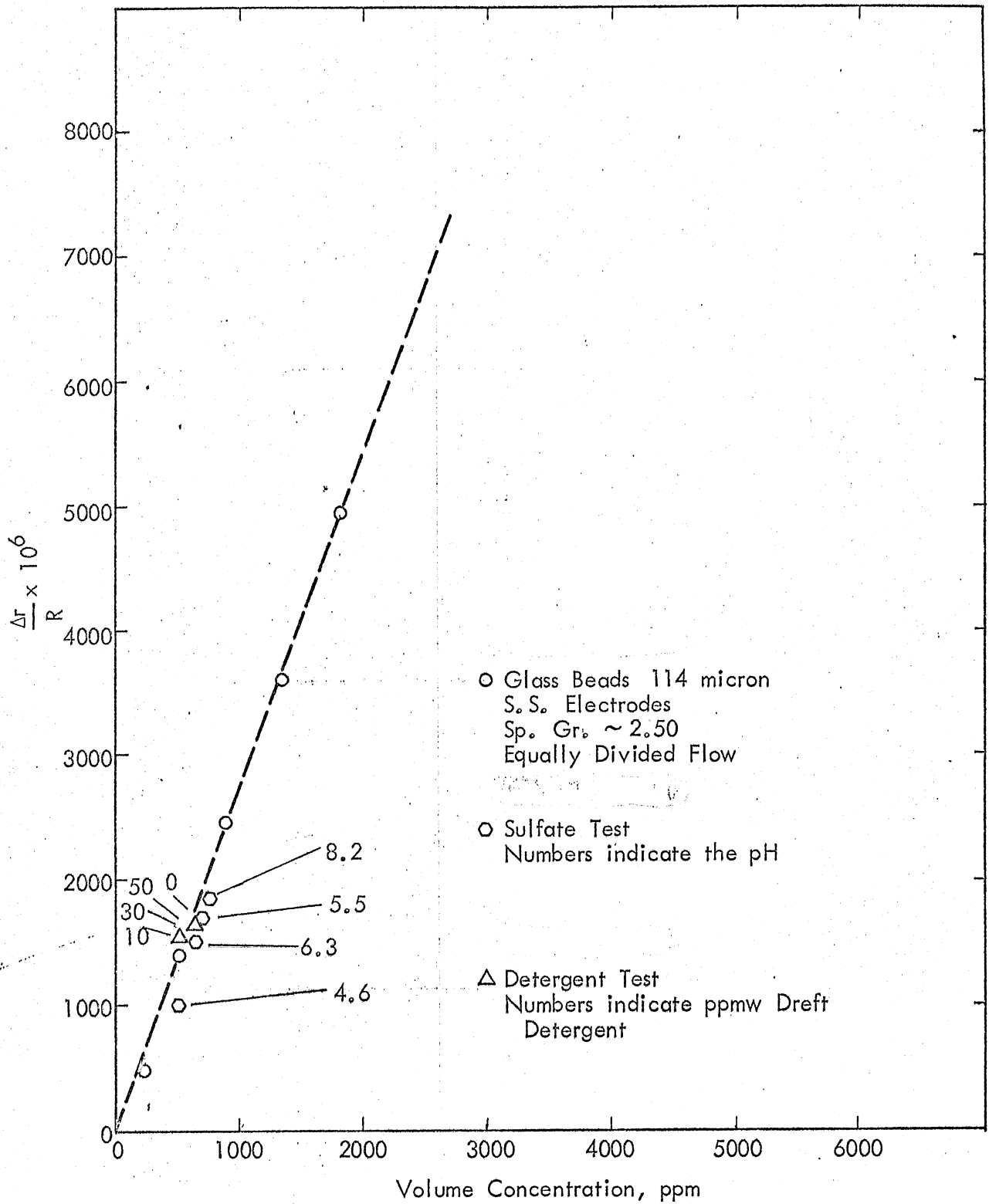


Fig. 7 - Effect of Contaminants on Concentration Measurements

