REPORT HH PROGRESS REPORT: DESCRIPTION AND TEST OF A STRAIGHT-TUBE FLUID-DENSITY GAGE FOR MEASURING SUSPENDED-SEDIMENT CONCENTRATION IN STREAMS

A STUDY OF METHODS USED IN

MEASUREMENT AND ANALYSIS OF SEDIMENT LOADS IN STREAMS

FEDERAL INTER-AGENCY SEDIMENTATION PROJECT

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A Study of Methods Used in

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A Cooperative Project

Sponsored by the

Interagency Advisory Committee on Water Data

Subcommittee on Sedimentation

Participating Agencies

Agricultural Research Service
Corps of Engineers ** Geological Survey
Forest Service ** Bureau of Reclamation
Federal Highway Administration ** Bureau of Land Management

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PROGRESS REPORT: DESCRIPTION AND TEST OF A STRAIGHT-TUBE FLUID-DENSITY GAGE FOR MEASURING SUSPENDED-SEDIMENT CONCENTRATION IN STREAMS

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Federal Inter-Agency Sedimentation Project
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Minneapolis, Minnesota

Published by
U.S. Army Engineer District, St. Paul

1986

CONTENTS

ILLUSTRATIONS

ABBREVIATIONS AND CONVERSION FACTORS

For the use of readers who prefer to use inch-pound units, conversion factors for terms used in this report are listed below:

Multiply	By	To obtain
	Length	
millimeter (mm)	0.03937	inch (in)
meter (m)	3.281	foot (ft)
	Volume	
liter (L)	0.2642	gallon (gal)
	Flow	
meter per second	3.281	foot per second (m/s)
	Mass	
gram (g)	0.002205	pound (lb)
kilogram (kg)	2.205	pound (lb)
	Temperature	
degrees Celsius (°C)	F = 1.8° C + 32	degrees Fahrenheit (°F)
	Density	
gram per cubic centimeter (g/cm^3)	0.03613	pound per cubic inch (lb/in^3)
	Pressure	
kilopascal (kPa)	0.1450	pound per square inch (lb/in^2)

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ABSTRACT

An instrument for measuring suspended-sediment concentration in streams was designed, constructed, and tested. The instrument is designed to be suspended in a stream while flowing water passes through a tube within. The tube is vibrated and assumes a frequency dependent on the sediment concentration in the water.

Sediment in the silt and fine-sand ranges was tested. The instrument had a linear response and a sensitivity of about 770 milligrams per liter per microsecond change in period of vibration for both sediments. Tests with sugar water produced similar results.

Other significant findings are that the instrument responds nearly linearly to temperature, at the rate of 1.69 microsecond per degrees Celsius. This held true over the range of 1.0 to 40.2 degrees Celsius.

Flow through the tube decreased the vibrational period 10 microsecond per meter per second increase in flow velocity in the range of 1 to 2 meters per second.

Pressurized helium gas proved effective in transferring heat from the interior of the instrument. As a result, the instrument can adjust to temperature changes more quickly than before use of helium.

INTRODUCTION

An industrial instrument that measures fluid densities was tested for use in determining suspended-sediment concentration. Test results were presented in previous reports (Skinner and Beverage, 1982; Beverage, 1984).

The instrument, known as a density cell, has a vibrating U-shaped tube through which fluid flows. The density of the fluid affects the frequency of vibration. Frequencies, therefore, can be converted to density values. After the density cell was calibrated for sediment/water mixtures, it was installed in a shelter next to a stream. Water from the stream was pumped through the U-shaped tube, and suspended-sediment concentrations were determined. Details of this prototype installation are presented by Skinner and others (1986).

A straight-tube version of the density cell would have the advantage of being directly immersible in the stream. Because an appropriate straight-tube density cell was not available, one was designed and built. An investigation was then conducted to test the new instrument.

This paper describes the instrument and presents the results of an investigation to:

1) Determine the instrument's response to changes in fluid density and to changes in suspended-sediment concentration.

2) Determine the instrument's response to factors such as water temperature, water velocity, abrupt changes in temperature, and other influencial factors.

3) Determine the relation between the stream velocity and the velocity of the flow through the tube.

4) Improve the design of this new instrument.

DESCRIPTION OF THE INSTRUMENT

The straight-tube fluid-density gage (figure 1) is designed to be used in a stream, much as the P-61 sampler is used (Interagency Committee on Water Resources, 1963, p. 71). Unlike the P-61, however, samples are not collected. Instead, sediment-laden water flows through a tube in the center of the gage. The tube is electro-mechanically vibrated at its natural frequency, which changes according to the density of the fluid within the tube.

The tube can be considered as being a composite circular beam with both ends rigidly fixed. The outer shell of the beam is the tube itself; while the inner core is a fluid such as air, clear water, or sediment-laden water. The tube must be thin walled and light in weight in order to maximize the effect of the fluid's density. A stainless-steel tube, 25.4 millimeters in diameter and 0.51 millimeter thick, was selected for the prototype instrument.

Because the tube must be constrained rigidly at both ends during vibration, a thick steel body encases the tube (figure 1). A 914-millimeter length of pipe, 168-millimeters in diameter, with an 11-millimeter wall thickness, was used. Discs, 25.4 millimeters thick, were welded to the ends of the pipe. These end plates were drilled to support the tube positioned within the pipe. The tube was brazed to the end plates. A leak-proof hatch provides access to the electro-mechanical hardware within the instrument.

The instrument, as so far described, weighs 45 kilograms. All but one test was conducted with this configuration. The instrument's total weight, with head and fins installed, is about 77 kilograms.

The instrument is designed to contain the batteries and the electrical circuit board needed to vibrate the tube. An underwater electrical cable, connected at the aft end of the instrument, is routed along the suspension

