The American Society of Mechanical Engineers

Reprinted From
Offshore Mechanics and Arctic Engineering
Editors: S. K. Chakrabarti, D. Myrhaug, R. C. Ertekin, and H. Maeda
Book No. H00938 – 1995

A NEW WATER LEVEL GAUGE FOR COLD REGION APPLICATION

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ABSTRACT

The traditional gas purging ("bubbler") water level gauge has been widely used because of its simplicity, ruggedness and ability to operate in areas of ice cover. However, its mechanically-based sensing and recording system and the need for density information to compute water level have caused inconveniences in field operations. This paper describes a new design that records and telemeters digital data and allows computation of water density directly from the pressure measurements. Major measurement error sources are also identified and quantified.

The performance in water level measurement is comparable to the National Ocean Service's standard air acoustic tide gauge. Deriving density from pressure measurements obviates the need for use of a separate conductivity/temperature/depth instrument, which can be prone to fouling. The uncertainty in density determination is less than 0.0005 g/cc in laboratory tests; in the field, it varies from 0.0015 g/cc under low wave conditions to 0.003 g/cc for high wave conditions. The instrument has been successfully deployed at several cold region sites including the Arctic and Antarctic regions.

INTRODUCTION

Long term, reliable water level measurements provide important information for the study of climate and global change. The United States' National Ocean Service (NOS) of the National Oceanic and Atmospheric Administration (NOAA) maintains a National Water Level Observation Network (NWLON) along the U.S. coasts, Great Lakes, and ocean islands. In addition, NOS has installed and maintains numerous stations in support of the Global Sea Level Observation Network. The primary measurement system is the Next Generation Water Level Measurement System (NGWLMS) which uses an air acoustic sensor (Mero and Stoney, 1988). However, in remote areas where there is not adequate shore structure to support such a system or in the cold regions where long periods of ice coverage exist, a pneumatic pressure gauge is often used. This type of gauge has been traditionally used for tide observations (Pugh, 1972 and Young, 1977) and for stage measurements in rivers and reservoirs (Rantz, 1982); it is also known as a bubbler gauge, a gas-purged pressure recording tide gauge, and a pneumatic tide gauge, and it will be referred to as bubbler gauge in this paper. The gauge is a proven, simple, and rugged instrument suitable for remote area installations. Since only a gas-purging tube and orifice are in the liquid media and pressure sensor is at a protected location safe from the adverse environment, it is often used for operations in hostile and hazardous environments such as Arctic and Antarctic regions, ocean islands, and at flammable and radioactive liquid material processing sites (Suda, 1990).

Traditional bubbler gauges use mechanical bellows transducers for measurement and analog charts for data recording. This mechanical instrument is not compatible with modern digital data collection, telemetry and processing systems; furthermore, it often requires frequent human intervention to maintain the system. The instrument also has problems with inadequate dampening of high frequency noise caused by wave action and gas leakage, and its measurement uncertainty was not well quantified.

To convert water pressure measurement into water level data one needs to know the density of water at the site. This is critical for remote areas since commercial water density measurement instruments require significant amount of human operations. Furthermore, modern density measurement instruments such as conductivity/temperature/depth probes are expensive and subject to measurement errors due to corrosion and marine fouling and require frequent replacement and calibration.

NOS has developed two types of digital bubbler gauge, single pressure orifice (port) and dual-orifice gauges. The latter is self-contained for water level determination since it measures both the water pressure and water density. This instrument measures pressures at two orifices separated by a fixed vertical distance. Vertically averaged water density values are derived from the pressure differences and are used in combination with the lower orifice pressures to determine the water level. With an additional measurement of water temperature, it is also possible to obtain an estimate of the mean salinity of the water column. The dual-orifice bubbler gauge provides a practical alternative for density determination.

This paper describes the digital bubbler gauges with emphasis on the dual-orifice gauge. Included are basic design and operating principles, measurement error sources and magnitudes, results of laboratory and field experiments, field installation and performance of gauges at the cold region stations.

OPERATING PRINCIPLE

As shown in Figure 1, a bubbler gauge consists of a gas purging unit, an underwater orifice fixture, a pressure sensing unit, and a data recording and telemetry unit. While in operation, a small steady amount of gas is fed into the tube to keep it dry at all times. Excess gas is bubbled away at the submerged end of the tube, the orifice. The pressure in the tube represents the hydrostatic pressure of the liquid column above the orifice.

For water level measurement, the water surface height above the orifice's gas-water interface, h_w, is determined from the hydrostatic equation:

$$h_w = P_0 / (\rho_w g) \qquad (1)$$

where P_0 is the gas pressure (gauge pressure unless specified otherwise) at the orifice, ρ_w is the water density and g is the local gravitational acceleration.

In a dual-orifice system with an additional pressure measured at a fixed vertical distance, s, from the first pressure orifice, one can also determine the vertically averaged water density as follows:

$$\rho_w = (P_{02} - P_{01}) / (g\, s) \qquad (2)$$

where P_{02} and P_{01} are the gas pressures measured at orifices 2 and 1, respectively.

