A STUDY OF METHODS USED IN

MEASUREMENT AND ANALYSIS OF SEDIMENT LOADS IN STREAMS

FEDERAL INTER-AGENCY SEDIMENTATION PROJECT

REPORT DD

PROGRESS REPORT: PERFORMANCE OF THE VIBRATING U-TUBE FLUID-DENSITY GAGE FOR MEASURING SUSPENDED-SEDIMENT CONCENTRATION

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U-TUBE FLUID-DENSITY GAGE FOR MEASURING
SUSPENDED-SEDIMENT CONCENTRATION

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PROGRESS REPORT: PERFORMANCE OF THE VIBRATING U-TUBE FLUID-DENSITY GAGE FOR MEASURING SUSPENDED-SEDIMENT CONCENTRATION

By Joseph P. Beverage

ABSTRACT

The vibrating U-tube fluid-density gage shows promise in automating the measurement of suspended-sediment concentration. A previous report (Skinner and Beverage, 1982) described the application of the U-tube for measuring suspended-sediment concentration and its response to several parameters. In that study, the U-tube was suspended in the horizontal plane. This report summarizes further testing of the fluid-density gage suggested by the earlier work.

The gage may be operated with the U-tube in the upright vertical position to increase sensitivity at low sediment concentrations by stopping the flow and letting the sediment settle to the bottom. Sediment with a particle-size range of 62 to 1000 micrometers was tested, and the sensitivity of the instrument increased by a factor of five.

The condensation of humidity within the case housing the U-tube was proved to be the cause of scattered readings at water temperatures below 12°C. The gage response is linear with case pressure.

An improved reference oscillator was tested and shown to be satisfactory at ambient temperatures from 15 to 35°C. The reference frequency was increased to 20 kHz from the 12.8 kHz of the earlier studies.

INTRODUCTION

Sensing devices often respond to undesired factors and the vibrating U-tube fluid-density device (see figure 1) is no exception. In the first report on this instrument, Skinner and Beverage (1982) described the use of the device for measuring suspended-sediment concentration and its response to several factors. The most important of these were floor vibration and the temperatures of the pumped fluid, the case housing the U-tube, and the ambient air. Suspending the case with heavy springs minimized sensitivity to vibration; wrapping the case in insulation reduced the effect of case and air temperature on the reading. Skinner and Beverage reported on the minor effects due to variations in sediment particle size and flow rate. They also studied transient response to changes in fluid temperature and sediment concentration. All of the studies given in the report were made with the U-tube suspended horizontally.

This report summarizes further testing of the fluid-density gage subsequent to the work by Skinner and Beverage (1982). The studies were undertaken to validate assumptions regarding the performance of the mechanism and to determine the value of circuit modifications.

Fluid density is directly proportional to the vibrational period of the U-tube. The device counts the number of cycles of a stable reference oscillator during 18,430 U-tube vibrational cycles. The number of reference oscillator cycles counted is directly proportional to the vibrational period of the U-tube and, thus, to the density of the fluid in the tube.

Skinner and Beverage called the number of reference oscillator cycles the "cumulative count," and the difference between the cumulative count of a sample and the cumulative count of a reference liquid was called simply "count." In this report, the term "count" refers to the raw or cumulative count (including a raw count less any convenient arbitrary constant). The term "net count" refers to a difference between counts, that is, a raw count less the count of a reference liquid or the same liquid at a reference temperature.