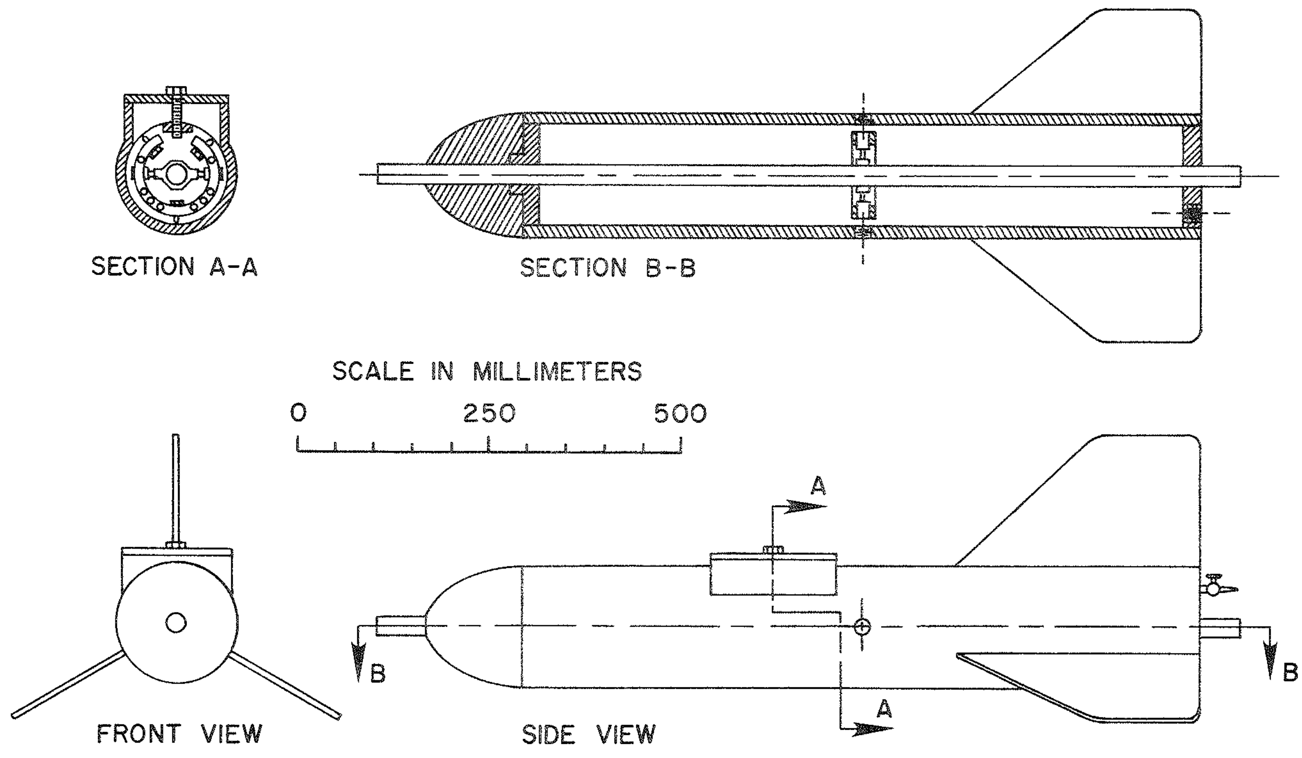

Figure 1.--Illustration of the straight-tube sediment gage.

line to the surface. The cable carries an output signal, and also allows for charging the batteries. During the tests, the internal batteries and circuit board were not installed. Instead, the circuit board and a power supply were located outside the instrument. Electronics inside the instrument were kept to a minimum; they consisted of the two solenoids, which were located at the center of the instrument, and the associated wiring. The plungers of the solenoids were replaced with rod-shaped magnets that are firmly attached to the tube (see figure 2). The solenoids are installed concentric to the magnets and are secured to a brass ring. The ring, in turn, is fastened to the body with three adjustment bolts.

The coil of one solenoid carries alternating electrical current. This causes the magnet within the solenoid to oscillate and, in turn, to vibrate the tube and the other magnet. The vibration of the second magnet generates an alternating current in the second solenoid. The induced current is then transmitted to the circuit board.

DESCRIPTION OF THE TEST APPARATUS

The multiple goals of the tests were to determine the performance characteristics of the instrument and to facilitate further development of the hardware. The tests consisted of submerging the instrument and passing water-based fluids through the vibrational tube. The flow of water through the vibrating tube had to be controlled and measured. Also, the flow rate and temperature of the water surrounding the instrument had to be controlled. Provision for sample collection was necessary when the tests with dissolved solids and suspended sediments were conducted.

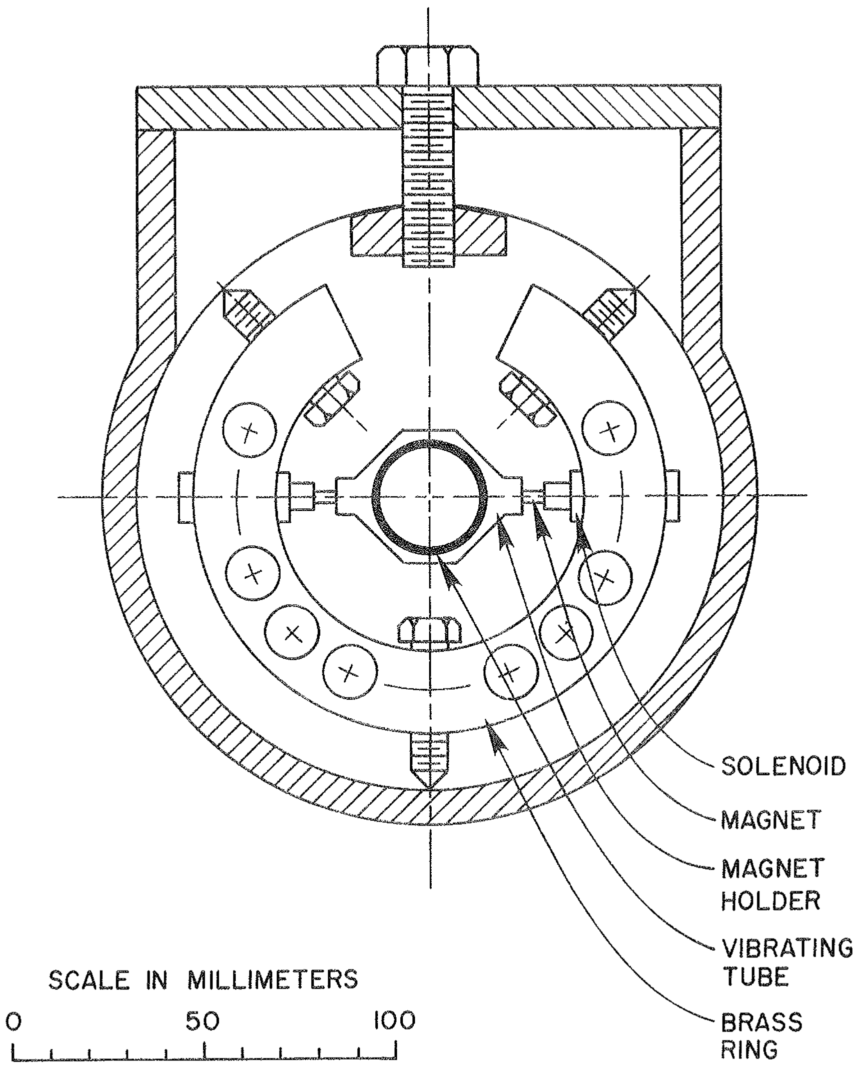

Figure 2.--Cross-sectional view of instrument.

A 210-liter barrel served as a constant headtank (figure 3). A 25-millimeter diameter flexible hose connected the barrel to the intake end of the vibrating tube. A similar hose connected the aft end of the vibrating tube to the reservoir. A sump pump, located in the reservoir, circulated the water back to the barrel. A box was constructed to provide a water bath for the instrument during some of the tests. A second hose from the barrel was connected to the box. Flow of water in the bath was controlled from a valve in the barrel. A hole or a weir, located at the aft end of the box, allowed water to flow into the reservoir.

Manometers at both ends of the vibrational tube were used to measure the average pressure head within the tube and the pressure drop across the tube. The pressure drop was converted to a flow rate. Subsequently, the head and flow velocity could be regulated by adjusting valves located immediately upstream and downstream from the vibrating tube.

When water that contained dissolved solids or suspended sediment was used, tests were conducted at room temperature. Flow through the bath was discontinued in order to isolate the test water from the bath water.

To suspend sediment, paddles rotated by variable-speed motors were installed in the barrel and in the reservoir.

