A STUDY OF METHODS USED IN

MEASUREMENT AND ANALYSIS OF SEDIMENT LOADS IN STREAMS

REPORT P

INVESTIGATIONS OF DIFFERENTIAL-PRESSURE GAGES FOR MEASURING SUSPENDED-SEDIMENT CONCENTRATIONS

JUNE 1961

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MEASUREMENT AND ANALYSIS OF SEDIMENT LOADS IN STREAMS

A Cooperative Project
Sponsored by the
Subcommittee on Sedimentation
Inter-Agency Committee on Water Resources
(Formerly Federal Inter-Agency River Basin Committee)

Participating Agencies

Corps of Engineers ** Geological Survey
Soil Conservation Service ** Bureau of Reclamation
Agricultural Research Service ** Coast and Geodetic Survey
Tennessee Valley Authority ** Federal Power Commission
Office of Indian Affairs ** Public Health Service
Bureau of Public Roads ** Forest Service

REPORT P

INVESTIGATIONS OF DIFFERENTIAL-PRESSURE GAGES FOR MEASURING SUSPENDED-SEDIMENT CONCENTRATIONS

Published Through Arrangements Made by
Project Offices of Cooperating Agencies
at
St. Anthony Falls Hydraulic Laboratory
Minneapolis, Minnesota

JUNE 1961

SYNOPSIS

Attempts to determine the concentration of sediment in flowing water were not successful. The dynamic pressure differences were so much greater than those associated directly with the presence of sediment in suspension that the identification of sediment concentration was seldom conclusive. Because our primary objective was measuring sediment concentrations in flowing water, the development of the pressure-differential devices was discontinued. Further investigation of possible adaptation to the determination of small pressure differences in the laboratory is recommended to those who might have the need for such an instrument.

Three types of pressure-differential equipment were tested for adaptability to measuring the concentration of suspended sediment in a water-sediment mixture:

1. A bellows differential-pressure gage with manometer water columns to the bellows was equipped with a linear-variable differential transformer and electric circuit to determine the bellows movement caused by differential pressures. The bellows system proved reasonably satisfactory to a sensitivity of about 300 ppm of sediment.

2. A null-balance bubbler gage was tested for direct recording of the pressure-head difference caused by the presence of sediment in suspension. The accuracy was not better than 2000 ppm of sediment. This was not considered adequate for further development.

3. A modified pressure-differential device combined a manometer system and a float and differential transformer device for determining the change in elevation in a manometer. This system was much more sensitive than the other two and for low concentrations had a sensitivity of about 25 ppm of sediment with a specific gravity of 2.65.

The sensitivity of the float differential-transformer bubbler gage indicated possible uses in the laboratory, especially for the measurement of small differential pressures or water surface slopes. The response time was considered too slow for application to the determination of sediment concentrations in the laboratory.

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INVESTIGATIONS OF DIFFERENTIAL-PRESSURE GAGES FOR MEASURING SUSPENDED-SEDIMENT CONCENTRATIONS

I. INTRODUCTION

1. Purpose of this investigation--Work on the differential pressure equipment is part of a general project for development of new devices for automatic measurement of suspended-sediment loads in streams. In this investigation the differential-pressure systems were used to measure the changes in pressure between two elevations in a fluid or in a fluid and suspended-sediment mixture, when the concentration of suspended sediment or dissolved solids changed. The investigation is an attempt to improve the accuracy of differential-pressure measurements and to evade dynamic pressure effects sufficiently to permit measurement of the suspended-sediment concentrations in normal stream flow. A secondary goal is development of differential-pressure equipment for laboratory use in the determination of sediment concentration or size distribution.

In flowing water the dynamic pressure differences were so much greater than the pressure differences caused by changes in suspended-sediment concentration that the identification of a difference in suspended-sediment concentration was practically impossible, at least for normal field concentrations of sediment. Consequently the development of differential pressure gages for measuring sediment concentrations in flowing water was discontinued.

2. Personnel and acknowledgments--This work is part of the program of the Federal Inter-Agency Sedimentation Project, which is located at the St. Anthony Falls Hydraulic Laboratory of the University of Minnesota. The project is under the supervision of an Inter-Agency Technical Committee and it is sponsored by the Subcommittee on Sedimentation of the Inter-Agency Committee on Water Resources. Funds are contributed by the Geological Survey, Corps of Engineers, Soil Conservation Service, Bureau of Reclamation, Agricultural Research Service, Tennessee Valley Authority, and Public Health Service.

The report was prepared by H. A. Jongedyk, who conducted the testing and development program. H. H. Stevens, Jr. assisted in design and fabrication of the equipment. B. C. Colby, project supervisor, designed the FDT manometer, supervised the operation, and reviewed the report.

The staff of the St. Anthony Falls Hydraulic Laboratory furnished technical advice and some of the equipment. The null-balance bubbler gage was developed by personnel of the Columbus, Ohio, Surface Water Research

Unit of the U. S. Geological Survey.

3. Phases of the investigation--The investigation was in four phases:

   A. Development of equipment and techniques for measuring pressure differences.

   B. Calibration of equipment for different fluid densities under static conditions.

   C. Testing of stability and dependability. Evaluation of the effects of temperature, bellows reactions, and changes in techniques of operation.

   D. Testing adequacy of equipment for evaluating changes in density in flowing water with or without sediment.

The following equipment has been tested:

   A. Bellows differential-pressure gage (manometer water columns to bellows)

   B. Null-balance bubbler gage

   C. Float and differential-transformer (FDT) bubbler gage

II. BELLOWS DIFFERENTIAL-PRESSURE GAGE

4. Equipment--The pressure sensing system shown in Fig. 1 was set up in the laboratory. It follows a system devised by Appel and Hubbard[15]*. It was connected interchangeably by three-way stopcocks to pressure taps in a recirculating flume containing suspended sediment, or to a cylindrical plexiglas tank having an inside diameter of 5.75 in., a height of 34 in., and a capacity of 14 liters. Equipment used included:

1. Size #12 Hydron bellows, 4.5 in. outside diameter.
2. Water-proofed 0.005 M-L linear-variable differential transformer.
3. A constant voltage transformer.
4. Audio-oscillator for primary voltage.
5. Vacuum tube voltmeter for measuring primary voltage.
6. Vacuum tube voltmeter for measuring secondary voltage.

The bellows was encased in a cylindrical holder having plexiglas walls and brass top and bottom. The transformer core could be adjusted in relation to the null point by an arrangement in the bottom of the bellows holder. The top of the holder had connections for tubing to form fluid columns for transmitting pressures from the pressure taps. A 115-volt constant-voltage transformer supplied an oscillator with a primary voltage of 3 volts at a frequency of 20 kilocycles. An auxiliary voltmeter was used to check the primary voltage input to the differential transformer which was enclosed in glass tubing below the bellows. The secondary voltage from the differential transformer was read in millivolts (mv) on a second voltmeter.

The pressure taps into the plexiglas tank were spaced 2 ft apart vertically. The taps into the flume were at various spacing 2 to 9 in. apart vertically and the connections were interchanged between them during testing. The stem joining the bellows to the transformer core was composed of joined sections of nickel, tungsten, glass, tungsten, nickel and copper in that order to minimize conductance and change of length with temperature, and provide material which could be joined together. Good grounding and shielding were provided to eliminate drift from electrical interference. Section 29 of the appendix contains additional information on the characteristics of the differential transformer and the electrical circuit used with it.

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* Numbers in brackets indicate references listed on pages 39 and 40.

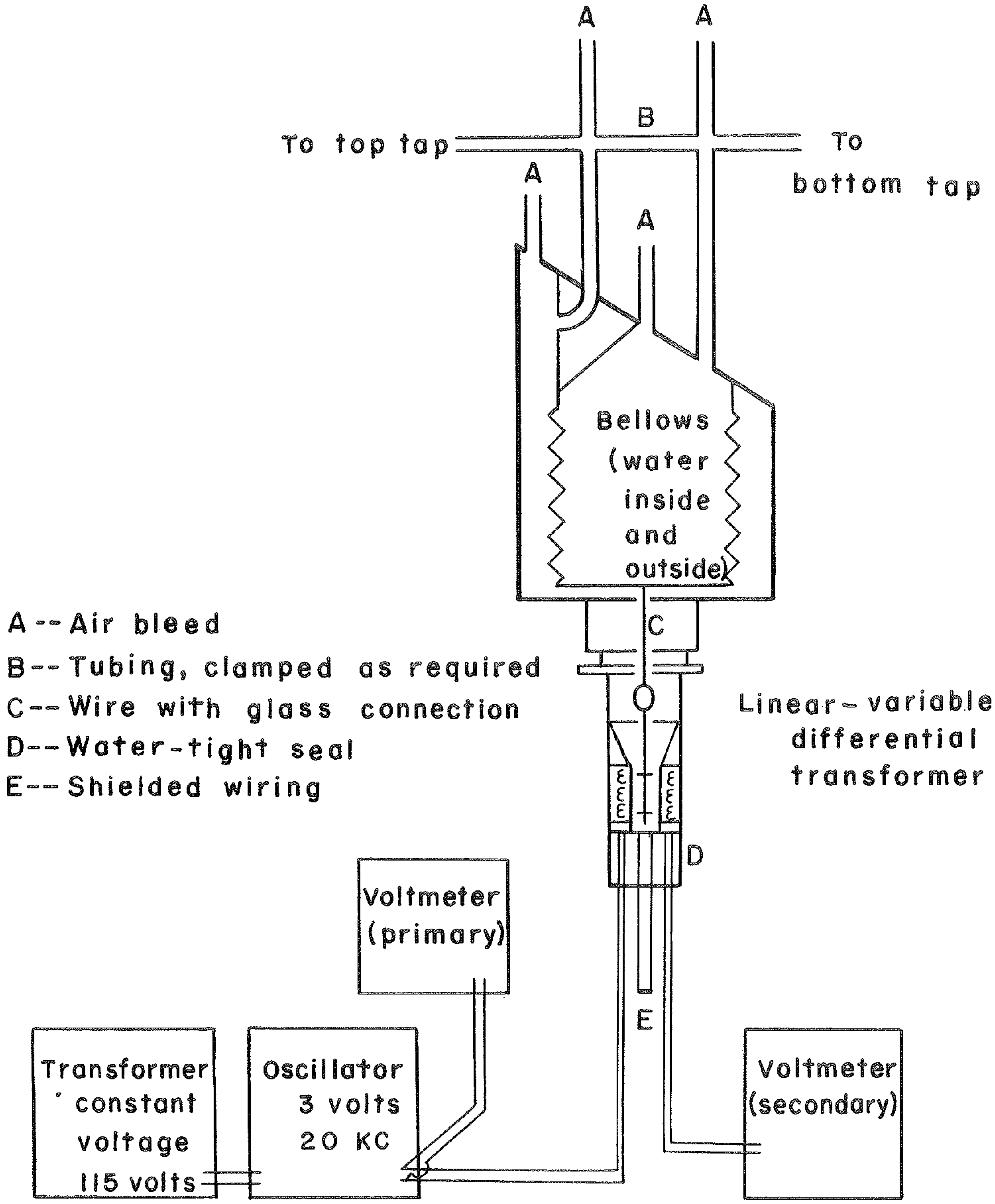

FIG. 1— SCHEMATIC DIAGRAM OF BELLOWS DIFFERENTIAL-PRESSURE GAGE (MODIFIED APPEL)

5. Preparation for operation--Water from which most of the air had been removed was slowly added to fill the inside of the bellows, the chamber surrounding the bellows, and all tubing, whether overflow tubing or tubing to pressure taps. Originally the bellows was operated in compression. This arrangement did not work well as indicated by lack of linear reaction to small changes of differential pressure in the plexiglas tank. The bellows reacted better to small pressure increments when it was extended somewhat. To extend the bellows it was necessary to add weight to overcome the buoyancy from water on the outside of the bellows. First, this was done experimentally by adding practically insoluble barium carbonate or small brass cubes to the inside of the bellows. Later, a more permanent arrangement was made by gluing small brass plates to the bottom of the bellows.