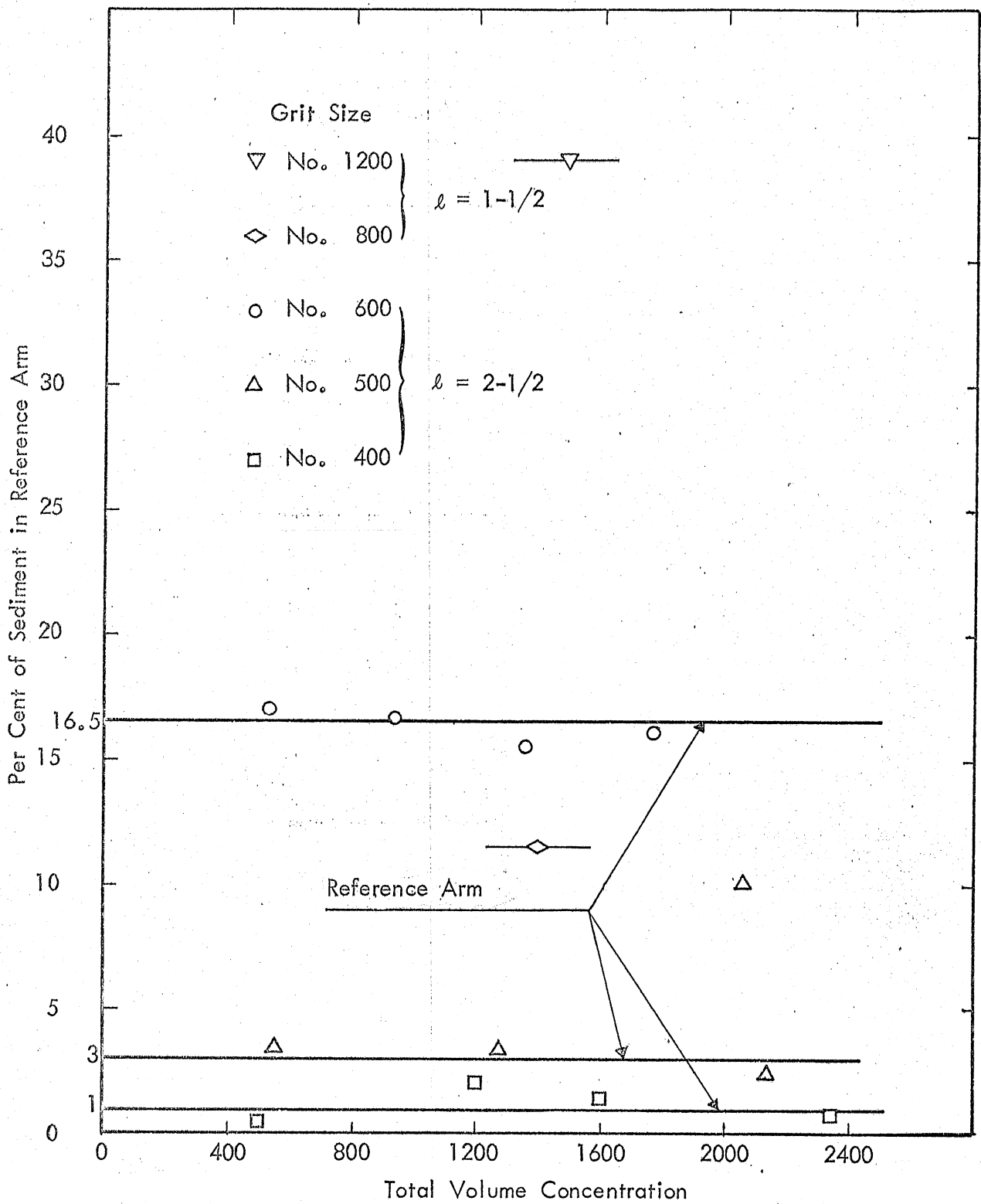


Fig. 8 - Performance of Separator with Carborundum Particles