The period of the output signal was displayed on a Hewlett-Packard* 5300B frequency meter and was recorded on a Hewlett-Packard 680 strip-chart recorder. The input and output signals were displayed simultaneously on a Tektronix 2215 60MHz oscilloscope. Temperature measurements were made with a

* Use of trade names in this paper does not constitute endorsement by the U.S. Geological Survey.

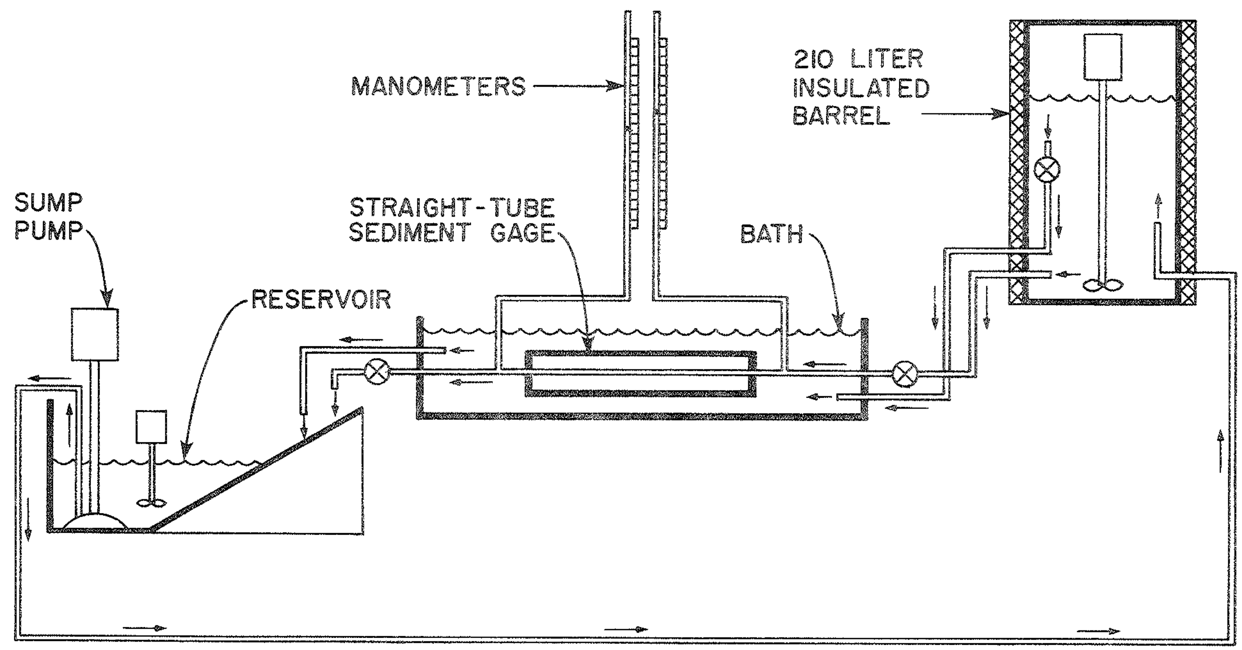

Figure 3.--Sketch of setup for testing the straight-tube sediment gage.

mercury-filled glass thermometer and with a YSI tele-thermometer using No. 401 probes.

The final test on the fluid-density gage was conducted in the St. Anthony Falls Hydraulic Laboratory free-water surface flume. The flume is 0.9 meter wide and 2 meters deep. Water from the Mississippi River flows through the flume and is regulated by two large hydraulic valves. Flow through the tube was monitored with manometers as previously explained. Stream velocity was measured with a Price current meter located 750 millimeters upstream from the fluid-density gage.

TEST RESULTS AND DISCUSSION

After the sediment gage was assembled, it was left running overnight and on weekends. A strip-chart record of the period of vibration was made during this time. The change in vibrational period was as small as 1 microsecond (μs) over a 10-hour time span, but typically was more variable.

During this initial period of observation, air in the instrument's inner chamber was evacuated to prevent condensation from forming on the vibrating tube.

A series of tests were performed to measure instrument response to various factors, and are discussed as follows:

Effect of Water Pressure Within the Vibrating Tube

The tube and manometers were filled with clear water after the ends of the vibrating tube were plugged with stoppers. By moving the manometer tubes vertically, the static pressure was varied within the vibrating tube. Figure 4a shows results of this test. Figure 4b shows part of the same data with the

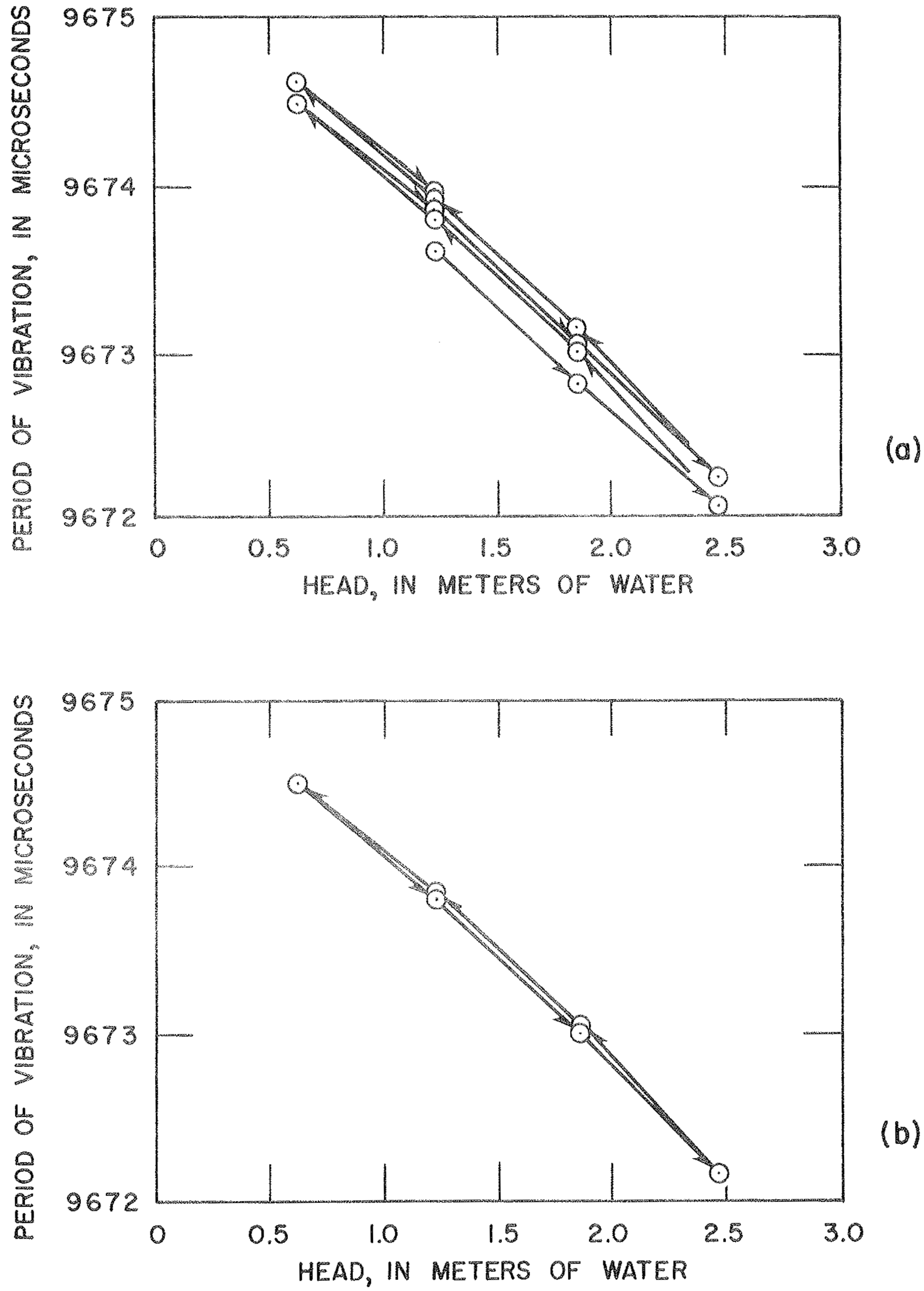

Figure 4.--Instrument response to static pressure (head) within the vibrating tube. (a) Data shown as recorded. (b) Data shown with drift removed.