6. Calibration procedure--The bellows differential-pressure gage was calibrated by adding known increments of analytical reagent sodium chloride to 13,000 grams of distilled water in the plexiglas tank under approximately isothermal conditions. The sodium chloride was stirred into the water and readings were made of secondary voltage until an equilibrium seemed to be reached. Over a 48 hour period the diffusion of sodium chloride in the 0.15 cm^2 cross section of the tubing to the bellows was negligible. In computing the pressure differences resulting from addition of sodium chloride to the water, consideration was given to the partial molar volume of sodium chloride in solution and to the effect of temperature on the specific weight of the solution. The density of the solution was expressed in terms of the concentration of sediment of specific gravity 2.65 that would have the same density.

The minor influence of temperature changes on the distance between taps in the plexiglas tank and on the length of the plexiglas and brass parts of the transformer holder was neglected. After an addition of sodium chloride, equilibrium was usually reached in ten minutes if the water was stirred.

Unless the sodium chloride solution was mixed, uneven concentrations resulted, at least temporarily, and there was a time lag in the linear relationship between the mean density of the sodium chloride solution and the secondary voltage response. Originally the null-point voltage was 6 to 9 mv but improved grounding, shielding, and wire connections reduced the null to 0.6 mv.

7. Calibration results--When analytical reagent sodium chloride in water was used for calibration there was an approximately linear

relationship between density of the sodium chloride solution and the secondary voltage output. (See Fig. 2.)

The first calibration showed a relation of about 1 mv of output voltage for a density difference equivalent to 135 ppm of sediment having a specific gravity of 2.65. The data were consistent to within 5% of an average curve except at extremely small concentrations. Because instabilities in instrument operation were evident, the bellows and electrical circuit were rechecked and improved.

A second calibration showed consistent results to 15,000 ppm with 1 mv of output voltage equal to 160 ppm of sediment. At higher concentrations the readings became more erratic. Instrument instability rather than the high differential pressure appeared to be responsible for the errors.

After the electrical circuit was rechecked a third calibration was made. The voltage for zero concentration of sediment was reduced slightly so that the data was offset about 2 mv from those of the second calibration. Otherwise the second and third calibrations were essentially the same.

In laboratory use with a tap spacing of 2 ft, the probable accuracy of the bellows differential pressure gage appears to be about 4% of the total concentration or ± 300 ppm of sediment, whichever is larger. For an orifice spacing of 1.00 ft the accuracy would be about 8% of the total concentration or ± 600 ppm of sediment.

8. Check with suspended-sediment--Fine sediment (silt and sand smaller than 88 microns) was added to the plexiglas tank in increments and mixed thoroughly with the water. Within a short time after mixing was stopped the change of pressure deflected the bellows and the bellows extension was shown by the voltmeter readings. Because the sediment settled before full displacement of the bellows occurred, the voltmeter readings of secondary output versus ppm of sediment only approximately confirmed the calibration with sodium chloride. There was first a rapid and later a gradual decrease of voltmeter readings as the suspended-sediment settled. Unless the support for the bellows was agitated the voltage readings did not return to the original clear-water readings.

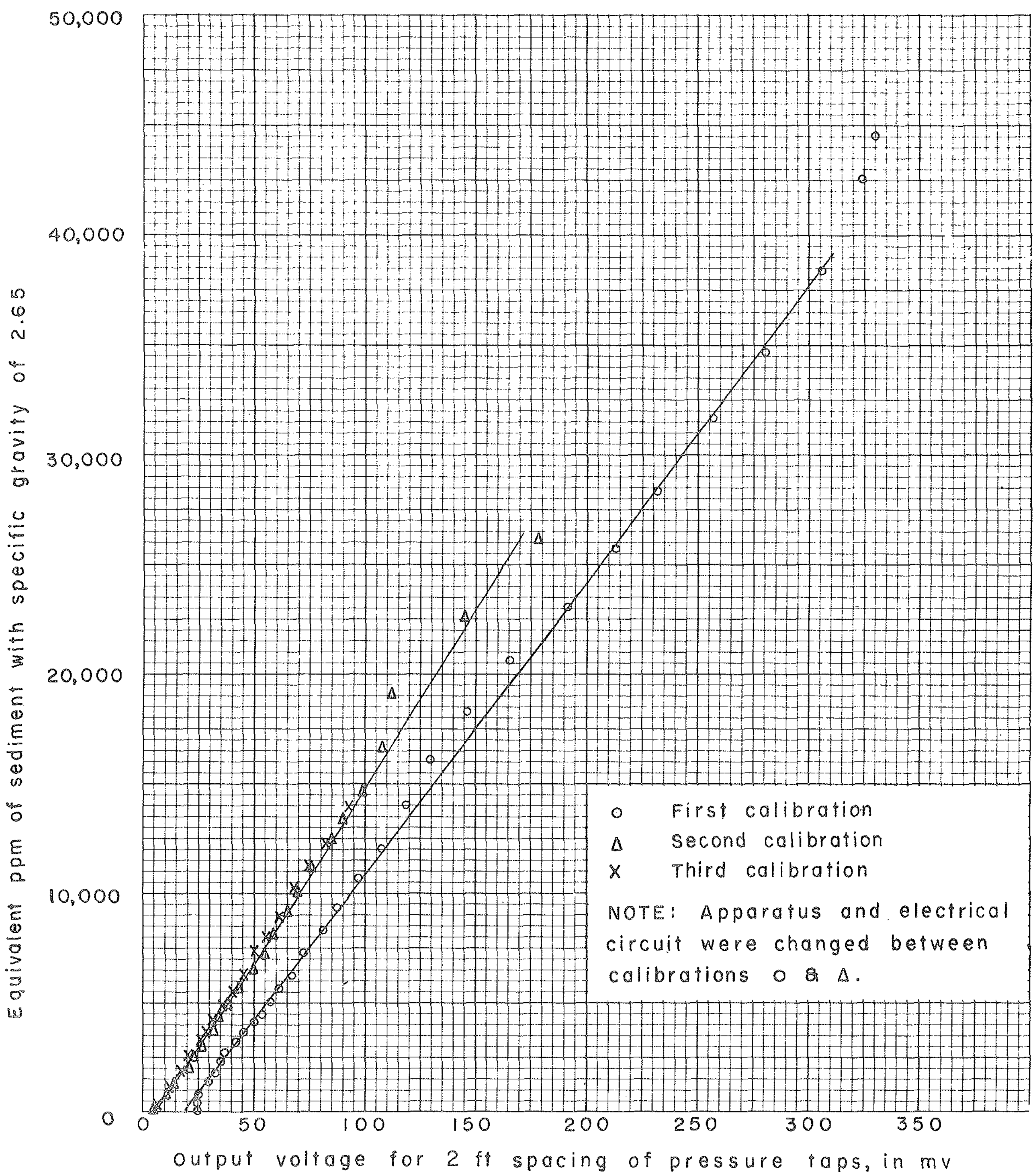

FIG. 2 – STATIC CALIBRATION OF BELLOWS DIFFERENTIAL-PRESSURE GAGE WITH SODIUM CHLORIDE SOLUTIONS

III. NULL-BALANCE BUBBLER GAGE

9. Background--Nelson[7] has reviewed some of the principles of bubbler gages in a study made by the Illinois Water Survey. Bubbler gages use the principle that the gas bubbles slowly released at an orifice have the pressure head of the water at the orifice.

Bubbler gages for remote reading or recording were developed for measurement of water levels by personnel of the Columbus, Ohio, Surface Water Research Unit of the U. S. Geological Survey. They developed a modification of the bubbler gage to measure a difference of water levels at two points of a stream, or variations of specific weight of liquid between two points spaced a known distance apart vertically. For purposes of this report the modification for pressure differences is called a "null-balance bubbler gage."

10. The null-balance bubbler gage--The null-balance bubbler gage consists of two identical gas lines, (Fig. 3) which transmit the pressures at two orifices back to the manometer. One side of the manometer is a stationary pot containing a float that actuates a switch contact arm (Fig. 4). The arm is one part of a system of electrical contacts through which a circuit is made when the float either rises or falls from the null position. On the other side of the manometer there is a motor-driven reservoir pot that moves up or down on an inclined threaded shaft to maintain the float in the stationary pot at the balance point. Movement of the inclined threaded shaft is transmitted by gears to a dial or to a continuous recorder or both. Power for the electrical circuits is supplied by two six volt dry cells.

11. Operation--Dry air or oil pumped nitrogen under pressure is supplied through a pressure reducer that releases the gas at a pressure of 20 psi (Fig. 3). The gas then passes through a second pressure reducing and valve control system that releases gas through a sight jar at a nearly constant rate. Just beyond the second pressure reducing unit the gas line branches, and one branch line is connected to a manometer pot. The main gas discharge follows the other line to a bubble orifice where pressure is to be measured. The gas in the branch line is stagnant except when temperature changes or displacement of fluid cause minor gas flow. A second gas line, identical with the first, is connected to the other manometer pot and a second orifice. The orifice with the smaller pressure is connected to the upper or float pot. The gas lines merely transmit pressure from orifice to manometer.

The difference in elevation of the water surfaces in the manometer pots is a measure of the difference in pressure heads at the two orifices. If the manometer fluid has a density near that of water the inclination of the