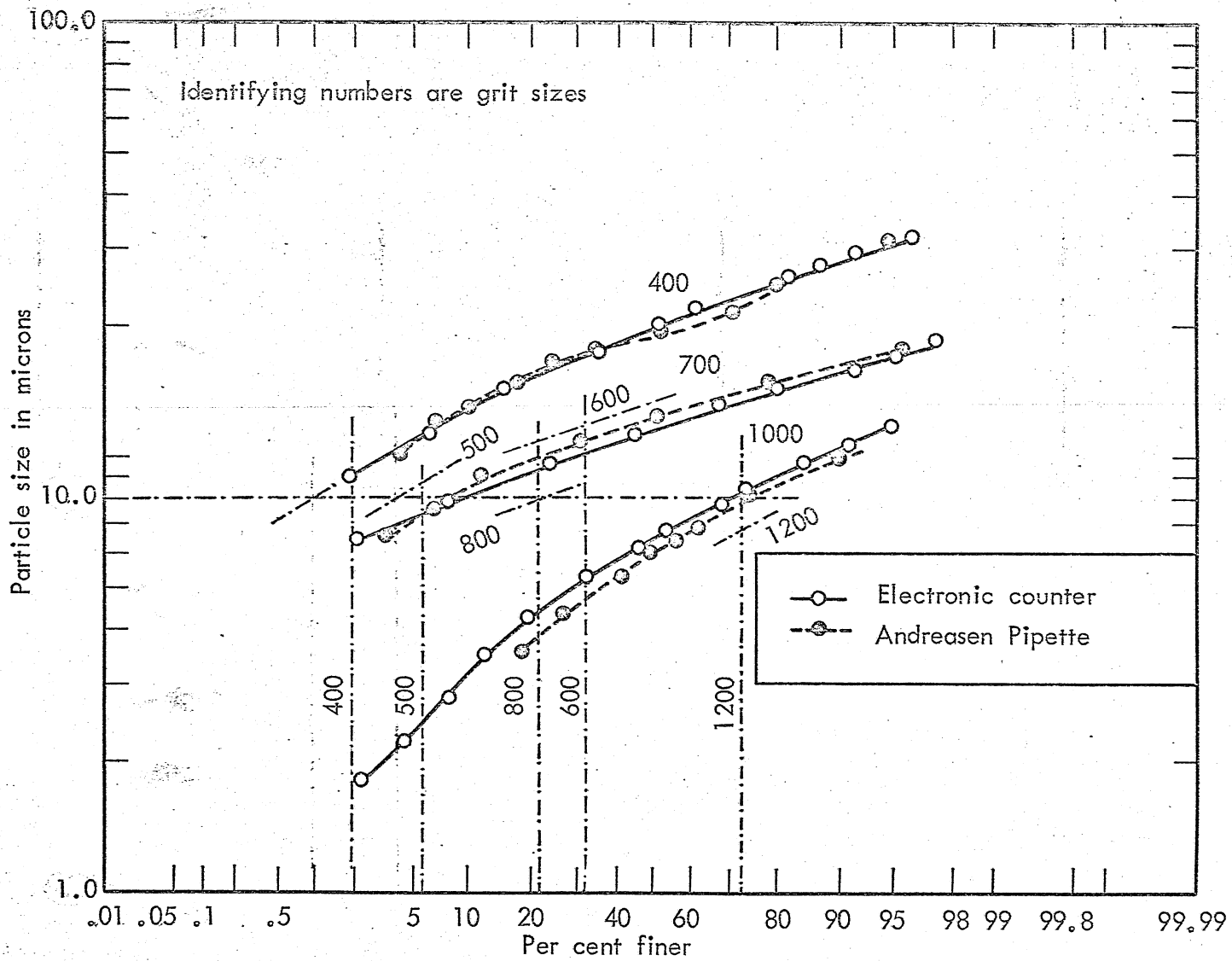


Fig. 9 -- Size Distribution of Carborundum Particles (Ref. [7])