instrumentation drift removed. The arrows indicate the order in which data were collected. The period of vibration changed about −1.3 microseconds per 1-meter increase in static pressure head.

Effect of Flow Velocity

Water was circulated through the vibrating tube at various rates of flow. When the period of vibration and manometer levels stabilized, readings were recorded. Flow from the vibrating tube was then diverted to a bucket. Velocities were calculated based upon the time required to collect 11.4 liters of water. Figure 5a shows a curve for the difference in pressures between the manometers for various flow velocities. Data shown are from two different tests and are represented by a single curve. The Darcy-Weisbach equation was then compared to the data. The equation is of the form:

$$\Delta P/L = (f/D)(\rho V^2/2)$$

where ΔP = the difference in pressure between the manometers,

L = the distance between manometer taps,

D = the internal diameter of the vibrating tube,

ρ = the density of the fluid, and

V = the velocity of the fluid.

The term "f," the friction factor, was assumed to be 0.018, based on handbook values. An "f" of 0.0191 provided the best fit for the higher velocities. The greatest discrepancy was a velocity of about 1 m/s (meter per second). The Reynolds number (Re) for flow in the tube at this velocity is 2.5×10^4. Inasmuch as the friction factor changes with the Reynolds number around this value, a correction was made. The friction factor can be

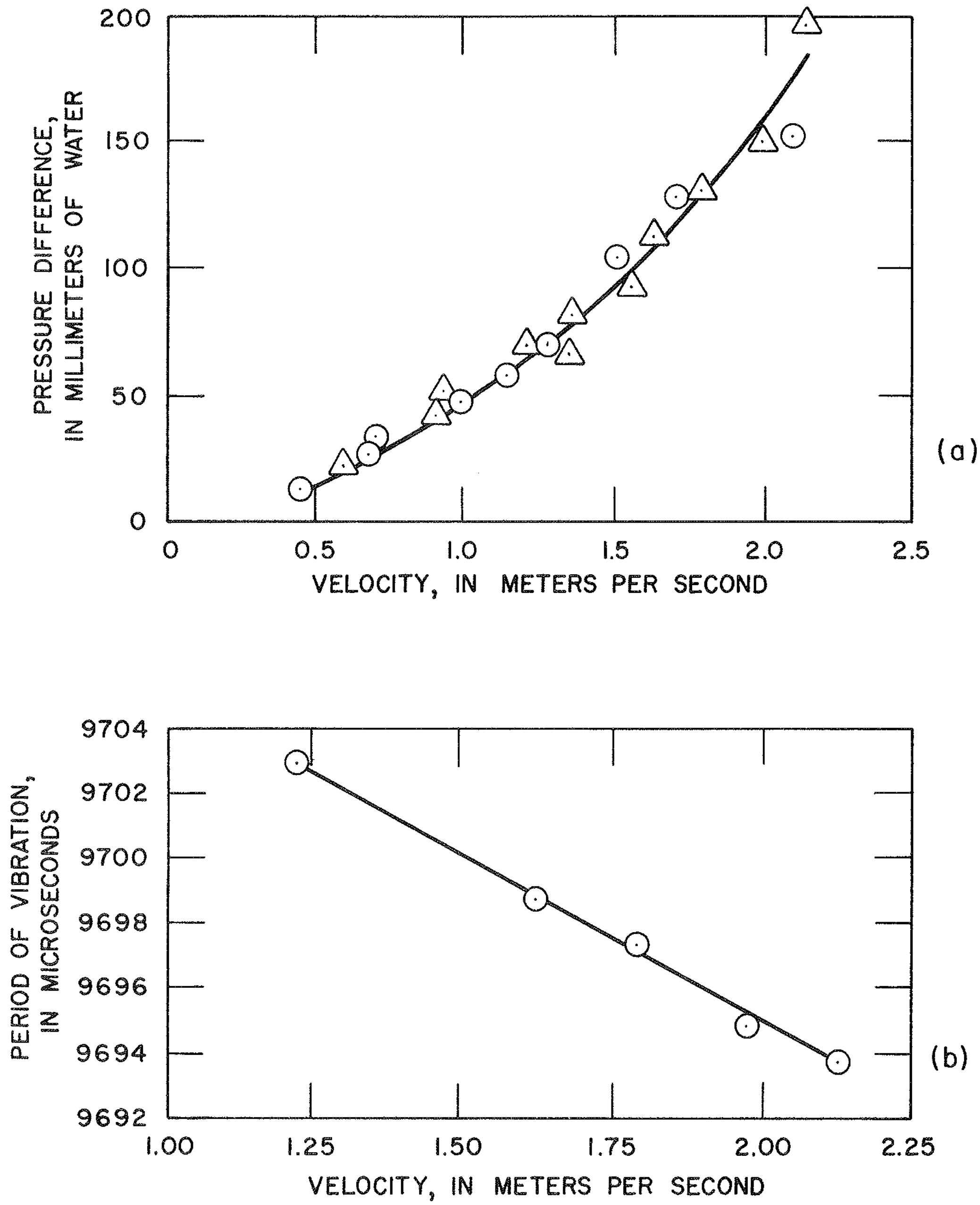

Figure 5.--Influence of flow velocity on the sediment gage. (a) Difference in pressure across the vibrating tube due to velocity. The (Δ) and (o) represent data from two separate tests. (b) Change in period due to change in velocity.

approximated by dividing 0.316 by $Re^{0.25}$. The Darcy-Weisbach equation can then be reduced to the form $\Delta P = kV^{1.75}$, where k is some constant. The value of k can be determined by selecting values for ΔP and V for a point on the curve in figure 5a. The modified equation is in close agreement with the empirical curve.

Figure 5b shows the effect of velocity change on the period of vibration. The curve represents the corrected relation after the effect of static head was removed. The effect on the vibrational period is −10 μs/(m/s) (microseconds per meter per second) increase in velocity for the velocity range from 1.2 to 2.2 m/s.

Effect of temperature

The temperature effect also was investigated. Water in the test setup was circulated until the system stabilized. The period of vibration and the water temperature were recorded. The temperature was then increased by heating the water with electrical heaters and by replacing some of the water with hot water. Water temperature was raised incrementally. The system was allowed to stabilize and data were recorded after each increase in temperature. Figure 6 shows a curve for a test which was started at 1.0° C and completed at 40.2° C. The curve is nearly linear, with a slope of 1.69 μs/$^{\circ}$ C (microseconds per degree Celsuis).