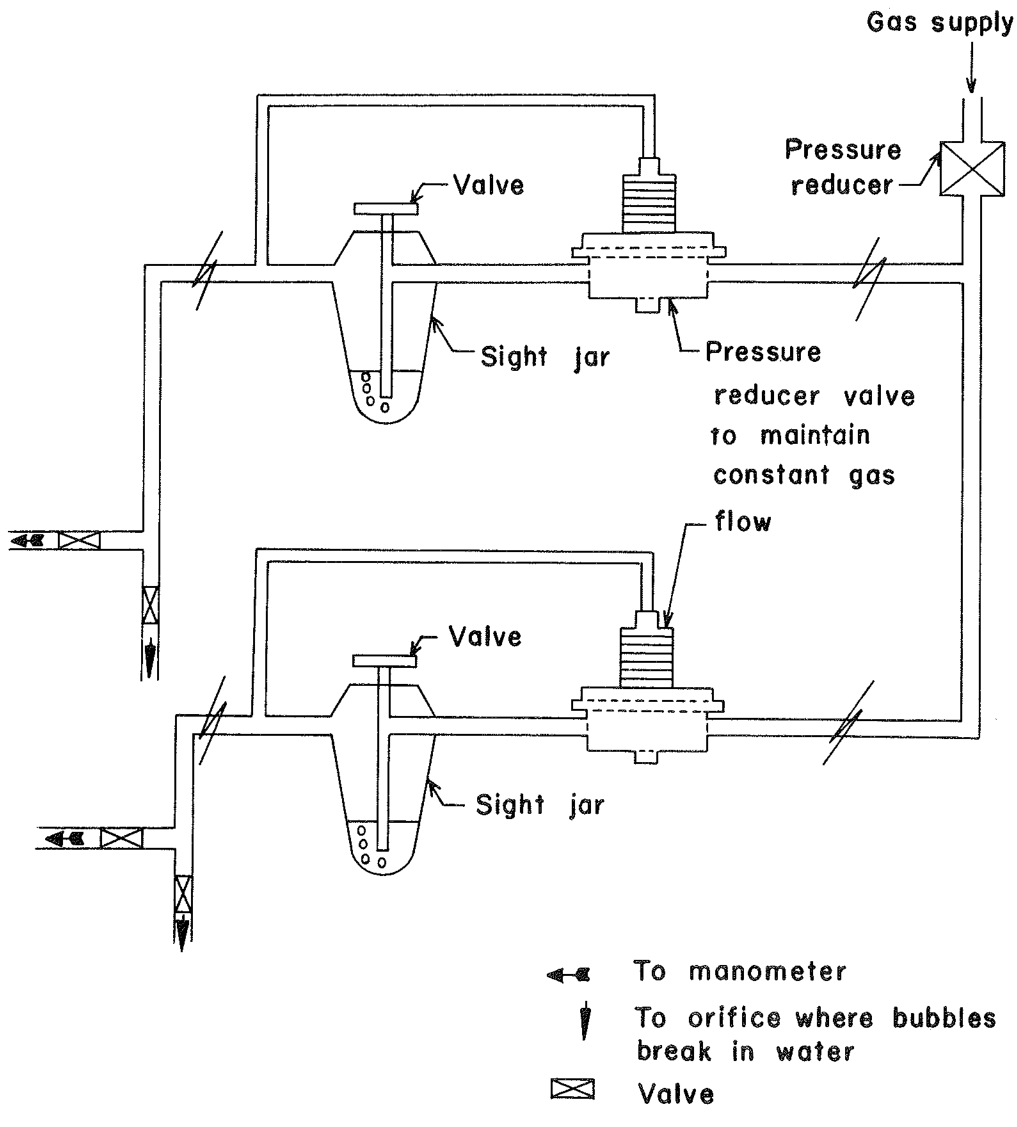

FIG. 3 - SCHEMATIC DIAGRAM OF GAS SUPPLY LINES OF BUBBLER GAGE

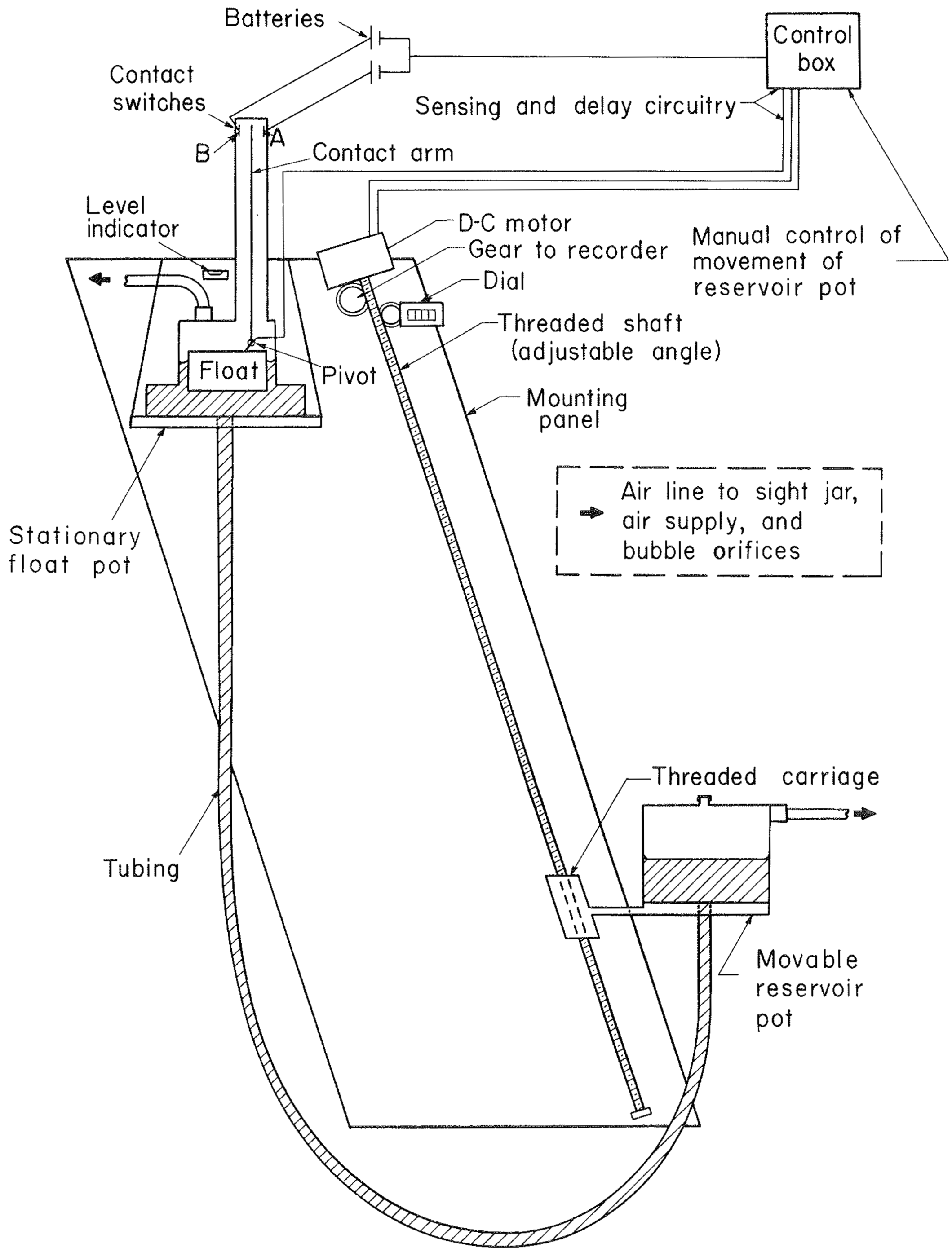

FIG. 4 - NULL- BALANCE BUBBLER GAGE MANOMETER

threaded shaft can be adjusted so that movement of the shaft is indicated on a dial directly in feet of water head.

When the instrument is in balance with the pressure difference between the two orifices no movement occurs. If the pressure difference increases, the fluid level in the float pot manometer rises, the switch contact arm (Fig. 4) tilts to the right closing the circuit through contact A, and the motor turns the threaded shaft to lower the reservoir pot and re-establish a condition of balance. If the pressure difference had decreased, operation would have been in the opposite direction. The movement of the threaded shaft would indicate an increase of differential pressure in the first case, and a decrease in the second.

It is possible to displace the reservoir pot of the manometer by manual operation of the motor. After the manometer has been moved from equilibrium the reservoir pot of the manometer moves back toward the correct position. A brief study showed that the time involved in reaching equilibrium could be as much as 1-1/2 hours but was usually about 20 minutes. The time was largely independent of distance of displacement.

In the null-balance bubbler gage (Fig. 4) the reservoir pot is moved to maintain equilibrium with the differential pressure. The motion is stopped by the contact arm and switches which are actuated by the fluid level in the float pot. Because of lag the movable reservoir pot over-travels before the fluid level control stops motion. The manometer becomes further unbalanced because of fluid momentum. Then the motion is reversed by the unbalance and comes back toward equilibrium but over-travels again. A condition known as "hunting" often results with the instrument reading swinging back and forth about the mean value.

A time delay circuit may be used to slow down the response to changes in the float level. When the delay was used the lower pot moved back and forth about 0.010 to 0.030 ft, frequently in the same range over an almost indefinite period. At the end of a movement there would be a pause before reversal of direction. The pause was 10 to 15 seconds without the delay circuit and 1 to 3 minutes with the delay circuit in use. Sometimes the reservoir pot would stop short of the equilibrium position. In this case it might remain there for hours, then creep to the true position or after a prolonged period start hunting about equilibrium position with no apparent cause.

The dial indicates to 0.001 ft. The smallest graduation which can conceivably be read is 0.0001 ft. However, the indicated differential pressure head between the orifices may be reliable only to 0.002 ft because the float does not necessarily actuate the switch for variations as small as 0.001 ft from true position.

12. Effect of bubble rates--The influence of gas flow rate on indicated differential pressure head was studied by adjusting the valves on the sight jars of Fig. 3 to vary the bubble rate. If the gas flow was increased in a gas line, there was an increase of pressure head loss and hence a change in differential pressure head reading. However, the null-balance bubbler gage is not sensitive enough to show significant differences unless the bubble rates are varied greatly.

13. Calibration of null-balance bubbler gage--The null-balance bubbler gage was calibrated with sodium chloride solutions. (See Section 6.) Increments of analytical reagent sodium chloride were added to the water in the plexiglas tank. The distance between orifices was 0.703 ft vertically with a solution temperature of 79° F. Even neglecting a 4° F temperature change during the tests, the observed readings agreed with the computed readings. Three types of observations were made for each increment of sodium chloride added:

1. Sodium chloride was added to the still water and a reading was made when equilibrium was reached.

2. The reservoir or lower pot was moved up or down about 0.004 ft and a reading was taken at equilibrium.

3. The solution was mixed with the instrument power off and then the power was turned on and an equilibrium reading was taken.

For the first step, equilibrium was reached in 10 to 90 min with 15 - 20 min usual. The other two steps took less time. In the last step, the time to reach equilibrium was frequently zero. The bubbles contributed to mixing of the solution in the plexiglas tank.

Part of the calibration is shown in Fig. 5, which illustrates the lack of consistency in coming to equilibrium. The solid line of Fig. 5 shows the theoretical relation between concentration in ppm and head in feet of water for an orifice spacing of 0.703 ft. The head in feet of water is the difference between the pressure heads with and without sediment (or with and without dissolved solids to give the same mixture density as the sediment). An accuracy of 3000 ppm is about the best that could be obtained with an orifice spacing of 0.703 ft, which is equivalent to an accuracy of 2000 ppm with an orifice spacing of 1.0 ft.