INSTRUMENT DESIGN

As shown in Figure 1 the gas purging unit regulates and maintains a steady flow of purging gas. Compressed nitrogen gas is typically used. It is moisture absorbing and does not support life which helps keep the tube dry and the orifice free from marine growth. Operating at a typical flow rate of 5 cc/minute, a 17.8 cm diameter x 94 cm high commercial compressed gas cylinder should last for up to a year. However, the service life is often shortened because of leakage from pneumatic components. This is a serious operational problem and was addressed in the new design. The gas purging unit is also configured to facilitate in-situ calibration of transducer zero pressure offset.

A precision pressure transmitter (Paroscientific Series 1000 Digiquartz® Intelligent Transmitter) is used for pressure sensing. It receives commands and data requests via a two-way RS-232 port and returns data via the same bus. It contains a dedicated microprocessor, time-base, frequency counters and memory. Sensor constants and configuration parameters are stored in non-volatile memory, and all computations are done internally. Program commands are provided to address any or all transmitters on the bus and control data sampling rates, sample integration time, baud rate, selection of pressure output units, sensor zero offset adjustment, and other operating parameters. The pressure data are fully compensated for temperature effects over the calibrated range of -54°C to +107°C. The sensor has an accuracy of about ± 0.01% FS and long-term stability of from 0.007% FS to 0.026% FS per year (based on NOS field test data). A signal integration time of 5 seconds is used and pressure data are recorded every 6 minutes.

A mechanical low-pass filter (optional) is attached to the pressure transmitter to reduce the wind wave-induced noise. The filter is made of a spool of mini-bore plastic tubing (typically 0.5 mm I.D. x 1.5 mm O.D.). The length of the tubing is computed from design wave height, wave period, and the desired noise attenuation level (Shih, 1989). The device is comparable to a fourth-order Butter worth low-pass filter and is better than numerical averaging in smoothing out the high frequency noise in a tidal record (Shih et al., 1992). Noise reduction is an important design requirement for a dual-orifice gauge operating in exposed coastal stations.

NGWLMS data collection platforms (Sutton Model 9000 DCP) unit) (Mero and Stoney, 1988) are used for data recording and telemetry. In addition to water level, the DCP accepts analog, digital, and frequency inputs from ancillary sensors. Wind speed and direction, air and water temperatures, barometric pressure, humidity, and solar radiation are among the sensors often deployed in NOS stations. The DCP transmits data to a ground station via GOES every 3 hours and the data are then retrieved daily through telephone link to the NOS water level central computers. The DCP is capable of storing up to one week's data.

The underwater orifice fixture consists of two 5 to 8 cm diameter brass orifice chambers separated by known vertical distance. The orifice design may include parallel brass plates. The large diameter orifice and the parallel plates are designed to reduce the ocean wave- and current-induced measurement errors (Shih and Baer, 1991). A tough polyurethane tube (3.2 mm I.D. x 6.4 mm O.D) connects each orifice to surface system.

1946). ΔP_b reaches maximum just before the bubble breaks away from the orifice. Assuming bubble radius of 1 cm during release, the increase in maximum pressure at this moment is about 0.1 cm of water. For typical orifice submergence depth of 3 m, the averaged bias due to bubble surface tension is less than 0.02% and is negligible compared to other terms. The effect on water density determination for the dual-orifice system is also negligible.

ERROR DUE TO WATER CURRENT

As shown in Figure 5a, water current could introduce significant measurement errors because of the Bernoulli effect at the pressure port (Shih and Baer, 1991). The error magnitude is sensitive to local flow condition and increases quadratically with current speed. Numerical correction during the data processing phase is not feasible due to the variability of the current speed and direction. An engineering design (Figure 5b), developed at NOS, has been shown to be very effective in mitigating the current-induced error. In most NOS tide stations current speeds are under 1.5 m/sec, the device reduces the water current-induced error to a negligibly small value.

ERROR DUE TO WIND WAVES

High frequency wind-induced ocean waves cause orifice pressure to fluctuate. The gas-water interface tends to move inside the orifice under wave crests since the gas flow rate is normally set for long period tidal waves. This represents a shift in the gauge reference datum and will result in a negative measurement error. An effective way to mitigate this bias is to use larger diameter orifice chamber (Shih, 1986).

Wind wave-induced water level measurement error also affects the accuracy of water density determined from dual-orifice gauges. This is due to unequal depth attenuation of wave pressure at the two orifices. It is a major source of noise in the density data.

ERROR DUE TO DENSITY STRATIFICATION

Water density stratification affects the accuracy in density determination from dual-orifice gauge. The error can be expressed as

$$\Delta\rho_d = (h_1/s)(\rho_{m2} - \rho_{m1}) \qquad (14)$$

where h_1 is the submergence depth of the top orifice, ρ_{m2} and ρ_{m1} are the mean density above the bottom and top orifice, respectively. Assuming h_1 = 1 m, s = 2 m, and a linear density gradient of 0.002 g/cc per meter, $\Delta\rho_d$ is 0.0005 g/cc.