Effect of Water Density

A test was conducted to determine the effect of fluid density on the sediment gage. Sugar water was used as the medium, and was held at constant

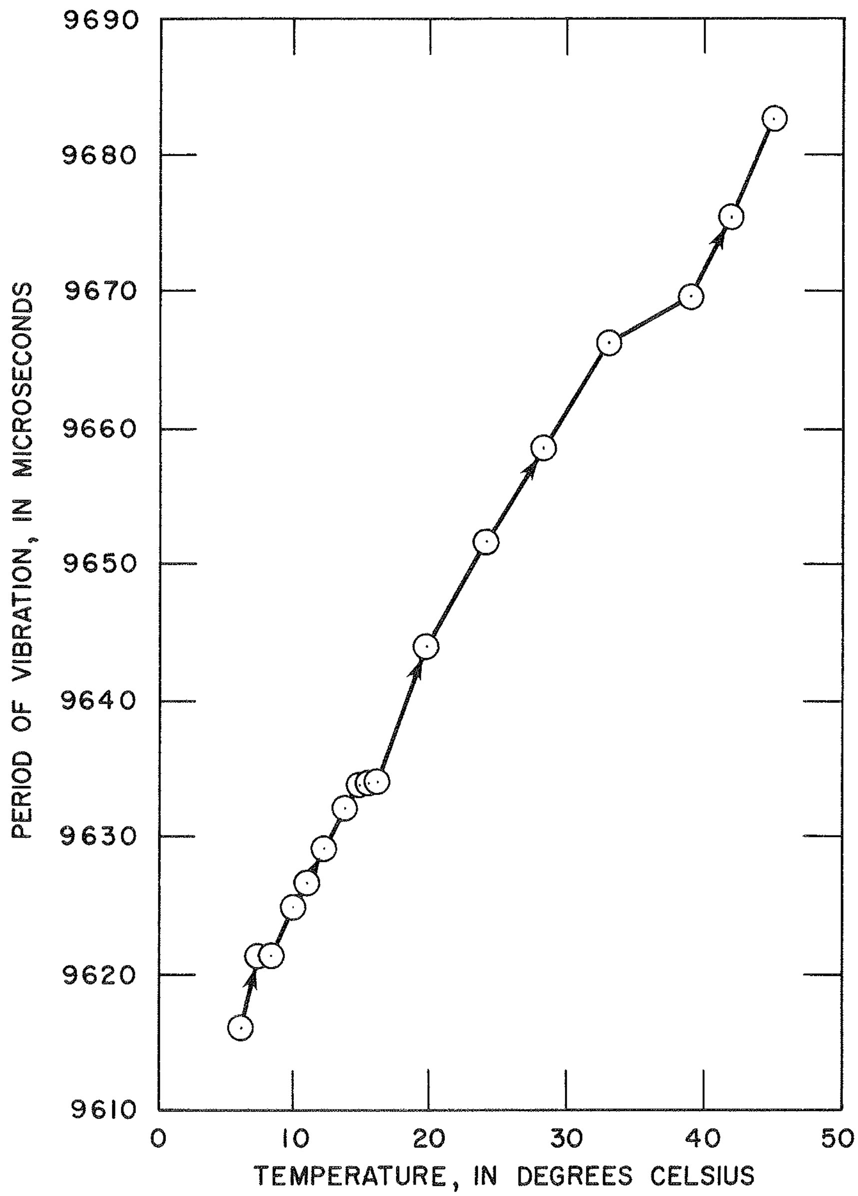

Figure 6.--Instrument response to changes in water temperature.

temperature throughout the test. Nine kilograms of granular sugar were dissolved in 8 L (liters) of water to make about 13.3 L of stock solution. Clear water was circulated in the system for several minutes before flow to the bath was stopped. The period of vibration was recorded and a sample of the clear water was collected. One liter of stock solution was then added to the system and mixed into the clear water. The period was recorded after the fluid became homogeneous: a fluid sample was then collected. This procedure was repeated until the circulated water contained 13 liters of stock solution. The densities of the samples were determined with a pycnometer and an electronic balance.

Results are shown in figure 7. The curve indicates the period increases 2.1 μs for a density increase of 0.001 grams per cubic centimeter. At the end of the test, the circulated fluid was about 138 liters in volume and contained about 8.85 kilograms of sugar. Because the period increased 83.7 μs during this test, the instrument's reponse was 770 (mg/L)/μs (milligrams per liter per microsecond).

Effect of Suspended Sediment

The density cell instrument described in this report was specifically designed to measure suspended-sediment concentration. Tests were conducted, therefore, to determine the instrument's response to various concentrations of sediment. In addition, two different particle-size ranges were tested to investigate the possible effect of particle size on the response. Commercially crushed silica in the silt-size range and in the fine-sand range was used during these tests.

The motor-driven paddle was installed in the barrel for these tests.

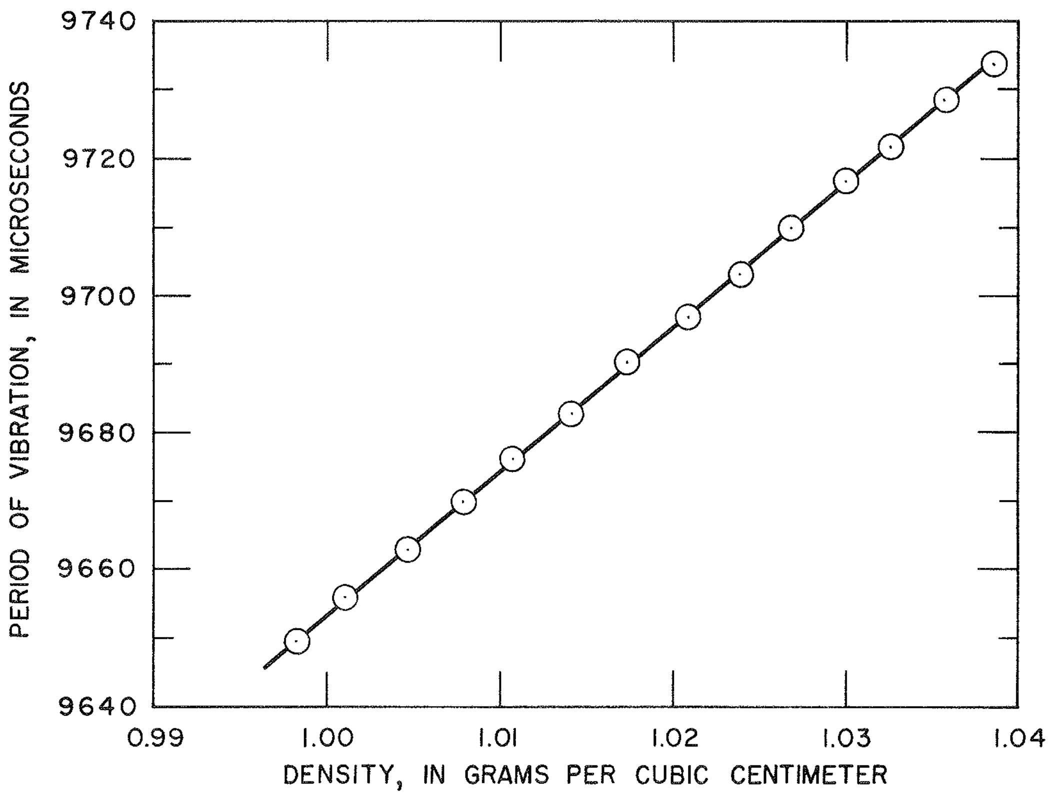

Figure 7.--Instrument response to changes in fluid density.