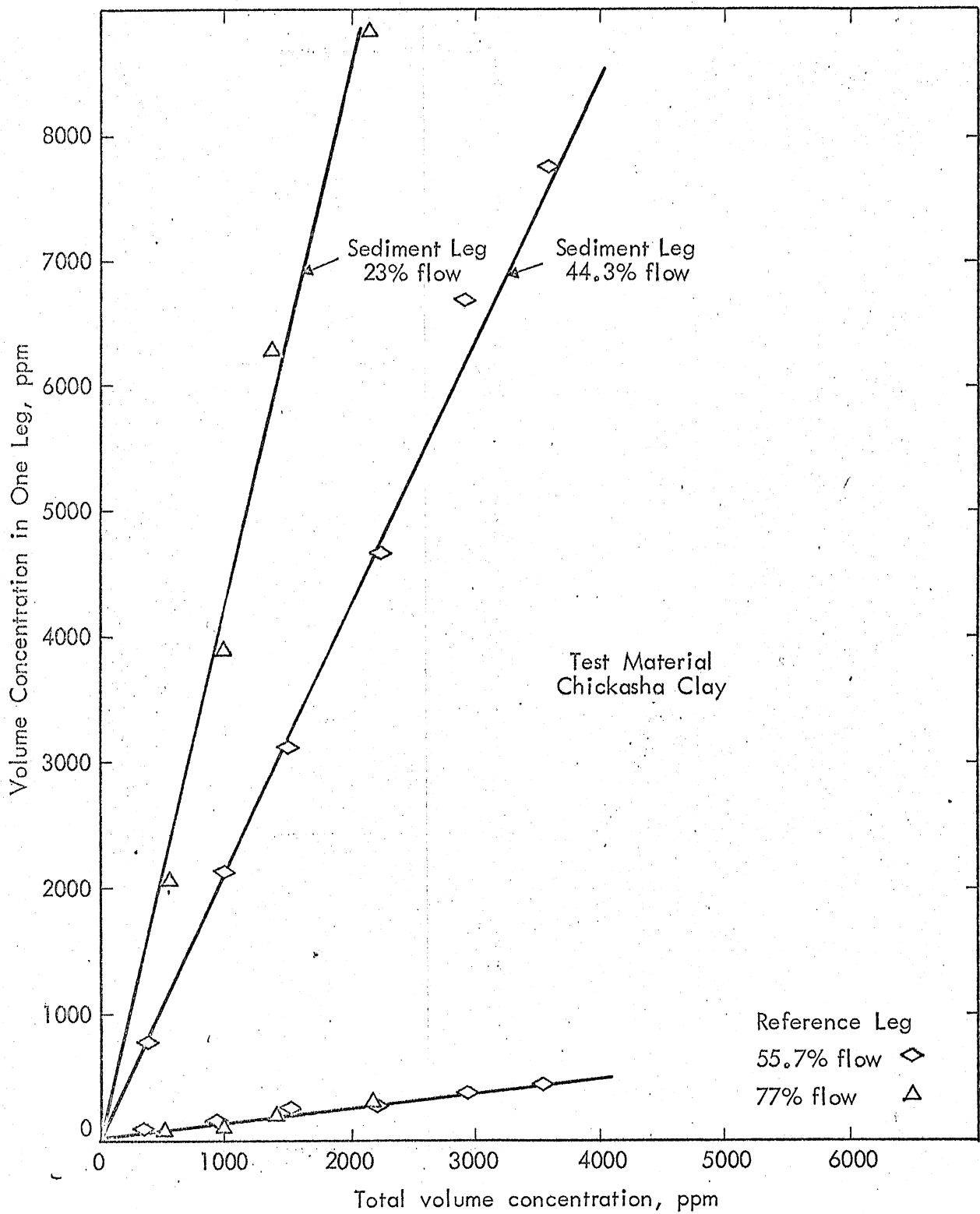


Fig. 10 - Effect of Flow Division between the Separator Outlets on Concentration Measurements