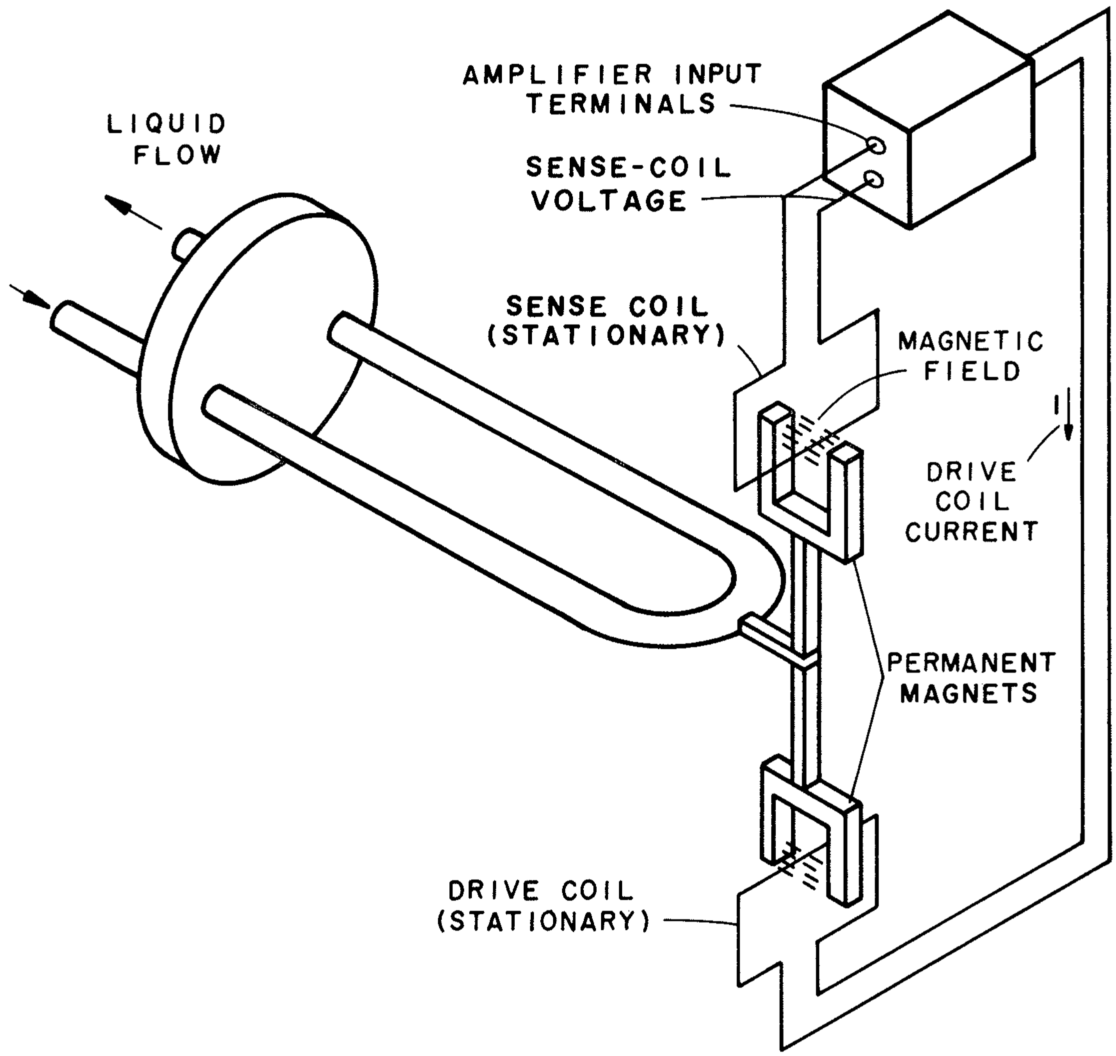

Figure 1.--Drawing of U-tube showing relation between components (from Skinner and Beverage, 1982).

HUMIDITY WITHIN THE CASE

The vibrating U-tube, fluid density gage is encased in a welded pipe 20 cm (centimeters) in diameter and about 60 cm long. The device is sealed with atmospheric air at the factory.

During their discussion of the effects of temperature, Skinner and Beverage (1982) noted the scatter and non-reproducibility of counts at fluid temperatures below 10°C. The counts were scattered between two envelope curves. They postulated that moisture in the air inside the case was condensing on the tube as it cooled. The count scatter then could be attributed to shaking some of the condensed moisture from the tube as it vibrated.

This condensation hypothesis was tested by evacuating the moist air in the case and refilling with dry air at atmospheric pressure. The case was drilled and tapped near the inlet and outlet ports. A vacuum gage and gas valve were installed. A small vacuum pump reduced the pressure in the case by 88 kPa (kilopascals), equivalent to 26 inches of mercury. A cannister of silica gel was attached to the valve, which was then opened to allow dry air to enter the U-tube's case. After a few minutes the valve was closed and the cannister was removed. A series of readings at various water temperatures was obtained with dry air. These results are shown in figure 2 as open squares. The open squares clustered around 4°C represent data collected over several days, which accounts for the greater apparent scatter of the "dry" data. The open circles are data obtained later with moist (Minnesota) air. At temperatures above about 12°C the two curves are essentially the same. Below 12°C the dry air curve drops rapidly, while the moist air curve is almost flat. Earlier tests (Skinner and Beverage, 1982) showed a great deal of scatter in the readings below 12°C for moist air. The points scattered downward from the "moist" curve of figure 2. The divergence of the two curves confirms the notion of condensation of moisture from the original air in the case.