The tests started with clear water circulated at room temperature. Flow through the bath was then discontinued and sediment was added to the reservoir. The sediment-water mixture was circulated until the period of vibration for the tube stabilized. The period was then recorded and a fluid sample was collected.

Sediment was again added to the reservoir, and the procedure repeated. During the latter part of the test, sediment began to accumulate in the reservoir. A small motor-driven paddle was then installed next to the sump pump to resuspend the sediment.

Figure 8 shows curves for both sediments. The curves are linear and are close to one another. The inverse slopes of the two curves are 775 (mg/L)/μs (milligrams per liter per microsecond) for the fine sand and 763 (mg/L)/μs for the silt. This agrees well with the 770 (mg/L)/μs established in the sugar-solution test.

Flume Tests

After all other tests were completed, the instrument was moved to the flume to measure the flow through the tube at various stream velocities. The bronze head was attached to the instrument at this time to make the instrument's front end more streamlined.

The instrument was held in a fixed position with a rigid steel frame. Initially, the tube was 0.7 meters below the water surface; however, as the stream velocity was increased, the water surface lowered.

Manometers were attached to the instrument as previously described. Before each manometer reading was made, the stream flow was increased, allowed to stabilize, and measured with a Price current meter located

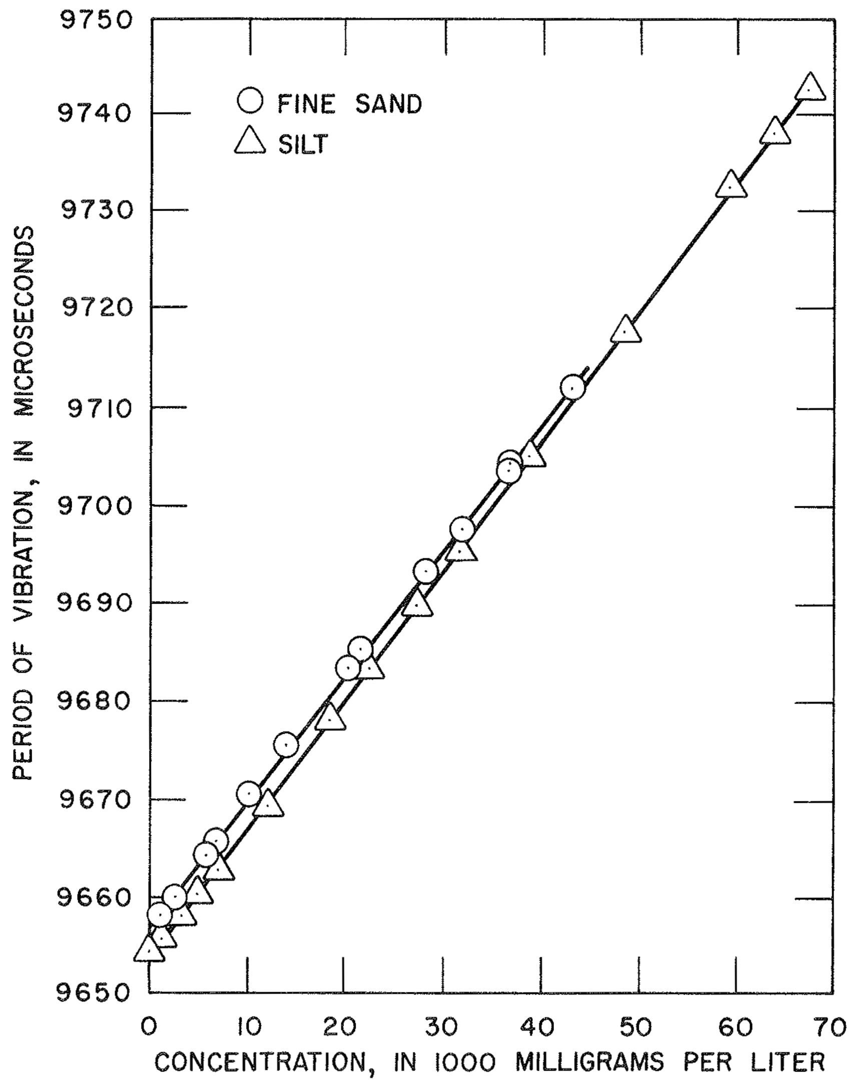

Figure 8.--Instrument response to changes in sediment concentration.

750 millimeters upstream from the instrument.

After this test was completed, flow rates through the tube were determined from the curve in figure 5.a. of this report. The data are presented in figure 9. The curve shown is in the form $y = a x^b$, where a = 0.555 and b = 1.75. Ideally, the flow through the tube should be the same as the stream velocity. The actual relation, however, when approximated by a straight line, is about two-thirds of the ideal relation.

Engineering-Development Tests

In addition to the "performance" types of tests, engineering-development tests also were conducted. The straight-tube gage was designed to be operated under a vacuum. Leaks, however, allowed water to enter the encasement. As an alternative method for eliminating moisture, the vacuum was replaced with pressurized dry gas. Figure 10 shows the change in period resulting from changes in pressure for nitrogen and helium. The slope of the curve for nitrogen is steeper than the slope for helium. Helium, therefore, causes a smaller change in period for a unit change in pressure.

Another desirable property of helium is that it conducts heat much better than air or nitrogen. Heat is generated by the solenoids and is conducted to the brass ring that holds them. In a vacuum, heat is transferred from the ring by means of conduction through the three adjustment bolts.

A series of tests were conducted to investigate ways to improve heat transfer from the ring. The effectiveness of a woven wire-fabric electrical-grounding strap bolted to the ring and to the instrument's body was tested. In addition, the effect of copper fins attached to the