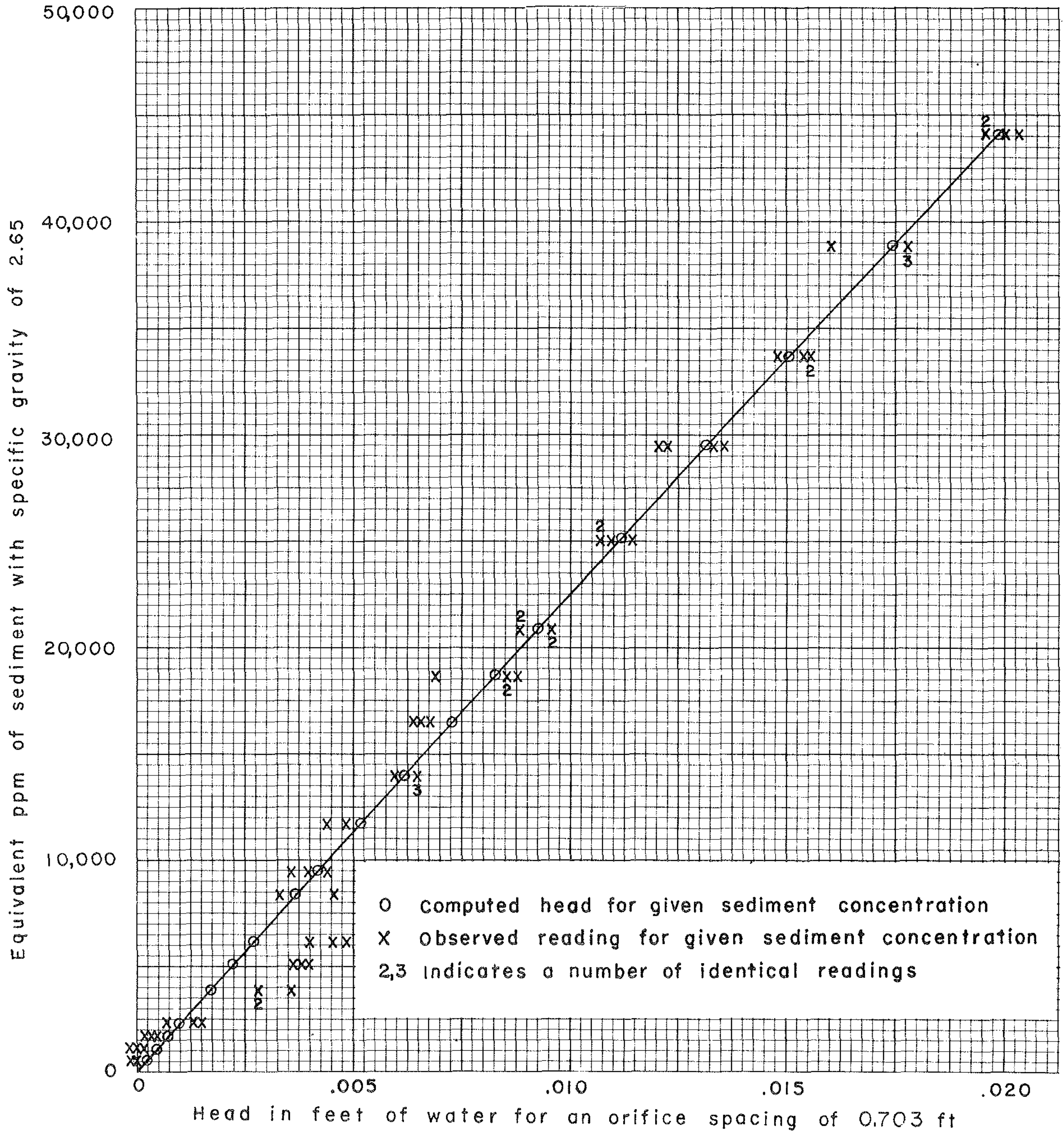

FIG. 5 — STATIC CALIBRATION OF NULL-BALANCE BUBBLER GAGE WITH SODIUM CHLORIDE SOLUTIONS

IV. FLOAT AND DIFFERENTIAL-TRANSFORMER BUBBLER GAGE

14. The FDT bubbler gage--Because the null-balance bubbler gage was not sufficiently accurate for determining suspended-sediment concentrations, a new type of differential pressure sensing device, the FDT manometer, was designed and built at the St. Anthony Falls Hydraulic Laboratory. (See Figs. 6 and 7.)

The FDT manometer is similar to that of the null-balance bubbler gage and it is connected to an identical gas line system. (See Fig. 3.) The manometer pots are spaced vertically so that they balance the minimum water pressure head from the orifices which have a vertical spacing of 0.703 ft at a temperature of 79° F. The reservoir pot elevation is adjustable. The manometer float moves in response to the small pressure changes between the orifices. The pressures at the orifices, for a given spacing of orifices, are a function of specific weight of liquid to be measured.

The core of a differential transformer is mounted on a vertical stem set into the top of the float. The transformer operates in moist air, but it is not immersed in the manometer fluid. An electrical system like that of the bellows differential-pressure gage (Fig. 1) indicates the float movement, and indirectly the change in pressure.

The present FDT manometer is made of type R plexiglas. The gage fluid is distilled water. The effective surface areas are 15.6 in.^{2} (includes 4.9 in.^{2} for float) in the float pot and 23.8 in.^{2} in the reservoir pot. Therefore, the float movement is 60.4 percent of the change in water pressure head $[23.8 \div (15.6 + 23.8)]$

15. Principles of operation--The float pot was set so that the core of the differential transformer was above the null point with distilled water at the pressure orifices. Any increase in differential-pressure head moved the float upward and moved the core with respect to the null position. The movement changed the secondary voltage in proportion to the displacement.

For a given primary voltage input to the transformer the secondary voltage varies directly as the change in water pressure head between the orifices; directly as the ratio of the effective water-surface area of the reservoir pot to the total water-surface area of both pots; and inversely as the specific gravity of the manometer fluid.

Because the density change of the manometer fluid is relatively greater than the expansion of the manometer bracket, and the coefficients of thermal

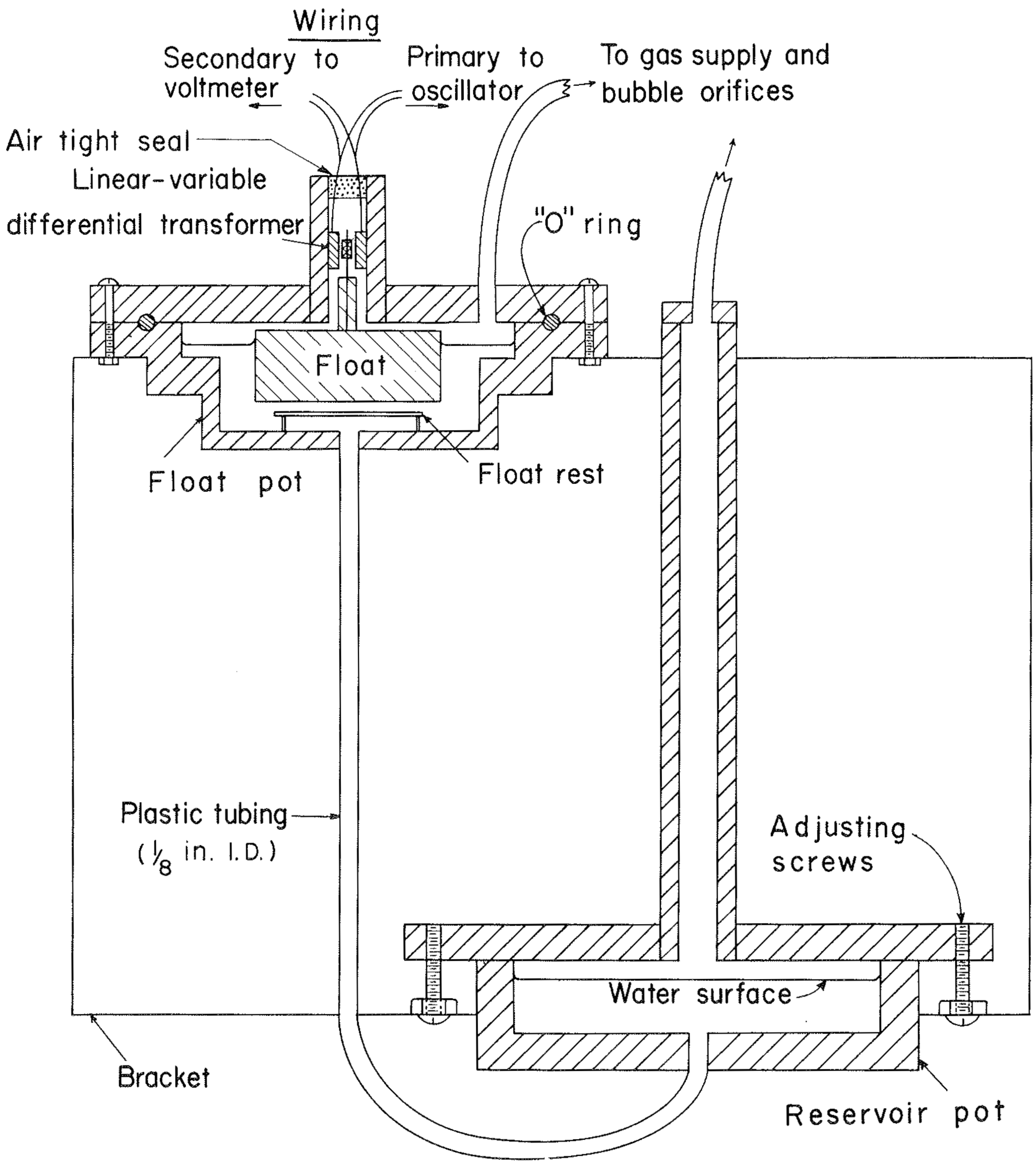

FIG. 6-FDT (FLOAT, DIFFERENTIAL-TRANSFORMER) BUBBLER GAGE

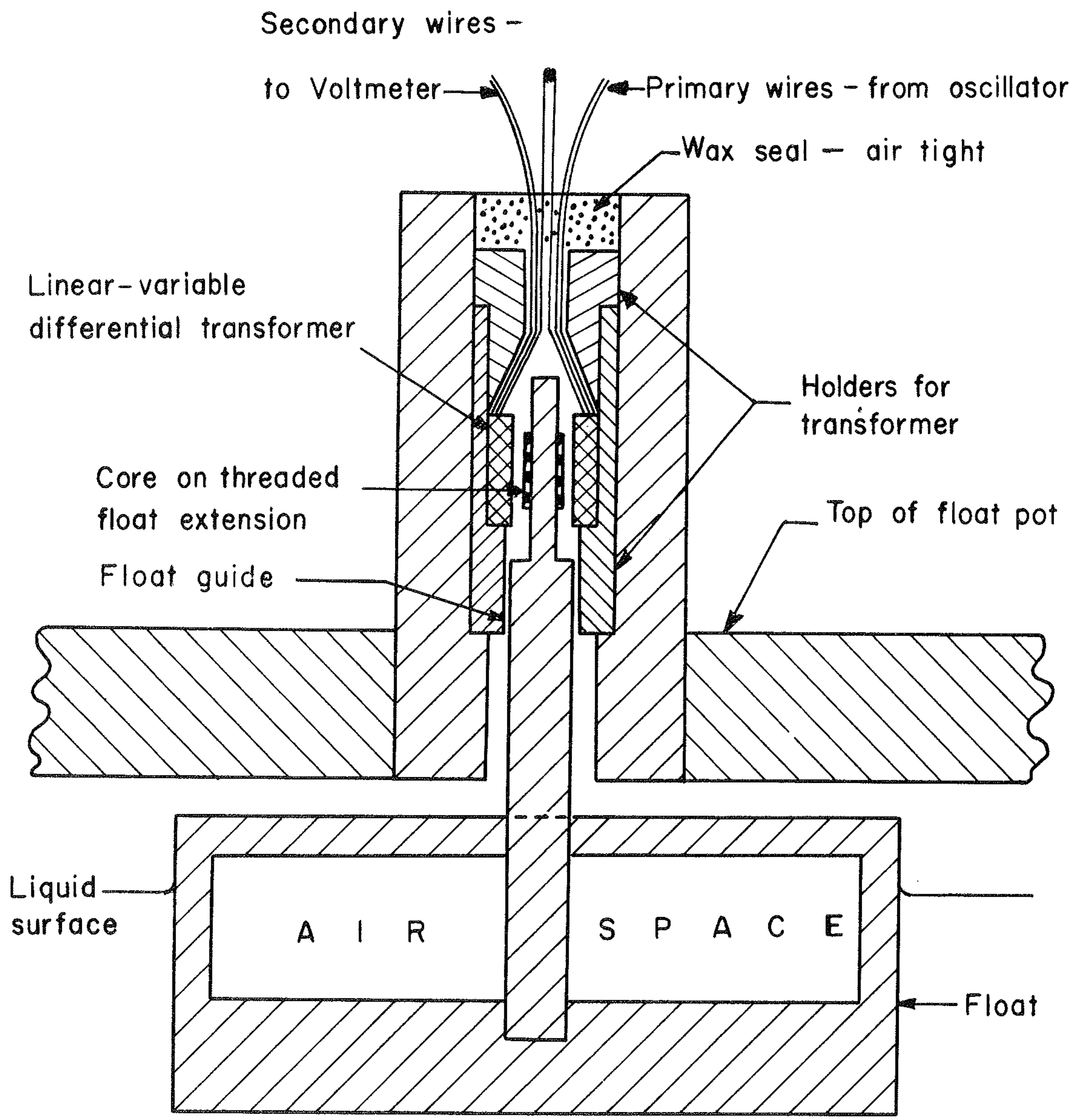

FIG. 7 - DETAIL OF TOP OF FLOAT POT OF
FDT BUBBLER GAGE

expansion of the fluid and of the structural material of the float and pots are not the same at all temperatures, temperature changes cause a displacement of the core relative to the transformer. Also the differential pressure at the orifices may be modified by unequal pressure losses in the gas lines.