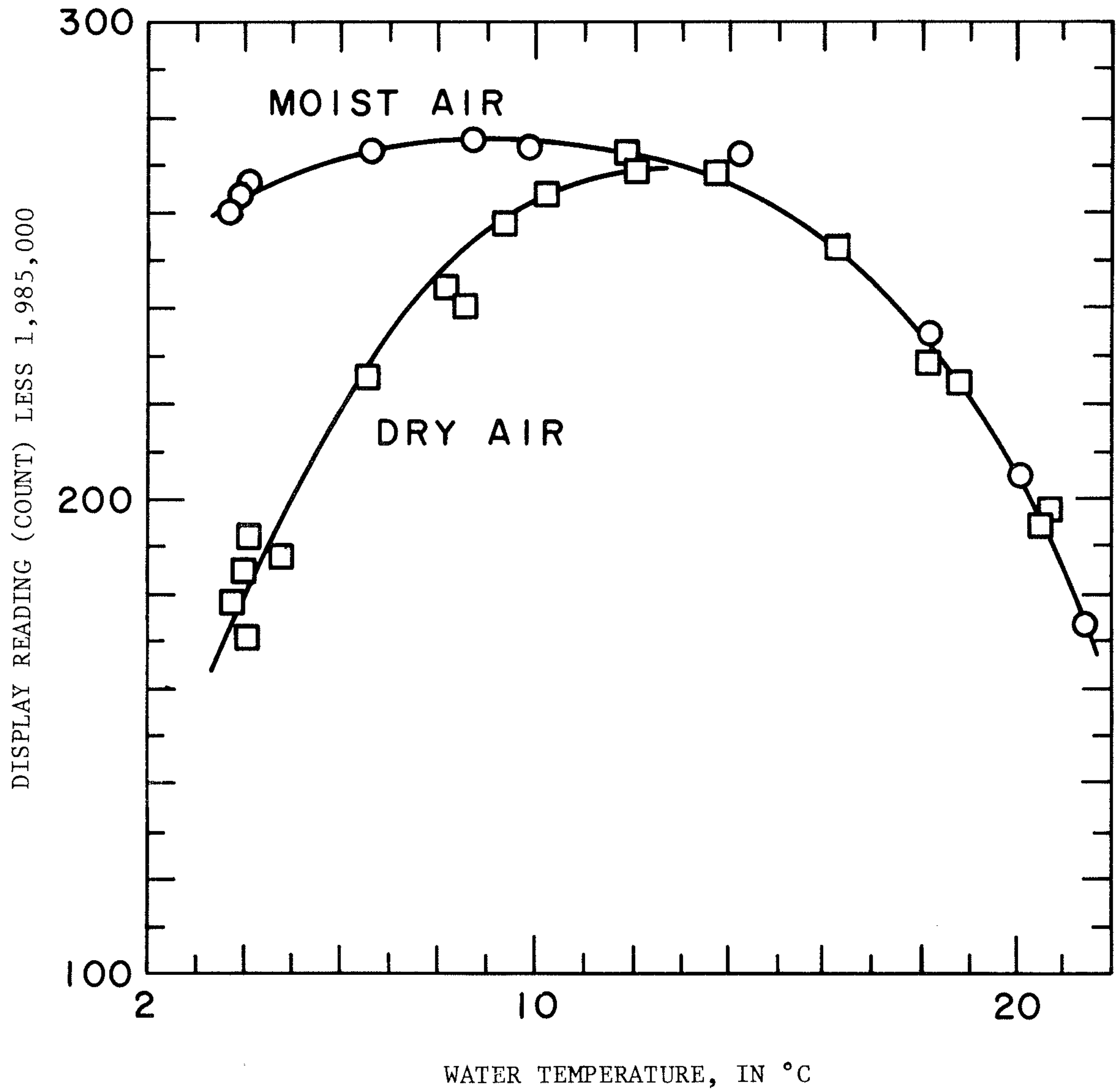

Figure 2.--Graph showing relation between count and water temperature for moist room air (circles) and for dried room air (squares) at atmospheric pressure within the case.

VARIATION WITH CASE PRESSURE

One would think that the air within the case would restrict the movement of the vibrating tube. The more air present, the greater the interference and the longer the measured average period. Having a pressure tap in the case permitted a test of the variation of the count with the pressure of air within the case.