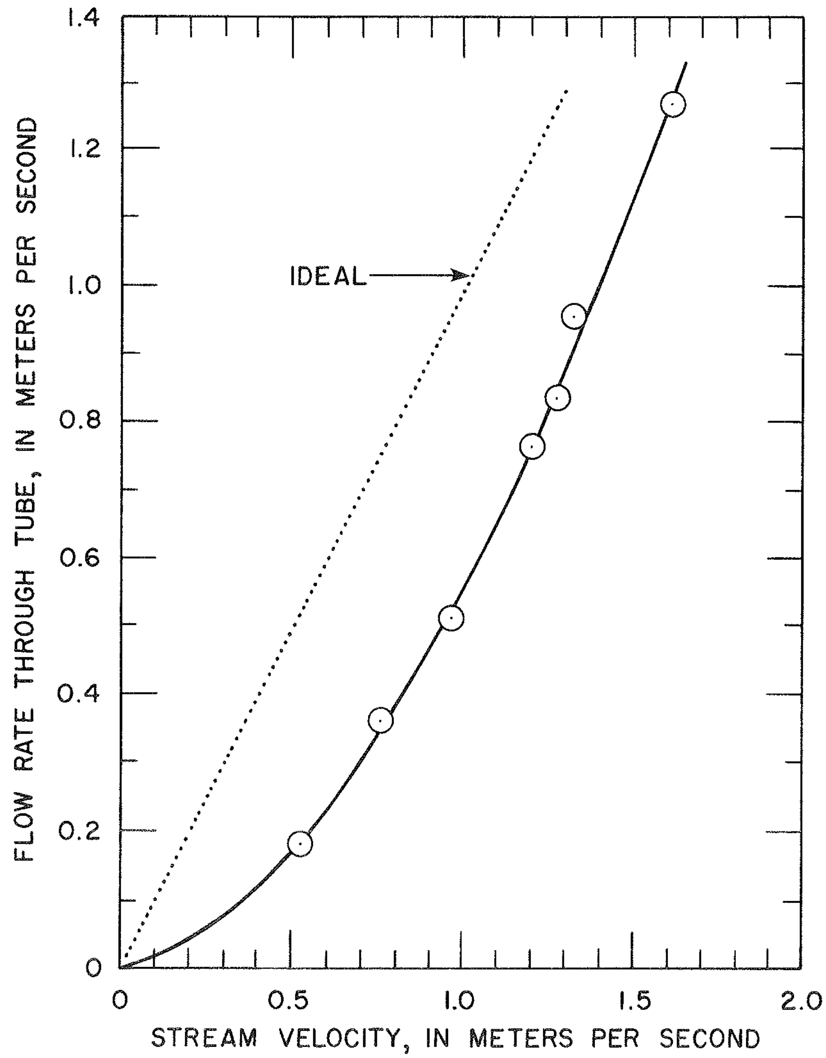

Figure 9.--Comparison of the flow velocity through the tube and the stream velocity.

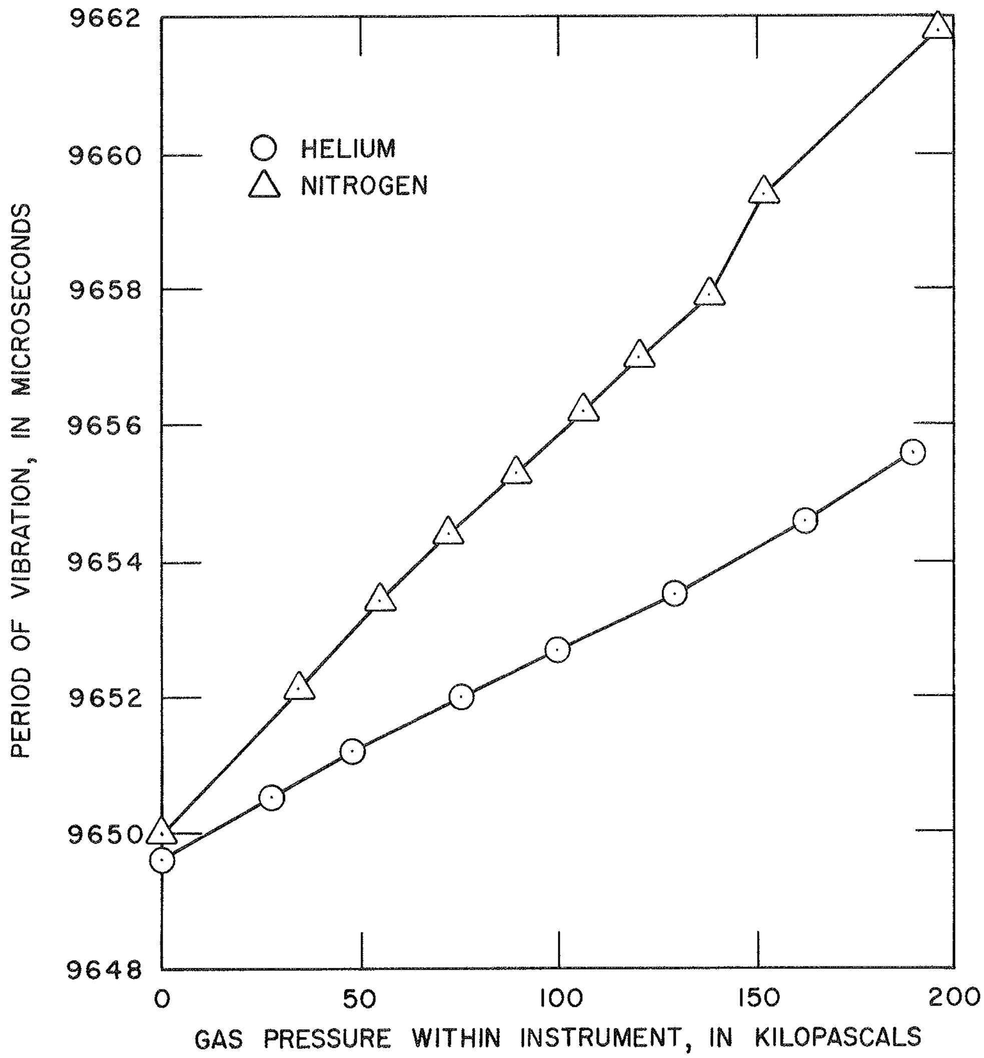

Figure 10.--Variation in vibrational period with changes of pressure within the instrument case. Pressure values are above atmospheric pressure.

ring were measured. There were eight fins on each side of the ring, approximately 300 millimeters long, 40 millimeters wide, and 1 millimeter thick.

The following arrangements were tested:

1) chamber under vacuum, no added conductor

2) chamber under vacuum, with the strap

3) chamber pressurized with helium, no added conductor

4) chamber pressurized with helium, with the strap

5) chamber pressurized with helium, with the copper fins

For each test, the instrument was stabilized at about 20.5° C and then rapidly cooled to about 15° C. Figure 11 shows graphs with the worst and best results. The vacuum, without added hardware, had the longest response time, while the combination of helium and the copper fins dissipated heat the fastest.

The three temperatures monitored during the test were measured with thermistors located on the brass ring, on the inside wall of the case, and in the hose leading to the intake of the vibrating tube.