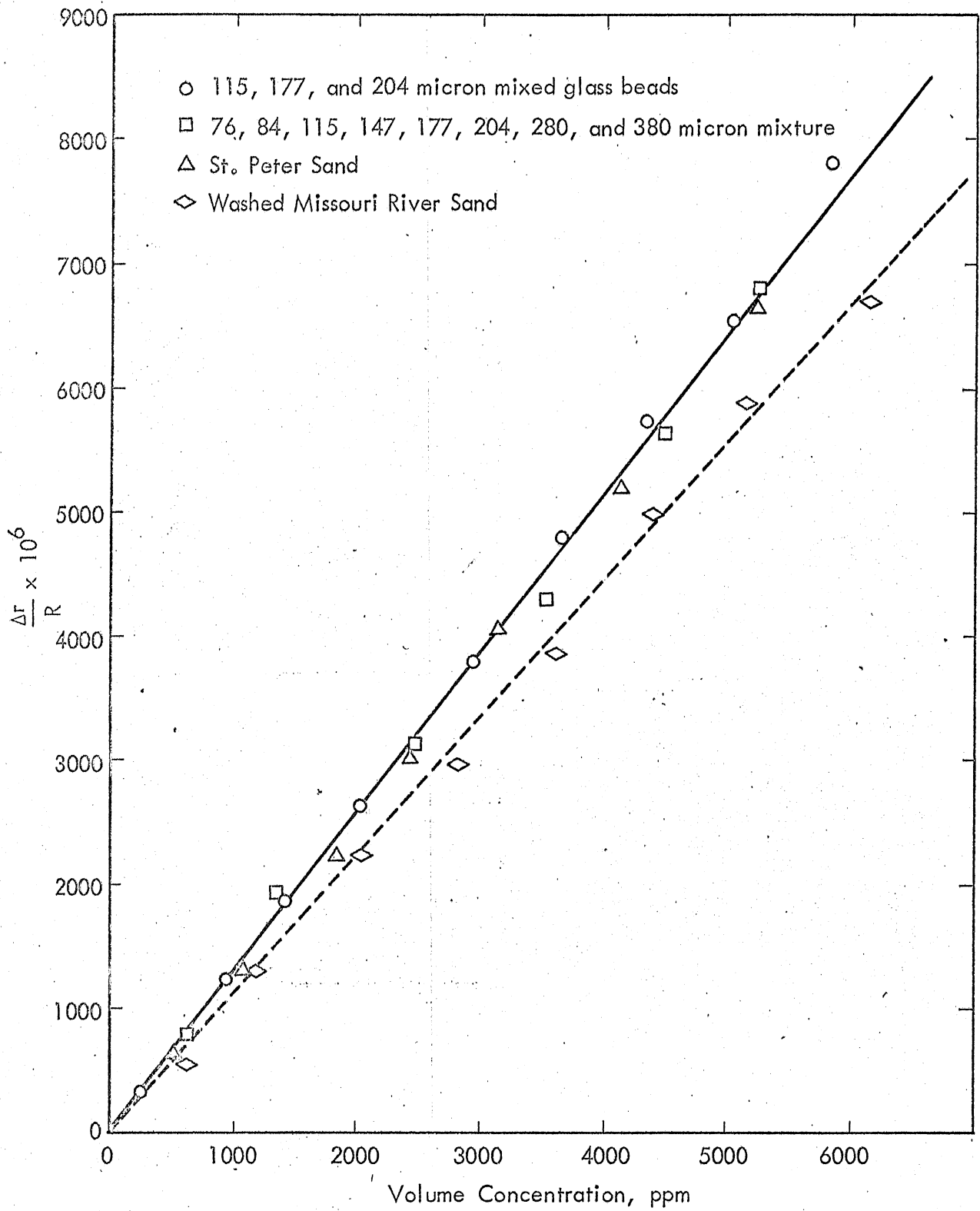


Fig. 11 - Performance of System with Composite Sediment Samples

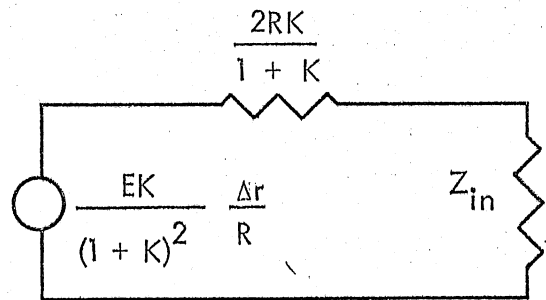