The procedure followed was to reduce case pressure by 88 kPa, then circulate through the U-tube water which is maintained within 0.1°C of the desired temperature. The water was circulated for 15 minutes so that all parts of the device were at nearly the same temperature. Then three successive counts of the constant-temperature flow were obtained. Next a column of dry silica gel was attached to the gas valve fitting and the valve was opened slightly. When the case vacuum reached kPa, the valve was closed. Three more readings were obtained at the same temperature before repeating the valve operation. In like manner, readings were obtained at case vacuums of 51, 34, 17, and 0 (atmospheric pressure) kPa at the same water temperature. The water temperature was then lowered 5 to 6°C and the entire operation repeated.

The data are summarized in figure 3. The curves show a strong family resemblence to the "dry" curve of figure 2. The systematic shifting of the curves with regular changes in case pressure indicates that data obtained with positive pressures would show similar regular shifts. Data were not collected with positive pressures, however, because of the lubricating oil in the pump's exhaust (pressurized) air. Regardless, the regularity of the shifting of the curves with vacuum led to the plotting of the data in figure 4. The differential counts are plotted for the range of pressures and for two temperatures, 4 and 21°C. A very regular shift with change in pressure is indicated by the plot. Each additional kilopascal of vacuum lowers the count by about 4.5.

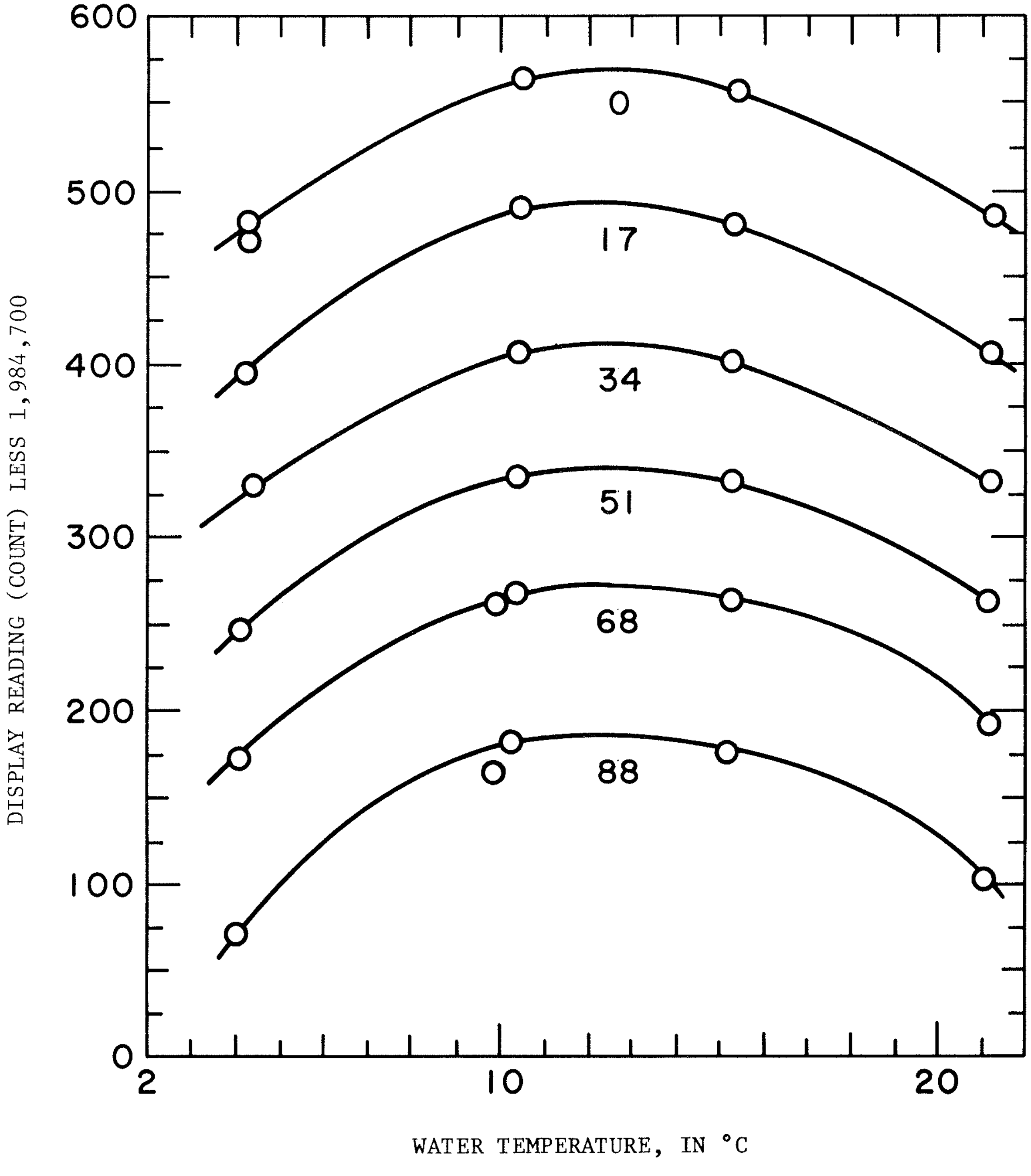

Figure 3.--Graph showing relation between count and water temperature for different case pressures. The number at the peak of each curve is the vacuum gage pressure, in kilopascals. Atmospheric pressure is shown as 0 kPa.