The FDT bubbler gage is extremely sensitive. Therefore, all influences on the accuracy must be evaluated as carefully as possible. At low gas flow rates and a low setting on the voltmeter scales, the breaking of individual bubbles at the orifices varies the voltmeter reading of output current.

16. Static calibration of the FDT bubbler gage--Sodium chloride was used for static calibration tests as reported in Section 6. First an approximate test was made as a guide. Then a thorough calibration was made of the response (in terms of output voltage) of the FDT bubbler gage to changes in the specific weight of the liquid in the plexiglas tank. Calibration was as follows:

1. Temperature in the building was controlled as completely as possible. Throughout the calibration temperatures were observed in the tank and adjacent to the FDT manometer pots.

2. The equipment was started 96 hours before the first addition of sodium chloride and many observations of equipment operation were made during the interval. Except at night, observations of operation and output voltage were nearly continuous as sodium chloride was added.

3. Bubble rates were set before the start of calibration and the variations during the test were small. (See also Section 19.)

4. The elevation of the reservoir pot of the manometer was not changed immediately before or during the calibration.

5. With one exception no water droplets were seen in the gas line. (Apparently water in the gas line to the lower orifice changed the gas flow resistance at one point on Fig. 8.)

6. All sodium chloride was nearly water free when weighed in predetermined amounts on an analytical balance. Increments of sodium chloride were carefully added to the fluid in the plexiglas tank.

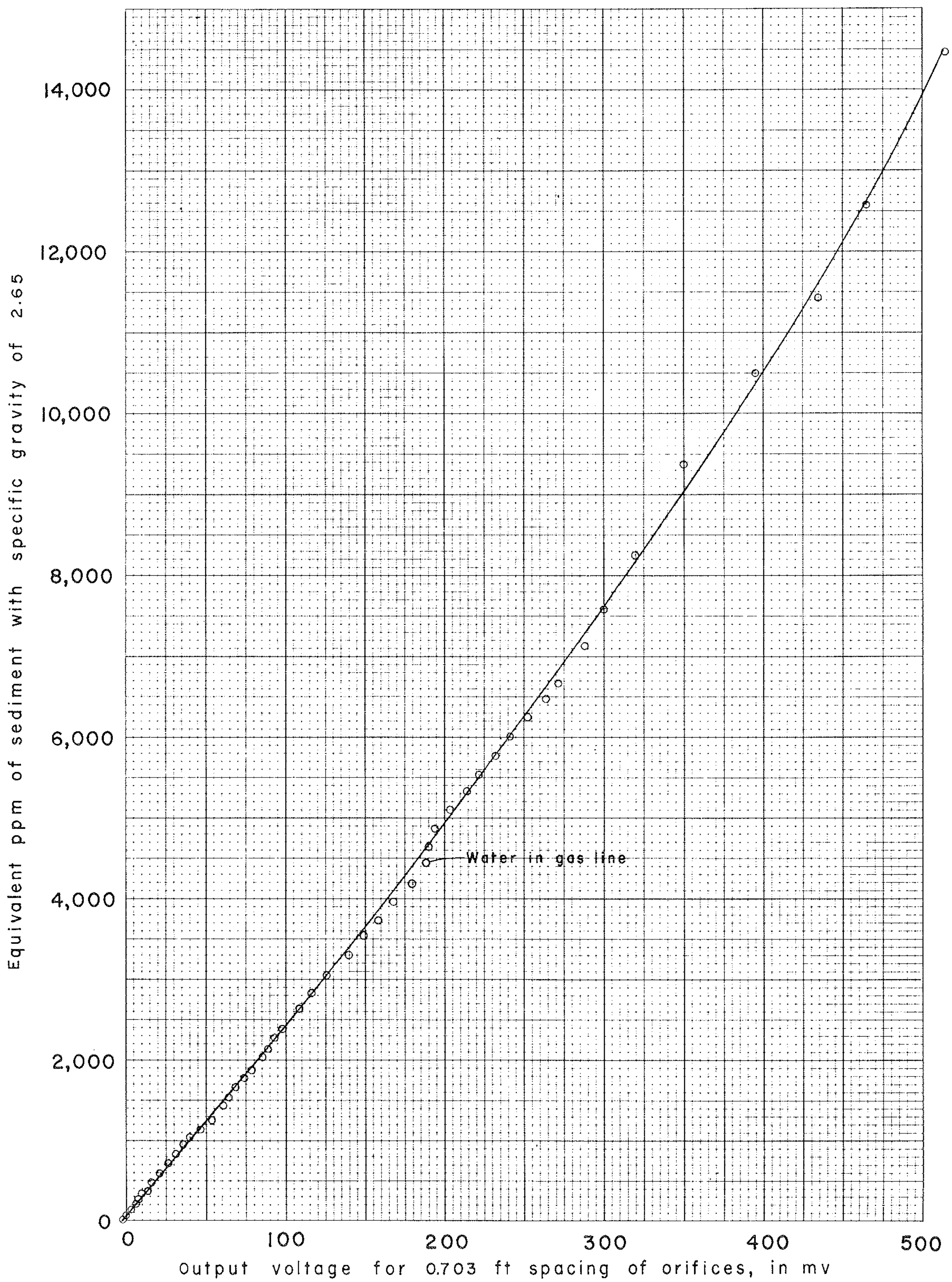

FIG. 8 — STATIC CALIBRATION OF FDT BUBBLER GAGE WITH SODIUM CHLORIDE SOLUTIONS

7. Output voltage readings reached equilibrium in from 10 to 20 min after an addition of sodium chloride. After the readings became reasonably stable an average reading was obtained.

8. Gentle stirring did not decrease the response time appreciably.

Fig. 8 illustrates the results of this calibration study. After correcting the specific weight of the water for temperature changes, the FDT gage indicated a density difference equivalent to about 25 ppm of sediment (assumed specific gravity of 2.65) in suspension per mv of output for the orifice spacing of 0.703 ft. The relation remains approximately constant over a range from -300 to +300 mv. The computed movement of the float and core of the transformer is 0.000079 in. per mv.

For an orifice spacing of 1 ft the output would be 1 mv for 17 or 18 ppm within the 300 mv limits.

17. Effects of transient pressure changes at the orifice--The water in the plexiglas tank was stirred to produce transient pressure changes at the orifices. Soon after stirring the voltage output of the FDT gage began to fluctuate. Positive and negative variations from the mean continued for perhaps half an hour after stirring stopped but ultimately the original static reading was restored approximately. The FDT gage might read more consistently if a means of damping transient pressure changes were incorporated in the system.

18. Liquid condensation in gas lines--If liquid condenses on the inner walls of the 3/16-in. gas lines to the orifices, the pressure losses in the lines change. A much larger change occurs when a water meniscus forms in the gas line.

Water in the gas lines could come from three sources:

1. The gas supply for the gas flow to the orifices.

2. The distilled water in the sight jars.

3. Water that backed up from the orifices and clung to the inside of the tube.

Several methods have been used for minimizing the effect of water in the gas lines. Oil pumped, dry nitrogen and air that has been dried with silica gel have been tried. A glycerine-water mixture which has a lower vapor pressure than water was used instead of water in the sight jars.

The length of travel of the bubbles through the liquid in the sight jars was shortened. The gas lines were tightly connected and laid on a drainage slope in order to reduce the backflow of water. A continuous flow of gas is necessary for optimum operation of the equipment. Rapid temperature changes promote condensation.

19. Effect of varying gas flow rates--The influence of gas flow rates on the pressure transmitted from the orifices to the manometer was investigated. Gas flow rate was measured by bubble rates in the sight jars. Because of frictional resistance to gas flow there is a pressure loss in the gas lines and the pressure loss increases as the gas flow increases. Also at very low bubble rates, and at rates so high that bubbles no longer form at the orifices, the effects of the surface tension in the air-water interface varies from that at moderate bubble rates. Normally the pressure losses in the two gas lines from the orifices to the manometer are kept equal by using the same gas flow rate in two gas lines that are identical. If the losses in the two lines and at the orifices are equal, the differential pressure will be accurate regardless of the actual magnitude of the losses.

Pressure changes at the orifices, condensation of moisture in the gas lines, and condensation or surface tension effects in the manometer may upset the manometer equilibrium, usually for 10 to 30 minutes, but sometimes for much longer. Meanwhile temporary and minor changes in gas flow rates occur as gas is diverted from one line or manometer pot to the other. The variation in pressure loss from the change in gas flow rate would be very small in relation to the pressure difference that caused the change in flow rate.

A series of gas flow rate tests were made in which the flow rate in one line was varied at the sight jar while the other was kept constant. As the variable flow rate increased from near zero, an increasing pressure loss and a consistent movement of the float of FDT manometer were expected. Some of the overall trends verified these expectations, but there was a considerable scatter and deviation of test points.

The bubble rates in the sight jar indicate that the gas flow rates vary slightly with time and temperature. However, any errors in FDT gage readings from changes in flow rates would be minor.

20. Effect of temperature variation--The effects of minor temperature variations were evaluated and used to correct the calibration of the FDT manometer. The computations may be expanded to cover wider ranges of temperature.

Temperature affects the pressure at the orifices in the plexiglas tank or in other types of container as follows: (1) The density of the fluid or fluid mixture varies with temperature, and for water or salt solutions the change in density can be obtained from tables or it can be computed. (2) The material of the container walls expands or contracts with temperature, and for plexiglas and some other materials it expands with an increase in water content within the material. The water content varies with temperature and relative humidity but may lag such changes by several days. No correction has been made for expansion of the plexiglas walls of the tank due to water content. Because the plexiglas length extends from orifice to orifice and because tank temperature tests were continued over several days the effect of water absorption is not necessarily small.

The manometer was designed so that the effect of thermal expansion in raising or lowering the fluid level in the manometer is counteracted by an equivalent lowering or raising of the float in the fluid. The two may be temporarily unequal when temperature lag between the upper and lower pots or between the plexiglas and the water becomes significant because of rapidly changing ambient temperature. Corrections for the changes in plexiglas dimensions with the change in water content were not made for the manometer. Because the lengths of plexiglas were short in relation to the water column and the tests were of short duration, the effects of water absorption would be very minor.

If the temperature change is assumed to be very slow, the change in voltage output of the FDT gage can be computed for temperature variations in either the manometer or the tank. In the examples that follow the manometer fluid is water.