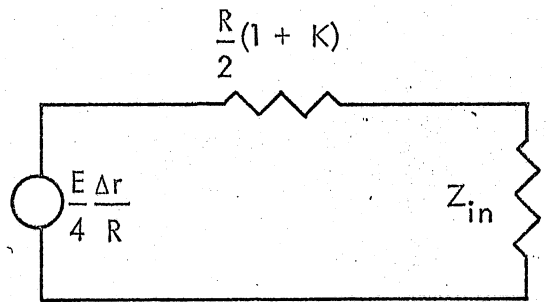
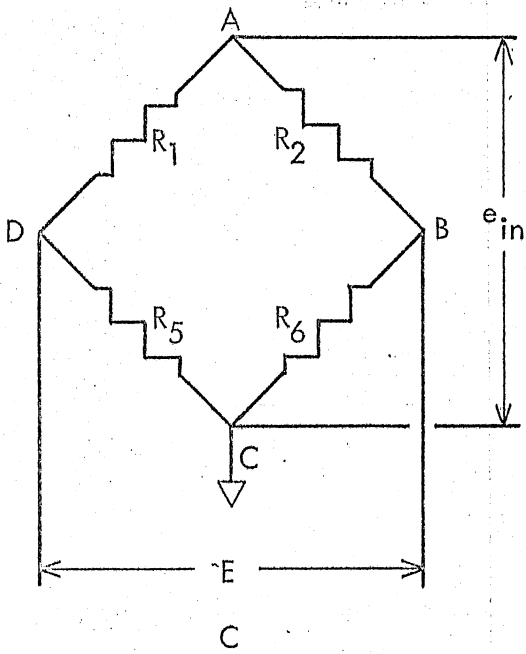
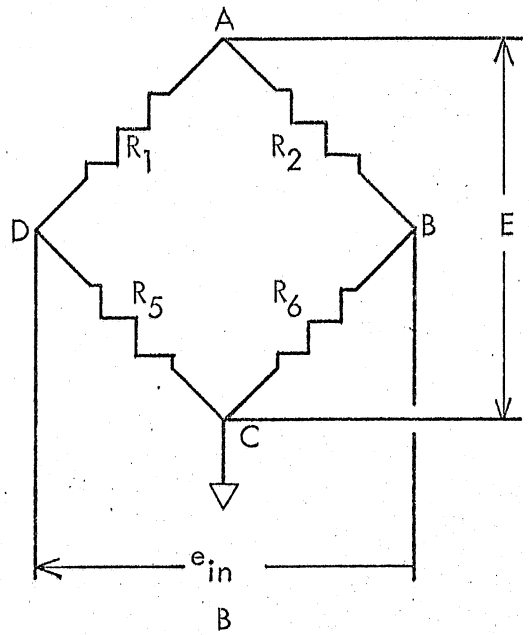
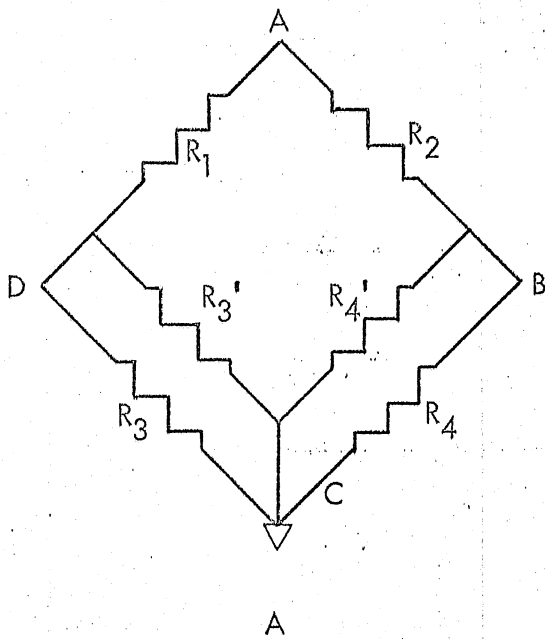