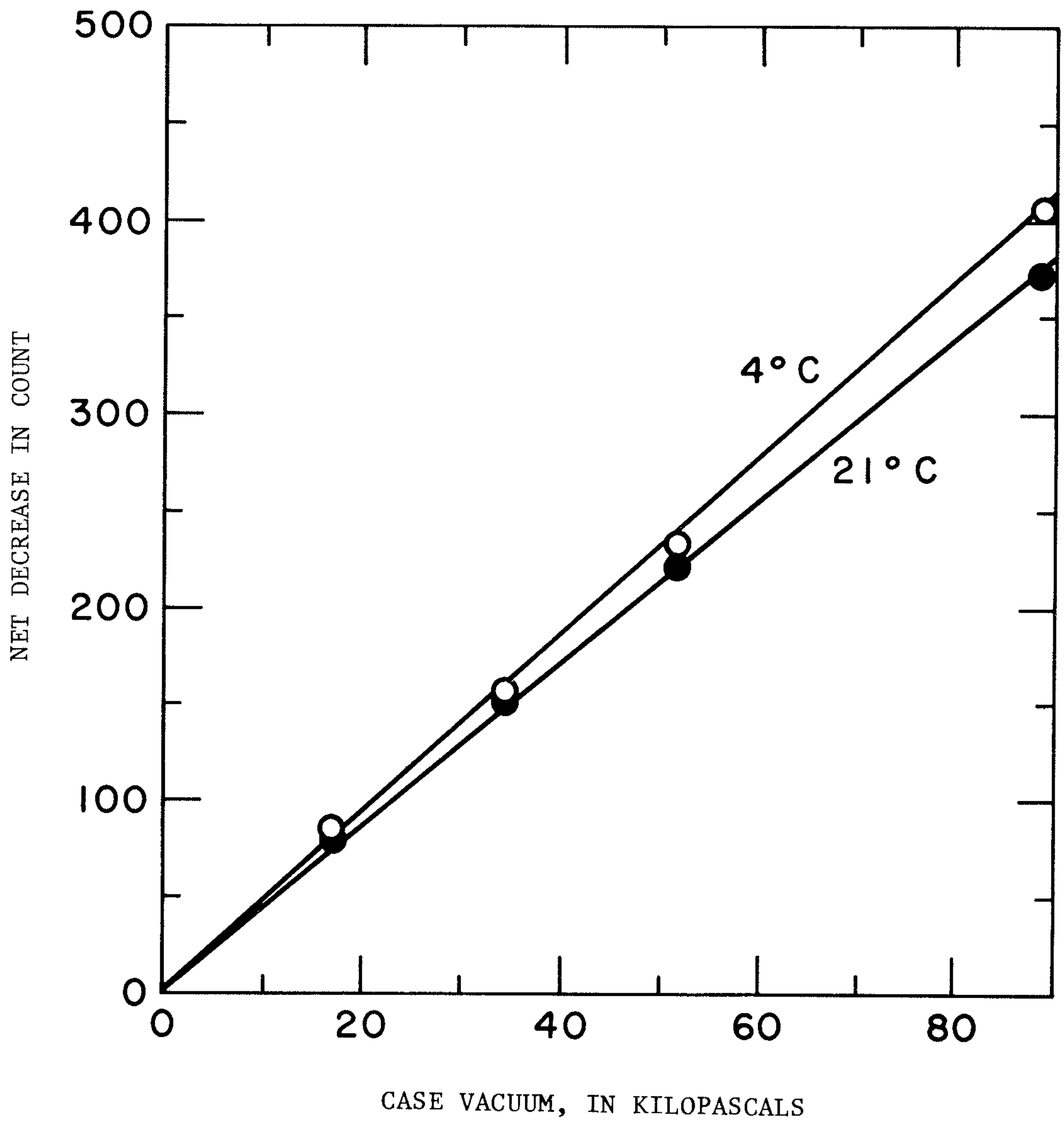

Figure 4.--Graph showing relation between net count decrease and case vacuum for two water temperatures. Data points are from fig. 2.