With a stable condition output voltage of 12 mv at 64° tank temperature as the starting point, the output voltage was computed for other tank temperatures. (See Fig. 9.) The tank temperature was assumed to be the same throughout both fluid and container; the manometer temperature was assumed to be constant at 70° F; and the orifice spacing was 0.703 ft. A sample computation follows:

The relative density of the water drops from 0.99866 at 64° F to 0.99800 at 70° F and to 0.99748 at 74° F, and the coefficient of thermal expansion of the plexiglas tank is 0.000040 in in./in. per degree F. In the temperature range of 64° - 74° F the change in pressure head between the two orifices in feet of water at 70° F is therefore:

$$- \left[\frac{0.99866 - 0.99748}{0.99800} - 10 \times 0.00004 \right] 0.703 = - 0.0005497 \text{ ft.}$$

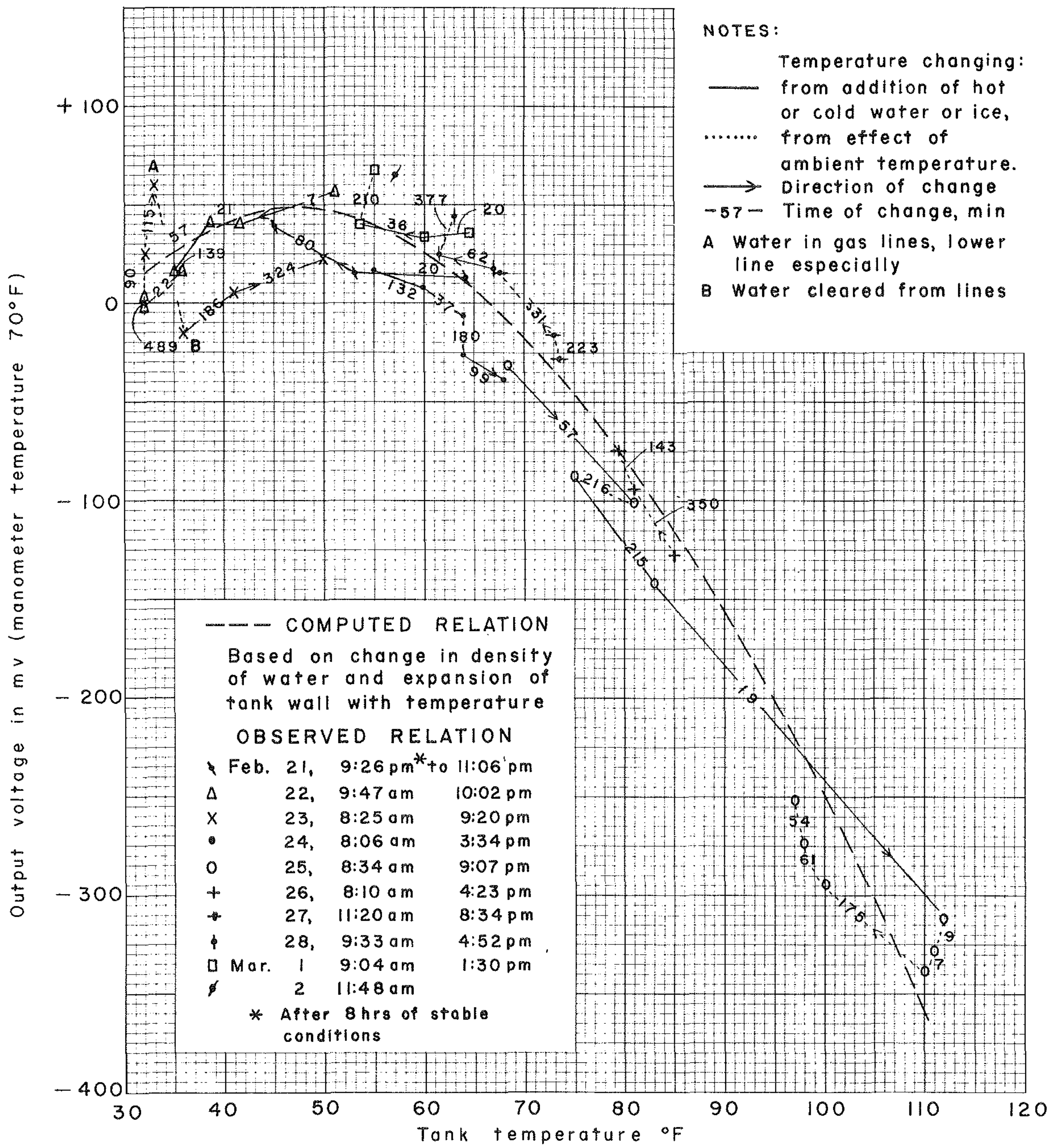

FIG. 9 — RELATION OF TANK TEMPERATURE AND OUTPUT VOLTAGE OF THE FDT MANOMETER

(FEB. & MAR., 1959)

From Sections 14 and 16 the float movement is 60.4% of a pressure head change and 0.000079 in. of float movement = 1 mv of output. Therefore, the change in voltage output from 64° to 70° F would be:

$$- 0.0005497 \quad \frac{0.604 \times 12}{0.000079} \quad = \quad -50.4 \text{ mv.}$$

The output reading of 12 mv at a tank temperature of 64° F would become 12 - 50.4 or -38.4 mv at 74° F.

Computations of the change of output voltage with changes in manometer temperature were made and the relation was plotted in Fig. 10. (Starting point was -102 mv at 70° F manometer temperature.) The pressure to the manometer was assumed constant with an orifice spacing of 0.703 ft and a water density of 0.99748. Temperature was assumed the same throughout all parts of the manometer. The bracket which supports the two pots was composed of about 7.9 in. of brass and 0.5 in. of plexiglas (between water surfaces). Coefficients of expansion of brass and plexiglas are about 0.0000106 and 0.0000395 in./in. per degree F.

If the manometer temperature falls from 70° to 64° F the change in pressure head in inches of water is:

$$- \left[\frac{0.99866 - 0.99800}{0.99748}\right] 0.703 \times 12 + 6(7.9 \times 0.0000106) + 6(0.5 \times 0.0000395)$$

$=$ - 0.004964 inches change in head.

$$- 0.004964 \times \frac{.604}{.000079} = $$ -38.00 mv change in output voltage from -102 mv at 70° F to -140 mv at 64° F.

A study of thermal expansion shows that: (1) The manometer bracket could be designed so that over a moderate range in manometer temperature the only change in output reading would be for the change in density of the water (or other manometer fluid); (2) if the material of the manometer bracket (from manometer fluid surface in the lower pot to that in the upper pot) is the same as that of the wall in which the orifices are mounted, any temperature change that affects the whole system (that is, manometer, bracket, orifice plate, liquid being measured, and manometer liquid) will not alter the voltage output; and (3) temperature effects in the present system are relatively large because expansion applies over a water column that is long in relation to the differential pressure that is

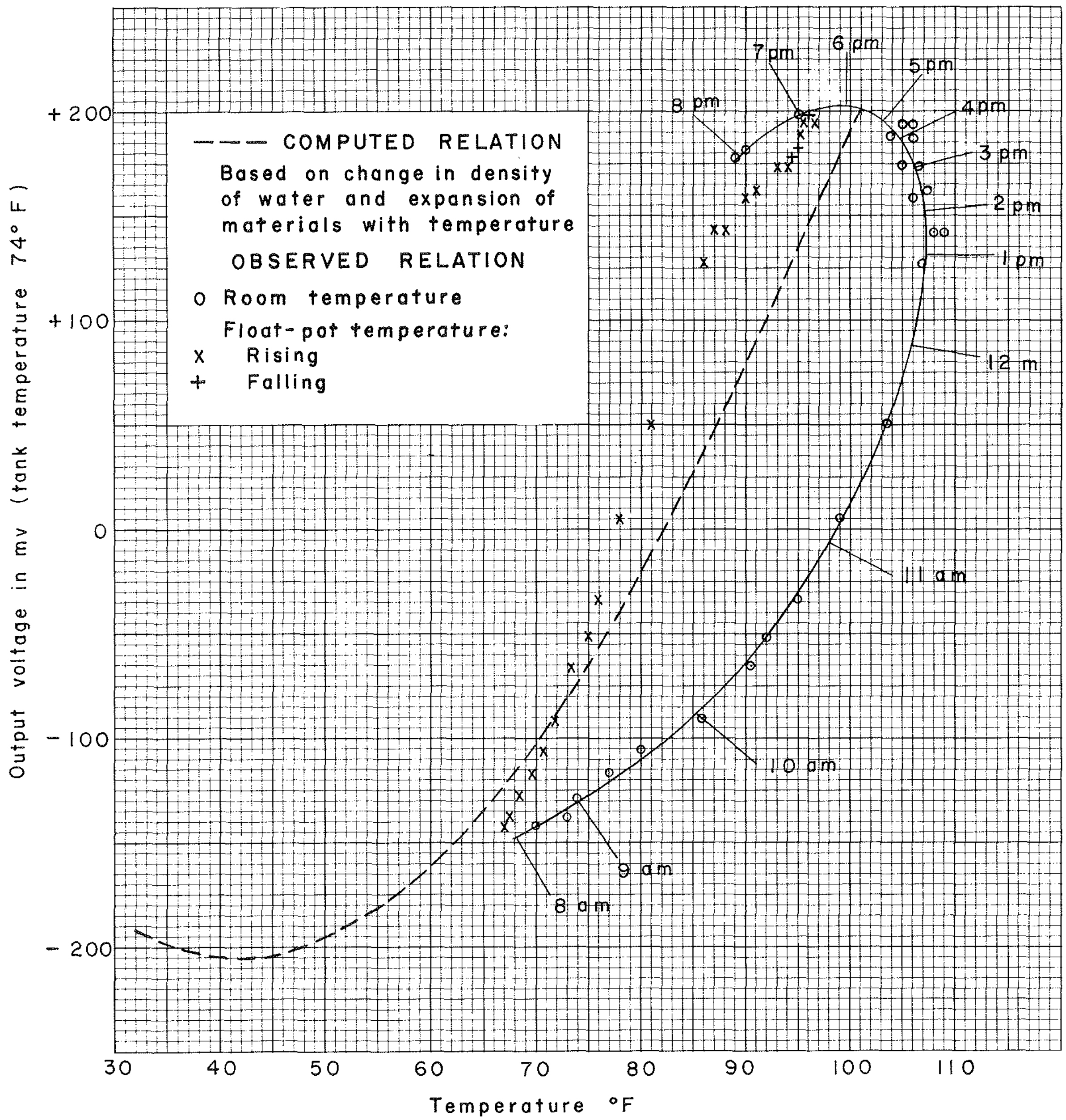

FIG. 10 — RELATION OF TEMPERATURE OF THE FDT MANOMETER AND OUTPUT VOLTAGE

(JUNE 19, 1959)

measured. For other uses, i.e., measuring a water surface slope, it would be possible to place the two orifices (and the two manometer pots) at approximately the same elevation and eliminate most of the effects of thermal expansion.

21. Tests of the effects of variations in tank temperature--During the period February 21 to March 1, 1959 a series of readings of tank temperature and output voltage of the FDT gage were made. Distilled water was the fluid in both tank and manometer. The temperature of the manometer was held as nearly constant at 70° F as possible and when minor deviations occurred the output voltage was corrected using corrections of about 7 mv per degree, as shown in Fig. 10, for deviations from 70° F.

The orifice spacing in the plexiglas tank was 0.703 ft at 79° F and the water was 1.9 to 2.8 ft deep in the tank. The plexiglas tank was placed in a box and surrounded by 3 in. of vermiculite for temperature insulation. Water was removed from the tank and distilled-water ice, cold distilled water, or hot distilled water was added as needed to vary the tank temperature. The tank temperature was measured above the top orifice, below the bottom orifice, and sometimes at the middle if an additional reading seemed necessary.

In Fig. 9, the first readings for each day were those found after the equipment had been undisturbed overnight. Solid lines connect readings under adjustment from the addition of hot or cold distilled water or distilled-water ice. Dotted lines indicate the effect of ambient temperature only. Numerals and arrowheads indicate time in minutes between readings and the direction in which time is changing.

In general the data substantiate the computed curve. Changes from reading to reading generally plotted parallel to the curve except for lag when the tank temperature varied rapidly. Data of February 21, 24, 25, 28, and March 1 clearly show the lag in output voltage when tank temperature was changing rapidly. Although there may be delays in temperature adjustment of the tank fluid and walls the effects of such delays are relatively small. The main delay is in the manometer response which is slow because of the small size of the tube connecting the two manometer pots. The tube could be made larger to hasten the response to pressure changes.

If the lag in voltage response is disregarded some of the more general relations of temperature and voltage output can be seen. Data for February 21 and part of February 22 seem to follow the computed curve reasonably well. (The morning reading on February 22 is probably high because the room temperature was rising rapidly and the manometer correction may not be accurate.) When the tank was cooled below the maximum density point of 39° F there was some tendency for the top of the tank to be cooler than the bottom. Probably some moisture condensed in the top gas line where it passed through the insulated area near the tank and gave low output readings. Overnight, and on February 23, the temperature in the tank became more uniform. Early on February 23 the output readings began to rise rapidly and inspection showed that water had condensed in both gas lines but there was more in the lower one. The tank temperature was raised and most of the water in the gas lines disappeared. Following a period of adjustment on February 23 the output readings plot below, but parallel to, the computed curve.