CONCLUSIONS

1) The straight-tube sediment gage responds to a wide range of sediment concentrations. Tests were conducted with concentrations ranging from near zero up to 65,700 milligrams per liter. The instrument's response was linear when factors such as temperature and fluid velocity were kept

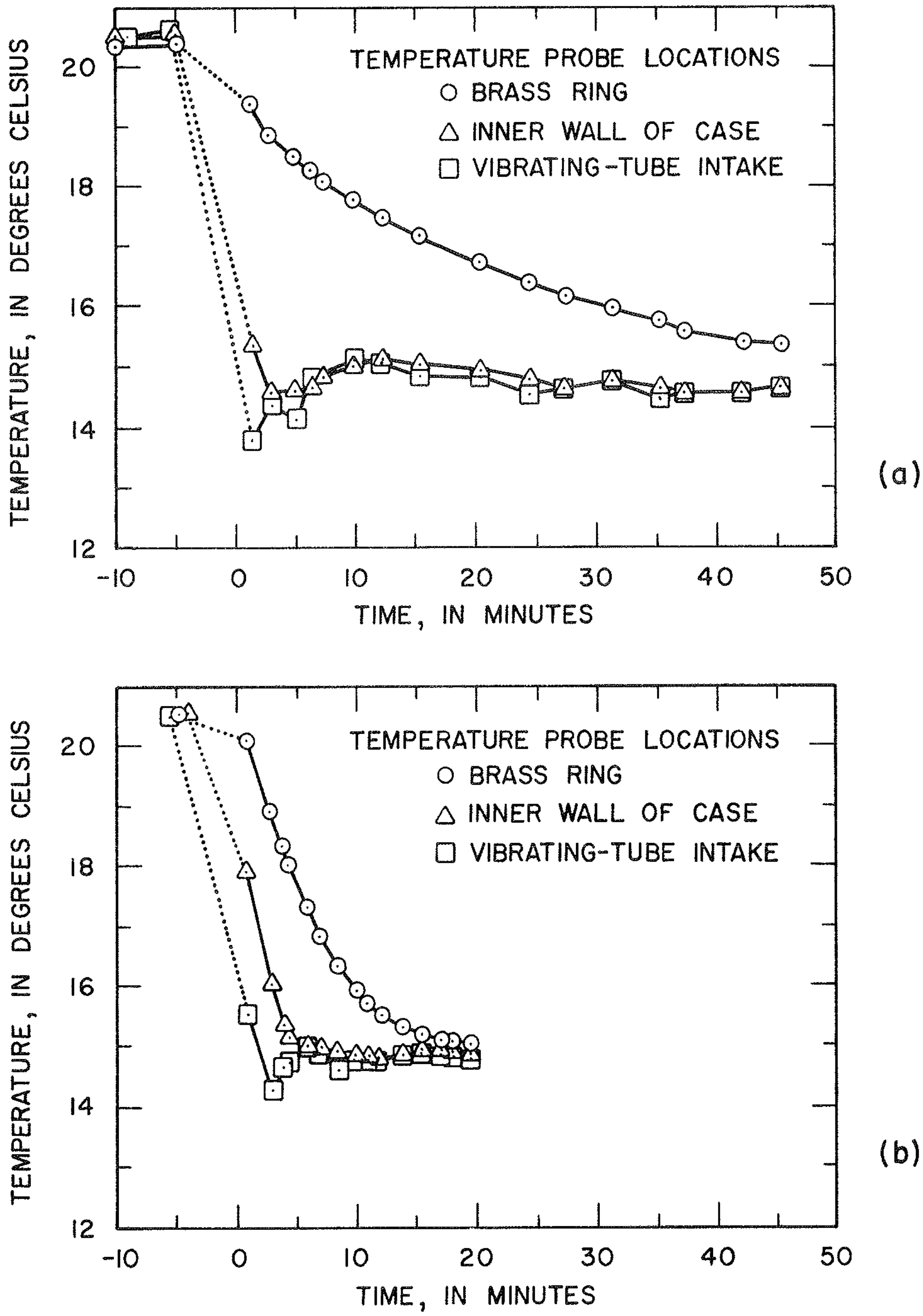

Figure 11.--Temperature response to a rapid change in water temperature. (a) Vacuum, without strap. (b) Helium, with copper fins. The three symbols represent temperature-probe locations: (o) on the brass ring, (Δ) on the inner wall of the case, and (□) in the vibrating-tube intake.

constant.

The instrument's sensitivity to dissolved solids and to sediment in the silt and fine-sand size ranges was similar and was about 770 (mg/L)/μs.

2) The period of vibration changed -1.3 microsecond per meter of water increase in static pressure within the tube.

3) The period of vibration changed -10 μs with each 1-m/s (meter per second) increase in flow velocity through the vibrating tube (for velocities from 1 to 2 m/s).

4) The period of vibration changed 1.69 μs/^{o} C over the range of 1.0^{o} C to 40.2^{o} C.

5) The instrument's adjustment to rapid temperature changes was improved by using pressurized helium and internal copper fins.

6) Flow through the vibrating tube is about two-thirds of the stream velocity, as determined in a test flume.

REFERENCES CITED

Beverage, Joseph P., 1984, Progress report: performance of the vibrating U-tube fluid-density gage for measuring suspended-sediment concentration: Minneapolis, Minn., Interagency Advisory Comm. on Water Data, Federal Interagency Sedimentation Project, Rept. DD, 16 p.

Interagency Committee on Water Resources, Subcommittee on Sedimentation, 1963, Determination of fluvial sediment discharge, Report 14 *of* A study of methods used in measurement and analysis of sediment loads in streams: presently published in Minneapolis, Minn., Federal Interagency Sedimentation Project, 151 p.

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 Sedimentation Project, Rept. X, 125 p.

Skinner, John V., Beverage, Joseph P., and Goddard, Gerald L., 1986, Continuous measurement of suspended-sediment concentration: Proceedings of the Fourth Federal Interagency Conference, 11 p.

APPENDIX

Additional details for conditions during selected tests are given below:

Effect of water pressure within the vibrating tube

Date of test: 1/28/85

The instrument was under a vacuum of -685 mm of mercury.

The ambient temperature was about 18° C.

Effect of water velocity

The instrument was under a vacuum.

Date of test: 2/8/85

Data in figure 5a. (o)

Temperature of the air: 17° C

Temperature of the water: 8 1/2° C

Date of test: 2/11/85

Data in figure 5a. (x)

Air temperature: 20° C

Water temperature: 19 1/2° C

Effect of temperature

Date of test: 4/26/85

Copper fins were in place.

Helium pressure was at 207 kilopascals above atmospheric pressure.

Manometers were at 421 and 393 millimeters of water.

The instrument was on a rubberized hair mat in the bath.

Effect of water density

Date of test: 4/25/85

Air and water temperature: 20 1/2^{o} C

Manometers were at 229 and 165 millimeters of water.

Copper fins were in place.

The instrument was set on a rubberized hair mat inside of the bath.

Effect of suspended sediment

Copper fins were in place.

Rubberized hair mat supported the instrument.

Fine sand:

Date of test: 4/30/85

Manometers at: 381 and 299 millimeters of water.

Water temperature: 18^{o} C

Air temperature: 22^{o} C

Silt:

Date of test: 5/1/85

Manometers at: 378 and 296 millimeters of water.

Water temperature: 21^{o} C

Air temperature: 19^{o} C

Flume test

Date of test: 12/4/85

Water temperature: 0.3^{o} C

Engineering-development tests

Difference in manometers was about 37 millimeters of water.

Flow in bath was about 60 mm/s.

Date of test: 3/28/85

Vacuum was at 685 millimeters of mercury.

Helium was at 120 kilopascals above atmospheric pressure.

Date of test: 3/29/85

A ground strap was connected from the brass ring to the case.

Pressures for the helium and vacuum remained the same.

Date of test: 4/5/85

Copper fins were installed and the strap was removed. Other parameters remained the same.

Date of test: 4/18/85

(gas pressure test)

Copper fins were in place.

Manometers were at 430 and 445 millimeters of water.

The instrument was pressurized first with helium at 185 kilopascals above atmospheric pressure.

After the first test was completed, the instrument was placed under a vacuum and then recharged with nitrogen at 190 kilopascals above atmospheric pressure.