Fig. 12 - Alternative Bridge Systems

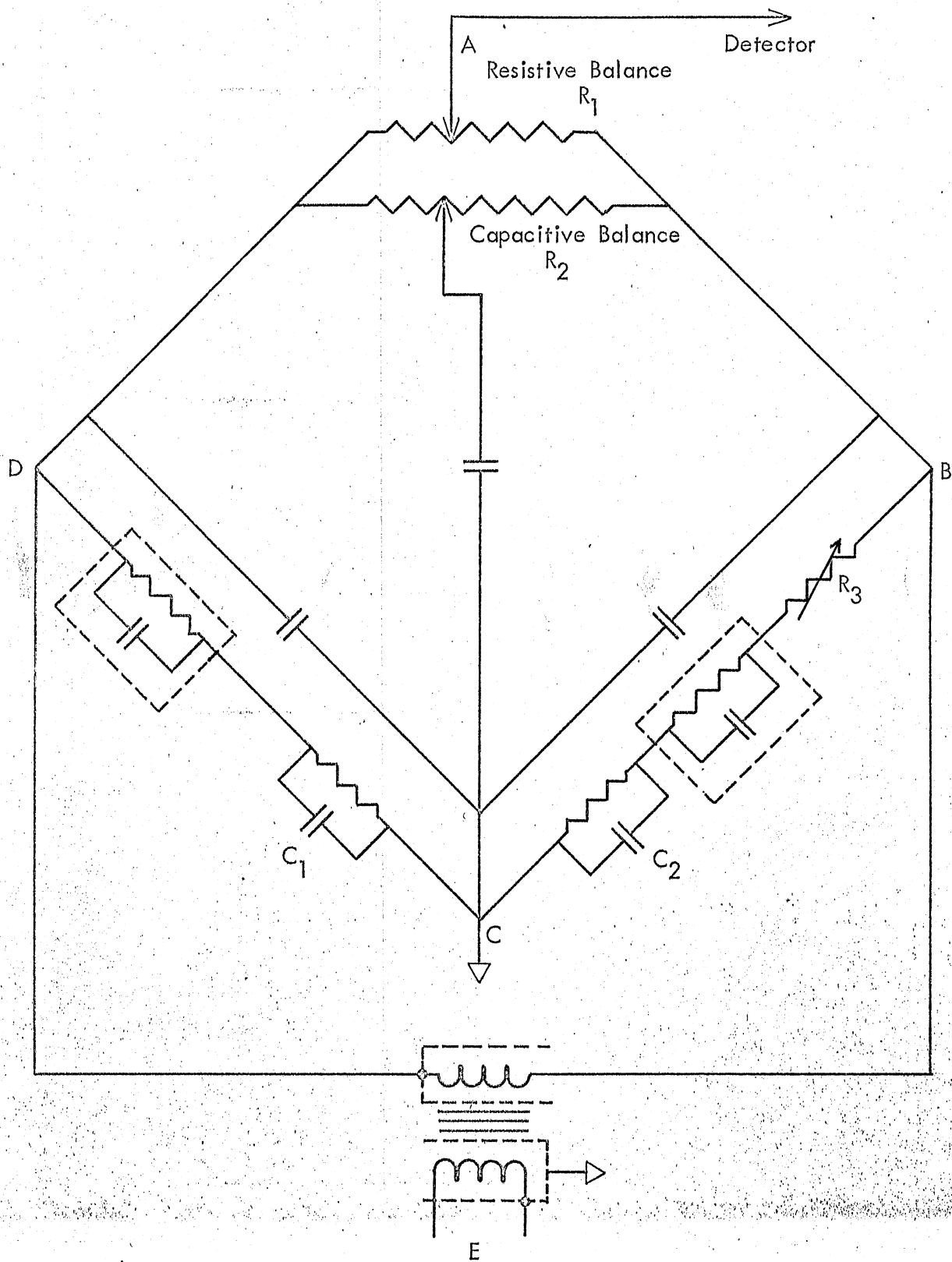


Fig. 13 - Equivalent Circuit of Instrument Bridge

Appendix I

ELECTRICAL RESISTANCE OF A SMALL LIQUID
COLUMN CONTAINING SUSPENDED PARTICLES

Assuming the area A of the tube or column can be divided up into many small tubes of area A' , each containing one particle of sediment of area a and length d ,

$$\Delta r = \frac{l}{\sum_1^n \frac{l}{\text{Change in resistance of all the tubes of area } A'}}$$

Summing up the parallel resistance change in all tubes of area A' in A :

$$\Delta r = \frac{l}{\sum_1^n \frac{l}{\sum_1^{n'} \frac{l}{\frac{\rho_w bd}{(A' - a)} + \frac{l}{\rho_p bd/a}} + \frac{\rho_w(x - bd)}{A'} - \sum_1^{n'} \frac{\rho_w x}{A'}}$$

where

ρ_w = resistivity of the water

ρ_p = resistivity of the particle

b = length form factor

n' = number of particles in length x

n = number of areas A'

x = tube length from particle center

Δr can be rewritten

$$\Delta r = \frac{\rho_w}{\sum_1^n \frac{A'^2}{\sum_1^{n'} \frac{fad}{(1 - \frac{a}{A'})(1 - \frac{\rho_w}{\rho_p})}}} = \frac{\rho_w}{\sum_1^n \frac{A'^2}{\sum_1^{n'} \frac{fv}{(1 - \frac{a}{A'})(1 - \frac{\rho_w}{\rho_p})}}}$$

where

f = volume form factor

v = volume of particle

for insulating particles $\rho_p \rightarrow \infty$,

Assuming an average value of a/A' ,

$$\Delta r = \frac{\rho_w V f x}{\sum_1^n A'^2 (1 - \frac{a}{A'}) x} = \frac{R_o C f}{1 - \frac{a}{A'}}$$

with n representative areas in the tube, or

$$\frac{\Delta r}{R} = \frac{fC}{1 - \frac{d^2}{D^2}}$$

where

R_o = resistance of the tube without particles

C = concentration of sediment

d = diameter of particle

D = diameter of tube

The effect of a small tube and large sediment is shown, for example, for the 0.3 mm diameter sediment in a 3 mm diameter tube; the average correction is 0.09/9, or one per cent.

When the particles are very small (0.01 mm), many particles occupy a cross-section and the concentration in the tube cross-section becomes the same as that in the media. The term $1 - a/A'$ can be written $1 - na/nAd$. Then na/nAd is approximately the concentration C , and

$$\Delta r/R_o = fC/(1 - C)$$

which is in the form given by Velick and Goren [2] and quoted earlier in this report.

The concentration measured here is 10,000 ppm by volume maximum. Since $1 - C$ is very nearly one, $\Delta r/R_o = fC$ applies as an approximation. The form factor f determined by Velick and Goren should also apply.