The rapid changes in temperature on Feb. 25 developed a loop of output lag. (See Fig. 9.) Above a tank temperature of 50° F it is normal for the output voltage to decrease as the tank temperature increases. On Feb. 25 the decrease was slower than the computed value as the tank temperature rose rapidly from 83° to 112° F. However, the output voltage continued to decrease as the tank temperature started to fall, which shows that normal equilibrium between tank temperature and output voltage had not been reached. At 100° F the tank temperature was decreasing more rapidly than the output voltage could increase, but at 98° and 97° F the rate of decrease in temperature became smaller and the relation between tank temperature and output voltage again approached the computed rate of change. There may have been a slow change in the water content of the plexiglas in the tank wall. As temperatures inside the tank insulation rose the relative humidity on the outside of the tank wall decreased and as temperatures fell the process was reversed. The magnitude of the change and the degree of lag are generally reasonable for such an effect.[10] However, the data indicate some unexplained discontinuity for the period when tank temperatures were below 40° F.

22. Tests of the effects of variations in manometer temperature--In April 1959 the apparatus described in the preceding section was moved to an uninsulated attic where temperatures varied widely (45° to 117° F). Although other operating characteristics of the FDT gage were noted during these temperature variation tests (Section 23), the main study was of the effects of variations in manometer temperature on output voltage. Because the tank was heavily insulated and because of the volume of plexiglas and water the tank temperature varied relatively slowly. The manometer was lightly insulated but its temperature varied much more rapidly.

A median tank temperature was chosen for each set of tests. Corrections to output voltages of the manometer were made for deviations from the median. Corrections per degree F were taken from Fig. 9, i.e., about 7 mv at 80° F and 5 mv at 70° F.

"Manometer" temperatures were taken at various points. For some series of tests the room temperature was taken; for some series temperature was taken next to the manometer bracket; and for all series temperatures were taken at the outside surface of the manometer pots.

After the output voltages had been corrected for variations in tank temperature the June 19, 1959 data for the relation of room temperature (outside the insulation) to the voltage output was plotted on Fig. 10. The approximate relation of time of day to readings is shown. A typical lag loop was obtained and the lag was large because the manometer was insulated. Room temperatures fluctuated rapidly during part of the afternoon.

The data of June 19, 1959 were also plotted against the temperature of the float pot of the manometer. Rising temperatures were indicated by an "x" and falling temperatures by a "+". The effect of thermal expansion is mainly in the water column in the small tube connecting the manometer pots. The temperature of the pots is relatively insignificant. Because no temperature was taken near the tube the best approximation is that at the float pot at the top of the tube. In the early morning, voltages were lower than for the computed curve but they increased rapidly and in the afternoon they were higher than the curve. The voltage response appeared to lead the temperature. Actually the float-pot temperature lagged the room temperature by an amount greater than that by which the manometer lagged the room temperature. Although the room temperature receded from the peak and the float-pot temperature and voltage output also started downward, the voltage readings did not cross the computed curve. The maximum room temperature was about 109° F at 1:30 pm; the maximum "effective" manometer temperature was about 101° F at 5:30 pm; the maximum float-pot temperature was probably about 96° F sometime between 5 and 7 pm (because the float pot temperature may be at a point on a temperature gradient it could start to fall slightly before the room temperature dropped to 96° F). If the "effective" manometer temperature is defined as the manometer temperature that would give the voltage output under steady temperature conditions, the effective temperature will fall more rapidly from 101° F than the float-pot temperature falls from 96° F and the two will be equal at perhaps 10 pm. Similarly the early morning voltages plotted low because the effective temperature, although rising faster, was still below the float-pot temperature.

The observed temperatures in degrees F varied as follows on June 19, 1959: room 70 to 109, float-pot 67 to 96, tank 74 to 80.

The test data show the general correctness of the computed curve of

Fig. 10. The data is consistent but because the effective temperature was not better determined the test relation of temperature and output voltage is rather indirect.

23. Other characteristics of FDT bubbler gage--Variable amounts of the manometer fluid condensed on the top surface of the manometer pots when the plexiglas surfaces cooled more rapidly than the water. During the tests the condensation was somewhat difficult to observe without disturbing the insulation about the manometer. With water as the manometer fluid minor errors of FDT gage reading are to be expected when the temperatures are changing at the manometer.

The FDT gage and other equipment were mounted on an unstable floor. On successive days (latter part of June) uneven settling changed the vertical alignment of the manometer and readings lagged, because of added friction on the float stem. (The float pot must be level for smooth operation and maximum accuracy.)

Surface tension often caused errors when attempts were made to measure very small differential pressures. Transient errors from surface tension were also caused by lag in wetting of surfaces in the manometer.

Prolonged high temperatures affect the differential transformer and such instruments as the audio oscillator and voltmeter used in the FDT gage. Minor variations in the primary voltages to the transformer also caused errors. (See Section 29.) The properties of the plexiglas introduce additional errors when the temperature varies. Plexiglas can expand or contract as it gains or loses water because of a moisture gradient. In addition, with a humidity or temperature gradient across a plexiglas panel, bowing can take place so that the geometry of the manometer parts is changed.

V. BEHAVIOR OF DIFFERENTIAL-PRESSURE GAGES MEASURING PRESSURES IN FLOWING WATER

24. Bellows differential-pressure gage--After calibration under static conditions the bellows was also connected by way of 3-way stopcocks to pressure taps in the side of a contracted section of a 12-in. recirculating flume. Fine sand was on the flume bed. A number of tests were made by varying vertical and horizontal tap spacings, speed and geometry of the flow, and bed conditions. In almost all cases the pressure differences from other causes were greater than those caused by a change of sediment concentration. If one of the water columns was disconnected from the flume and exposed to the atmosphere, the other tap transmitted pressure changes caused by changes in water elevation.

Sand waves on the bottom, surface waves, or an obstruction on either surface or bottom affected the pressure at the pressure taps. Pressure effects varied with velocity, size of obstruction, and distance from obstruction to pressure tap. The bellows reacted quickly to large pressure changes, but the initial reaction was only approximate.

When the connections were switched from the flume taps to the plexiglas tank taps, the output voltage readings were not consistent within 5 to 10 mv. With a tap spacing of 0.5 ft, 10 mv represented a pressure equal to about 6000 ppm of sediment, which was far more than the sediment concentration in the flume.

Over a distance of 5 ft in the uniformly contracted section a horizontal series of 5 pressure taps was installed. A second horizontal series was installed 5 in. lower with taps vertically aligned with those of the upper series. All 5 of the lower taps were connected through a manifold to the bellows and all 5 of the upper taps were connected through another manifold to the outer chamber around the bellows. The velocity in the flume was 1.9 ft/sec. As sand dunes or water-surface waves passed individual taps or if a large obstruction was placed near one of the taps, the influence of transient pressure fluctuations was much less than for a single tap at each elevation, because the indicated pressure was an average over 5 points along the flume. Over a period of 4 to 5 hours output voltage readings varied widely but an average of the readings over that time compared to readings at the beginning when material was not in suspension showed the approximate reading for the particular sediment concentration.

25. Null-balance bubbler gage--The null-balance bubbler gage was also connected to the recirculating flume. The sediment content was negligible

throughout these tests. As in other situations the null-balance bubbler gage required an excess amount of time (usually about 20 minutes, occasionally in excess of one hour) to come to equilibrium after a change of differential pressure between taps.

Under static conditions the null-balance bubbler gage is accurate to 0.002 ft of water head. A velocity of about 2 ft per second through the contracted section gave new equilibrium readings up to 0.005 ft different from those in still water.

When obstructions 2 to 4 inches high were placed in flume flow 1 ft deep (tap spacing 8 in.) the readings varied no more than 0.005 ft from static conditions. If the turbulence was made more uniform and isotropic by placing 1/2 to 1 in. mesh screens upstream from the taps the pressure difference between the taps approached that for still water.

In an extreme situation in which a metal block 2 in. high and 4 in. long was placed directly under the low pressure tap there was a reduction of 0.02 ft of differential-pressure head at a velocity of about 1.9 ft per sec and a total flow depth of 1 ft. As the velocity was reduced the pressure difference quickly approached that for still water.

Compared with the bellows gage the null-balance bubbler gage reacted more rapidly but took longer to reach equilibrium after a pressure change. Because the null-balance gage takes a long time to reach equilibrium it does not accurately show pressure changes in flowing water.

26. <u>FDT bubbler gage</u>--The FDT gage was not tested with flowing water. It was thought that the reaction of this gage to transient pressure variations would be analogous to that of the other differential-pressure gages. (See Section 17.)

VI. CONCLUSIONS AND RECOMMENDATIONS

27. Evaluations--At present the differential-pressure gages described in this report do not appear to be adaptable to measuring suspended sediment in streams. They may be usable for determining sediment concentration and size distribution under laboratory conditions that are carefully controlled. The differential-pressure null-balance bubbler gage was developed to determine stream slopes. Its accuracy is probably adequate for such determinations.

Bubbler gages somewhat similar to the differential-pressure null-balance gages are widely used for determining water surface elevations.

To determine sediment concentrations in moving water differential-pressure transducers would have to determine very accurate average pressure differences between two elevations in the moving water. Special and transient variations of pressures from turbulence, bed roughness and surface irregularities would have to be damped out or compensated. For measuring suspended sediments in either moving or stationary liquid the response time of the pressure transducers should be reduced. An improvement in the stability and consistency of differential-pressure transducer readings would be desirable, especially for the bellows differential-pressure gage. Further investigation of possible adaptation to the determination of small pressure differences in the laboratory is recommended to those who might have the need for such an instrument.

28. Suggestions for improvements--Several specific modifications in the pressure-differential gages might improve the equipment.

A. General

1. In flowing water the average differential pressure between two elevations is difficult to determine. Pressures between single taps vary rapidly. Five inter-connected taps, horizontally distributed, at each elevation gave better average readings. Perhaps a narrow horizontal strip of porous material at each elevation would average and damp out the variable pressures to even better advantage.

2. Materials for differential-pressure transducers should be selected and the parts designed to minimize temperature and humidity effects. The reduction of temperature and humidity effects is probably the greatest opportunity for improving the accuracy of the pressure transducers.

B. Bellows differential-pressure gage

1. The water-proofing of the transformer was not entirely satisfactory and should be improved if possible.

2. A gentle high frequency vibration might be applied to the differential-pressure bellows and/or transformer to eliminate mechanical hysteresis. This could be done, for example, by attaching a small motor with an eccentric shaft to a water bath tank surrounding the bellows.[20]

C. Null-balance bubbler gage

1. Refinements in the switch and in the recording mechanism could be made to improve the accuracy somewhat.

D. FDT bubbler gage

Because the FDT gage is inherently more sensitive than the others greater refinement in construction and operation is required to obtain optimum results.

1. The use of a dry gas is essential to avoid condensation difficulties. When the fluid in the sight jars and manometer has a low vapor pressure condensation in the gas lines is reduced.

2. If manometer pots larger than those tested were used some surface tension effects might be avoided.

3. A larger tube connecting the manometer pots would speed up the reaction to pressure changes.

4. Frictional resistance to movement in the float stem should be reduced if possible.

5. Better control of gas flow rates would help avoid some minor errors.

6. Regardless of possible improvements in the FDT gage system, precautions are necessary if high accuracy is to be obtained: The transformer and electrical system must be water-proofed and maintained in top condition; gas leaks must be avoided; and the temperature of the manometer and electrical system must be held fairly constant.