OPERATION IN THE VERTICAL POSITION

The vibrating U-tube normally is operated in the horizontal position; that is, the U is in the horizontal plane. Three other positions are possible: 1) a lazy position with the U on its side and one port inlet or outlet above the other; 2) with the U as in the normal printed position--inlet and outlet ports above and the curved part of the tube below; and 3) with the U inverted--inlet and outlet ports below and the curved part uppermost. The lazy-U position offers no advantages in operation. The inverted-U position lets the coarse suspended materials settle away from the sensing zone when the flow is stopped. This allows the operator to obtain a "clear water" measurement at regular intervals. On the other hand, air bubbles must be eliminated from the flow or they will cause errors.

Operating the U-tube in the other vertical position, upright, as on a printed page, with the inlet and outlet ports up makes the instrument very sensitive to sediment which settles to the bottom of the tube if the flow is stopped. One possible benefit would be to measure very low concentrations of coarse particles. Another possibility is to use the instrument to determine particle-size distribution by recording the increase in count with time, as the particles settle to the bottom of the tube.

Two questions are raised when operating in the upright-U position, however. The first question concerns the flow rate needed to insure that coarse particles do not settle in the tube during operation. At an insufficient flow rate, the particles will not leave the tube as frequently as they enter. This will cause an increase in concentration. Skinner and Beverage (1982) concluded that, for the horizontal position, a flow rate in excess of 85 mL/s (milliliters per second) would produce less scatter in the counts than at lower flow rates. In the vertical position, tests conducted at 113 mL/s, (the highest flow rate) gave satisfactory results.

The second question regarding the vertical position concerns possible particle-size effects, such as segregation or re-entrainment due to the vibrating tube. To test this possibility, small amounts of pre-weighed sediment from six narrowly sieved size ranges, from 62 to 1000 μm (micrometers), were added to the U-tube. The tube previously had been filled with distilled water and allowed to come to room temperature overnight. The sample of sediment was added to the tube and allowed to settle three to five minutes. Counts were then taken until at least three consecutive counts were within a couple of units of each other, the normal scatter. These consecutive counts were averaged and the base count, taken with only distilled water before the test, was subtracted. Three separate tests are shown plotted in figure 5 against the total added sediment mass. The first and second, respectively, are for sediment in the 833 to 1000 μm and 420 to 500 μm ranges. Both were conducted at a temperature of 24.7°C. The third test was at a later date when the temperature was 23.8°C. At that time sediment was added in four ranges: 210 to 250 μm, 115 to 125 μm, and 62 to 88 μm.

The data for fine material in figure 5 plots slightly lower than data for coarse material. The difference is too small, however, to conclude that segregation or re-entrainment took place. Temperature did not appear to be a factor because the data for coarser particles in the third test plot over the data for the first two tests.

The sensitivity of the instrument increased by a factor of about five due to settling to the bottom of the vertically mounted tube. The factors, which ranged from 4.8 to 6.3, were calculated by dividing the count from figure 5 at 1.00 g mass by the count estimated from regression equations for the U-tube in a horizontal position (table A-1, Skinner and Beverage, 1982). The triangular point in the lower right of figure 5 is the mean estimated count for 1.00 g mass computed from table A-1 for pumped mixtures.

REFERENCE OSCILLATOR STABILITY

A very stable frequency is the primary requirement of the reference oscillator. Oscillating at an exact frequency is not a requirement, as long as the selected frequency is very stable. The frequency should be high enough to allow division of the U-tube's vibrational period into a sufficient number of parts for the required accuracy. The earlier report (Skinner and Beverage, 1982) described a 12.8 kHz reference oscillator which oscillates at about 108 times the U-tube's frequency.