The resistance measurements were made in a chamber 1 inch by 1/8 inch in diameter (approximately 25 mm long by 3 mm in diameter). It is of interest to note the concentration per unit length which results from a sample of 0.3 mm diameter particles in a 1 mm long tube:

$$\frac{\pi}{6} \times (3)^3 / \frac{\pi}{4} \times (3)^2 = 2000 \text{ ppm per mm}$$

For the 25 mm long tube this is 80 ppm. The concentration can only increase in increments of 80 ppm as more particles enter the tube irrespective of the possibly much lower concentration in the source liquid. This property can be used to obtain a much increased sensitivity as in some commercially available particle counters. The manner of operation here requires a larger tube or the ability to average the variation of a rapidly varying resistance, as is done here. This is possible since the response of the instrument is linear with concentration. A simple average (0) of voltages gives a time average of concentration which is equal to the concentration in the source.

Appendix II

ELECTRICAL BRIDGE SYSTEM

The electrical bridge system used can, for purposes of discussion, be likened to a 4-arm Wheatstone bridge. The two liquid arms were arranged so that they were grounded at their midpoints. The equivalent circuit is shown in Fig. 12, where R_3, R_3' and R_4, R_4' are the liquid resistors formed by the measuring chamber. Resistors R_3 and R_4 were held as nearly equal in value as possible through control of temperature, geometry, and salinity.

The design choice was the location of excitation voltage E and detector voltage e_{in} .

Let R_5 equal R and R_6 equal $R + \Delta r$, where R is the resistance of the liquid and Δr is the change in resistance due to the presence of sediment, and let the resistor R_1 equal R_2 equal KR , where K is the ratio of the resistances of the upper and lower bridge arms; then the voltage is given by

$$e_{in} = e_{AD} - e_{CD} = \frac{E}{2} \left(\frac{\Delta r/R}{2 + \Delta r/R} \right) \quad \text{Fig. 12-C}$$

If $\Delta r/R$ is small, e_{in} is $\frac{E}{4} \left(\frac{\Delta r}{R} \right)$ and the equivalent series resistance of the bridge is $R(K + 1)/2$. The input impedance of the detector cannot be neglected; it will be called Z_{in} . Then

$$e_{Z_{in}} = \frac{E}{4} \frac{\Delta r}{R} \left[\frac{Z_{in}}{Z_{in} + \frac{R}{2}(K + 1)} \right]$$

or the sensitivity equals approximately

$$s = \frac{e_{Z_{in}}}{\Delta r/R} = \frac{E}{4} \left[\frac{Z_{in}}{Z_{in} + \frac{R}{2}(K + 1)} \right]$$

This would indicate that the values of R_1 and R_2 should be smaller than R_5 and R_6 .

Interchanging the excitation voltage E and the detector e_{in} gives

$$e_{in} = \frac{EK}{(1+K)^2} \frac{\Delta r}{R} \quad \text{Fig. 12-B}$$

with an equivalent series impedance of $\frac{2K}{K+1} R$ and a sensitivity s of

$$\frac{EK}{(1+K)^2} \left[\frac{Z_{in}}{Z_{in} + \frac{2K}{K+1} R} \right]$$

This expression is seen to reach a maximum of $\frac{E}{4} \frac{Z}{Z+R}$ at $K=1$, which is the same as configurations B and C at $K=1$.

Configuration C gives much more flexibility in the choice of K for nearly the maximum sensitivity. The value of the liquid resistor changes over a considerable range in application; consequently the "C" configuration appeared to be the best compromise.

The lower limit on K is a value which will not load the oscillator excessively, while the maximum value of E is limited by the heating effect in the liquid.

Unfortunately, the bridge system rarely behaves as a pure resistance system, and a balance system for capacitance was also required. The complete bridge system is shown in Fig. 13. The resistance capacitance in the dotted square is an approximately equivalent circuit of the electrode interface. The capacitors C_1 and C_2 are the equivalent of the capacitance arising from the sediment in each arm which sometimes appears.

A phase-sensitive detector and a conventional null detector were employed as a bridge balance indicator. The bridge was first balanced with the null detector for resistance and capacitance and then for zero on the phase-sensitive detector with the "resistance balance" only. The phase-sensitive detector served two purposes: It was insensitive to capacitance changes and it averaged out fluctuations in the null reading due to varying sediment concentration. The conventional null detector gave an up-scale reading for a positive or negative fluctuation from the balance point.

A convenient instrument which contains all the elements described is a Baldwin strain analyzer. The damping of the instrument needs to be increased slightly by adding a capacitor across the meter movement. The initial null balancing can be omitted.