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VII. APPENDIX A

CHARACTERISTICS OF EQUIPMENT

29. Characteristics of the differential transformer and electrical system--Calibration of the differential transformer in terms of displacement by a screw attachment for the transformer core was not as satisfactory as calibration with the transformer in the equipment.

A constant voltage transformer was necessary to limit the drift in the primary voltage. Without this voltage control and adequate shielding for the wires there was excessive drift in primary voltage, and the secondary voltage at the null point was too high. The capacitance of switches or of plugs that brought primary and secondary wiring close together also caused drift and high null voltages.

The approximately linear relation of primary and secondary voltages is shown by Table 1.

TABLE 1

VARIATION OF SECONDARY VOLTAGE AS PRIMARY VOLTAGE CHANGES

Primary Voltage (volts)	Secondary Voltage (millivolts)
2.0	320
2.5	390
3.0	460
3.5	530
4.0	600

The voltmeter used to record secondary voltage was accurate to ± 2% of the full scale reading but it was consistent to finer accuracy with itself. Table 2 shows the reading accuracy on each voltmeter scale in terms of the concentration of suspended sediment of specific gravity 2.65 that would correspond to the pressure accuracy with a tap spacing of 1 ft.

TABLE 2

ACCURACY OF READINGS OF SECONDARY VOLTAGE

Reading scale	$\pm$ 2% of scale (mv)	Reading accuracy (mv)	Bellows gage (ppm)	FDT gage (ppm)
3 mv	0.06	0.1	30	1.7
10 mv	0.20	0.2	60	3.5
30 mv	0.60	0.5	150	8.7
100 mv	2.0	2.0	600	35
300 mv	6.0	5.0	1,500	87
1,000 mv	20	20	6,000	350

The 0.005 M-L linear-variable differential transformer had the following characteristics:

Excitation voltage	-	3 volts
Excitation frequency	-	20,000 cycles per sec
Output load	-	0.5 milliohms
Linear range	-	$\pm$ 0.005 in.
Null voltage	-	1 mv
Maximum output voltage	-	70 mv

In the vicinity of the null point the output voltage varied about 1 mv for each 0.000079 in. of core displacement.

Temperature may change the electrical characteristics of the transformer sufficiently to vary the output voltage significantly.

30. The bellows gage--Manufacturer's specifications of the bellows are:

Diameter	-	4.5 in.
Movement	-	1.29 in. for each lb per sq in.
Convolutions	-	10
Effective area	-	10.45 sq in.
Rated pressure	-	15 lbs per sq in.
Free length per convolution	-	0.298 in.

The output voltage at the null point varied from 0.06 mv to 0.60 mv after a satisfactory wiring circuit was established.

The bellows gage equipped with the linear-variable transformer and calibrated with a 2 ft orifice spacing showed an approximate relationship of 160 ppm per mv for a 2 ft spacing of the orifices or about 320 ppm per mv for a 1 ft orifice spacing. The concentrations given in ppm are the concentrations of sediment of specific gravity 2.65 that would correspond to the pressure differences in the tank.

The bellows deflection was about 1.15 in. per psi instead of the 1.29 in. per psi of pressure difference suggested by the manufacturer.

VIII. APPENDIX B

OTHER TYPES OF PRESSURE GAGES

31. Introduction--Two pressure sensing devices of different types that have been reported are summarized in the following sections. Devices were selected that are unique and interesting even though their accuracy or adaptability do not make them immediately usable on project problems.

32. Bellows pressure recorder--An interesting bellows pressure recorder was reported by T. O'Donnel, D. H. Edwards, N. Collis-George, and E. G. Youngs[9]. They used a bellows installed in a brass chamber and separated from external water by a sintered glass filter (Fig. 11). The interior of the bellows was subjected to varying air pressure that was recorded elsewhere. When the air pressure inside the bellows was equal to or less than the liquid pressure, platinum-iridium contacts completed an electrical circuit. When the air pressure exceeded external water pressure by a small given amount, the contacts separated and the corresponding time and pressure were recorded on a moving chart.

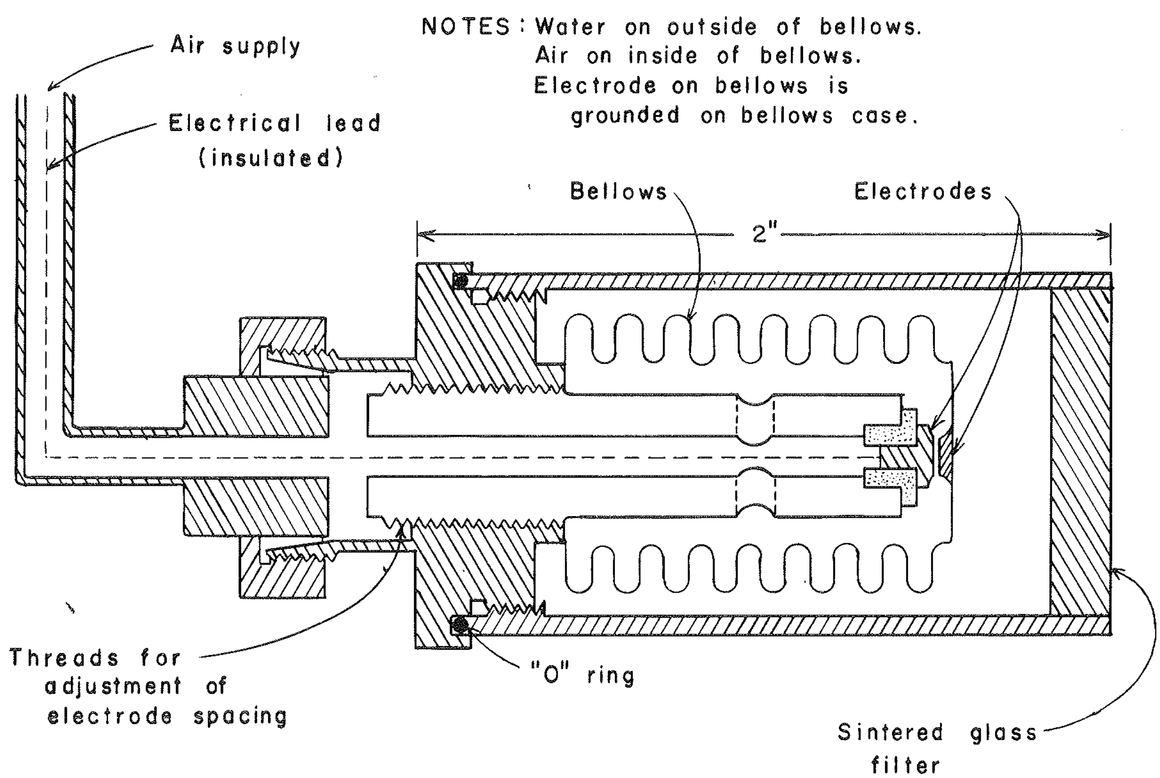

FIG. 11 -- BELLOWS PRESSURE RECORDER

The device permits remote recording of water pressures in soils. It is accurate to perhaps 0.5 cm of water head.

33. Tilting-mirror differential-pressure gage--An extremely sensitive mirror device for determining small pressure differences was developed by R. Eichorn and T. F. Irvine, Jr.[3] of the Mechanical Engineering Department of the University of Minnesota. The instrument was sensitive to differential pressures as low as 0.000032 in. of water head. Concentric glass tubes formed the fluid columns of a manometer. The water level in the central tube could be determined accurately by means of a mirror mounted on a float, a directional mirror, a telescope, and a scale. (See schematic sketch, Fig. 12.)

Significant items in construction and operation of the micromanometer are:

1. Temperature control is very important.

2. The float is sensitive to vibrations.

3. Large liquid surface areas are required to minimize surface tension effects.

4. A special hydraulic oil was required for the manometer liquid.

5. Pressure fluctuations were reduced by placing a length of capillary tubing in the air pressure lines.

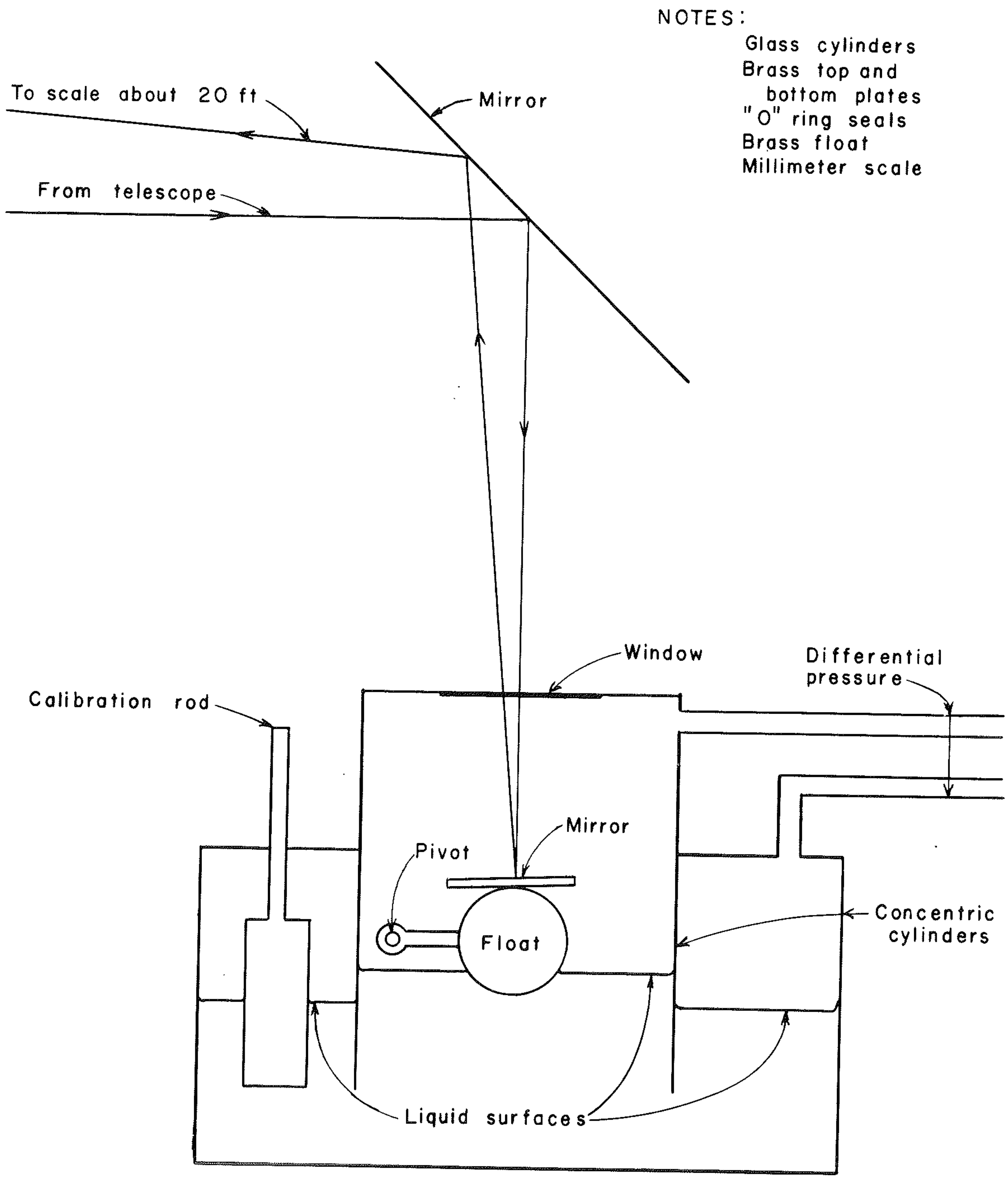

FIG. 12 -- TILTING MIRROR DIFFERENTIAL PRESSURE GAGE