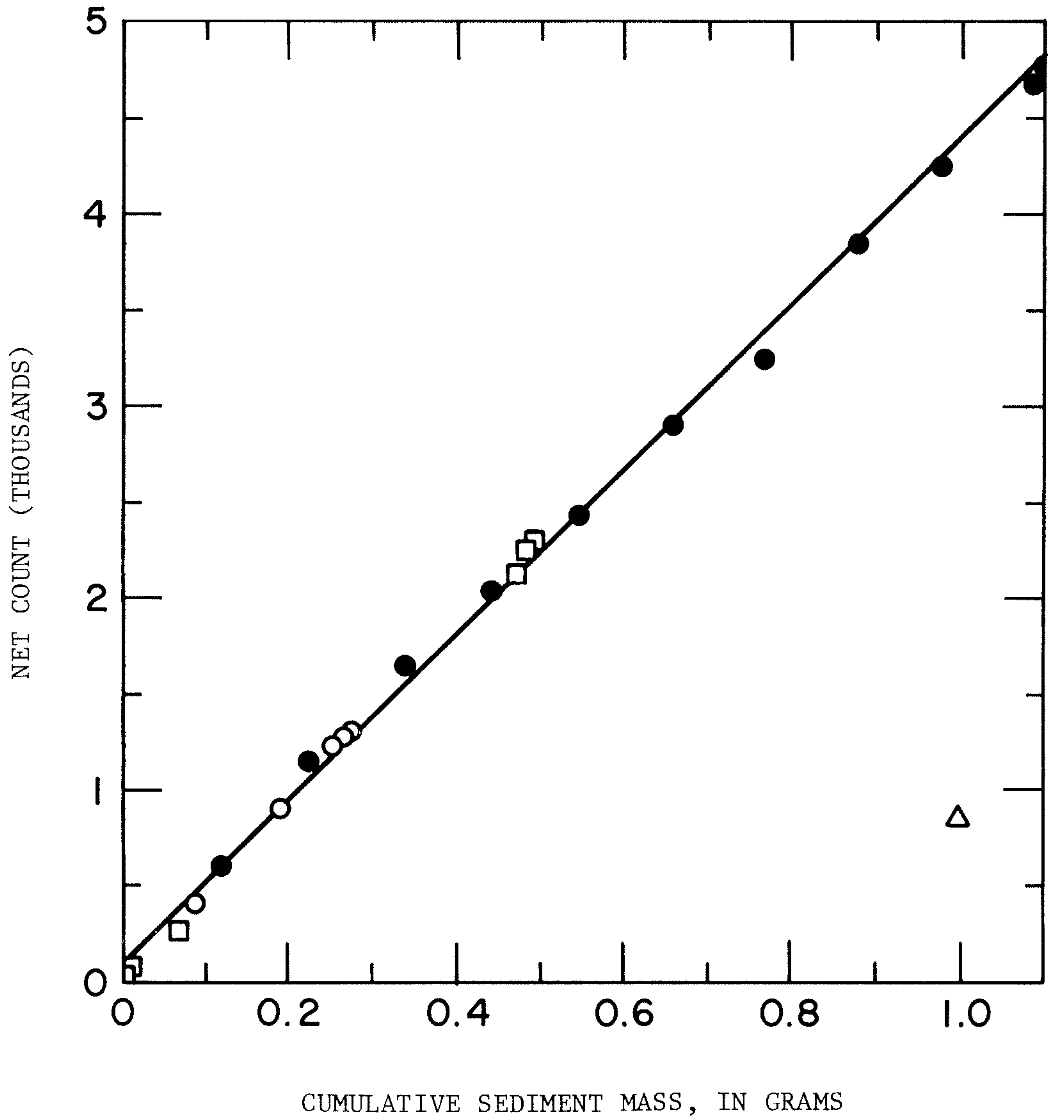

Figure 5.--Graph showing relation between net count (count with sediment less the distilled-water count) and cumulative sediment mass. The water stood quietly in the upright U-tube at ambient temperature. Data from three tests are shown. The squares are for sediment sieved to 833 to 1000 μm (micrometers) and the open circles for 420 to 500 μm. The solid circles are for four sizes: 210 to 250, 115 to 125, 88 to 105, and 62-88 μm added in that order. The solid line was computed by least squares. The triangular point represents the mean estimated count for 1.009 grams computed from Skinner and Beverage (1982, table A-1) for the horizontal position and pumped mixtures.

The 12.8 kHz oscillator operated inside an oven heated by 115-Vac power. The heater in the oven was switched on and off with a snap-action thermostatic switch having a hysteresis of several degrees Celsius. The switching action occasionally caused electrical interference which was picked up by the counters and gave erroneous counts. The hysteresis in the thermostatic switch produced a rising and falling oscillator frequency. The frequency swing, which was about half a part per million, was barely below detection by the output counter, but might well add with another effect to change the count.

For these reasons (electrical interference and hysteresis), a more stable oscillator-oven combination was chosen for upgrading the circuitry: a commercial temperature-compensated crystal oscillator (TCXO) with a frequency stability of 0.55 parts per million within the temperature range of 25 to 35°C. Additional stability was obtained by wrapping the oscillator with one-sixteenth-inch aluminum heated to 33°C by an electronic feedback circuit, and with the entire unit also wrapped in insulation. Also, a high frequency of 20 kHz was chosen for the TCXO. Higher frequency improves the sensitivity of the instrument, but does not necessarily improve the accuracy. In the present case, however, there is an input frequency limit of 25 kHz for the display counter. The selection of 20 kHz for the TCXO is thus a compromise with existing hardware specifications. As it is, the TCXO oscillates about 169 times for each cycle of the U-tube. This works out to each count being equal to about 7 milligrams per liter.

How much stability is required? A working definition should be in terms related to the output measurement: less than one count change between recalibrations of the U-tube. The most likely control scheme will require recalibration (determination of the "zero" count for sediment-free water) about every three hours. During an eight-day test the TCXO frequency drifted 0.0049 Hz, which was equivalent to about 0.39 counts. The maximum drift in any three-hour period was far less than this figure.

The eight-day test was carried out in a room with little change in temperature. To test the effect of temperature, heated air was blown around the electronic circuitry. The heat was removed after half an hour. The temperature of the oscillator rose above 33°C, causing the frequency to drift 0.0066 Hz, which was equivalent to about 1.0 count. More than two hours was required to return to a normal count. Although temperatures exceeding 33°C are likely to be found in a field situation, a rapid increase of 15°C or more in the TCXO temperature in a 3-hour interval is not considered likely.

DISCUSSION

The inverted-U shape of the "dry" curve in figure 2 raises the question of operating the device over the full temperature range. The possible problem arises because a given count does not uniquely relate to a single temperature. The density of pure water at the measurement temperature must be known so that it may be subtracted from the river-water measurement to obtain the estimate of sediment concentration. Two methods offer solutions. The simplest method is to measure the temperature of the river water. The measurement should be accurate to 0.01°C. The other method involves repeating the measurement cycle with a reference liquid maintained at the same temperature as the river water. A conservatively designed instrument should employ both methods.

The vibrating U-tube is welded into a steel case. The properties of the air trapped inside the case affects the calibration of the unit. Humidity, of course, is obvious. More subtle effects would include temperature-dependent properties such as viscosity. The air density would change only as the case volume itself changed because of temperature changes. If these effects seem inconsequential, the reader is reminded that the desired measurement increment is very small also. Indeed, secondary effects loom quite large when one measures such small quantities. If these effects can be eliminated, minimized, or compensated, then the calibration effort is greatly reduced. Removing as much air as possible from the case should reduce some of these secondary effects.

As the air pressure within the case is lowered, there is less air mass to be moved aside by the vibrating tube and there is less drag on the tube. Meeting less resistance the tube vibrates faster. This is shown in figure 3 by a decreasing count as the vacuum increases. The influence of temperature dependent properties of air, however small, is minimized by operating the U-tube with a reasonable vacuum.

The present reference oscillator should perform acceptably well at ambient air temperatures between 15° and 35°C. The unit was not tested below 15°C, and it is possible that a more powerful heater may be needed. Suitable operation above 35°C will depend on how rapidly the temperature rises or falls, how high it rises, and how steady it remains. A TCXO may become quite sensitive to temperature outside of its specification range. If more stability or a wider operating temperature range become necessary, very stable oscillators are commercially available with outputs which are essentially independent of ambient air temperature. These oscillators are built into small ovens which use a comparatively large amount of power, 5 to 15 watts compared to the 0.56 watts of the present instrument, and are very expensive. In addition, oven-type oscillators would require a separate power supply and buffer circuits.

CONCLUSIONS

1. The condensation of humidity within the case caused the scattered readings found in earlier studies at water temperatures below 12°C. Replacing the humid air in the case with dry air at ambient pressure eliminated the scattered readings at lower temperatures.
2. The air within the case slows the vibration of the U-tube. Reducing the air pressure by one kilopascal lowers the average period about 4.5 counts.
3. Because viscosity and other properties of air are temperature dependent, future studies will use an evacuated case.
4. When operated in the upright vertical position, a flow rate of 113 mL/s is sufficient to prevent deposition of coarse sediments. Stopping the flow and letting the sediment settle increases the sensitivity of the instrument by a factor of five.
5. The reference oscillator is sufficiently stable for operation at ambient temperatures between 15° and 35°C. The unit was not tested below 15°C.

REFERENCES CITED

Skinner, J. V., and Beverage, J. P., 1982, A fluid density gage for measuring suspended-sediment concentration: Minneapolis, Minn., Interagency Advisory Comm. on Water Data, Federal Interagency Sed. Project, Rept. X.