With the lack of wave and density stratification data, both wave- and density stratification-induced density errors can not be readily corrected.

GAUGE INSTALLATIONS AND PERFORMANCE

LABORATORY AND FIELD EXPERIMENTS

Both laboratory and field experiments were conducted to verify the gauge performance. A field experimental site was established at the U.S. Army Corps of Engineers' ocean research pier in Duck, North Carolina, to evaluate long-term performance of the instrument.

The bubbler water level data compared very well with a NOS standard air acoustic type water level sensor (Shih, 1989). Water density data computed from dual-orifice pressure differences were compared with measurements made by a hydrometer which is typically used at NOS field stations. The observer at these stations makes daily measurements on water samples collected from the surface layers. Figures 6a and 6b show the results of laboratory and field experiments, respectively. The difference in density determined by the two instruments is less than 0.0005 g/cc in the laboratory and less than 0.003 g/cc in the field. The former is within the precision of the instruments used. The latter is likely due to uncertainties related to hydrometer measurements (such as depth of water sample collected, water temperature, instrument calibration, and observation), ocean waves, and density stratification. A 12-hour moving averaging scheme was applied to the computed density data to smooth out the high noise level introduced by the waves.

FIELD INSTALLATIONS

Besides installations in several remote ocean islands, five gauges were installed in cold regions. These include single orifice gauges at Prudhoe Bay in the Beaufort Sea and Diego Ramirez Island at the south most of South America, dual-orifice gauges at Nome and Anchorage on the west and south coasts of Alaska, respectively, and a dual-orifice gauge at Esperanza on the northwest coast of Antarctica.

Figure 7 shows the gas purging tube/orifice installation configuration of single orifice gauge at Prudhoe Bay. A 2.5 cm diameter orifice made from Schedule 80 stainless steel pipe was attached to a solitary triangle piling outside of a seawater treatment plant. The orifice is about 0.4 m above the sea floor. Two 3.7 m sections of the same steel pipe were bolted to the orifice to protect the gas tube. Above the water surface about 8 m away from the orifice, the pipe was bent 45 degrees and went through the sheet piling inshore. The gas tube was protected by a 15 m long x 2.5 cm diameter Schedule 80 PVC pipe and leading to a small instrument room in the plant. Ice thickness in the winter time is about 2.5 meters. Figure 8 shows sample of orifice pressure data.

For the Nome installation, a dual-orifice assembly was fastened inside a steel U-channel which was welded to sheet piling of a breakwater (Figure 9). Gas tube was protected by a 2.5 cm diameter Schedule 80 PVC pipe and run underground to the tide house. Tide range is typically about 0.4 m. However, water surges of more than a meter high occur frequently. Figure 10a shows sample pressure data measured by the two orifices. The resulting water density is shown in Figure 10b.

In Anchorage, similar to Nome, the dual-orifice assembly was fastened inside a steel U-channel. The U-channel was welded to a steel piling of a ship loading pier at Cook Inlet. The water is characterized by high tide range up to 12 m and high current flow. Figures 11a and 11b show sample water level and water density from dual-orifice gauge pressures. Also included in Figure 11b are surface water density values measured daily using a hydrometer. A 12-hour moving average procedure was applied to the 6-minute density data. The difference is less than 0.0015 g/cc and is likely due to observation error, imprecision of the hydrometer, and density stratification. Wind wave-induced noise is much less than that found in Figure 6b.

For the Antarctic installation at Esperanza, two 5-cm 316L stainless steel orifices were fastened to a stainless pipe fixture which was then mounted on a vertical rock face about 100 m offshore. The top orifice is about 10 m below water surface and is 2 m above the bottom orifice. Gas tube was protected within 2.5 cm Penflex corrugated 316L stainless steel hose. The hose runs along the bottom contour and up into a tide house. It was fastened to the rock with stainless steel clips and 1-cm wedge anchors. Power is supplied by two battery banks, charged by two solar panels. Two alternative power sources: 220V AC power (converted to 110V through a conditioner) and a shipwright 30 amp marine battery charger together with a gasoline generator were also installed. Figure 12 shows the instrument house and meteorological sensor tower with satellite antenna. Examples of orifice pressure and water density is shown in Figures 13a and 13b, respectively.

These field gauges have been working well year round under various ice conditions and inclement weather. They have demonstrated the gauge characteristics of ruggedness and reliability. Field service was rarely required except for replacement of gas supply cylinders.

CONCLUSIONS

Based on laboratory and field tests and field deployments the following conclusions can be made:

a. The automated digital bubbler water level gauge has greatly improved measurement accuracy and data collection and communication capabilities over traditional bubbler gauges. With errors properly corrected, the accuracy in water level measurement is comparable to NOS air acoustic sensors.

b. The dual-orifice bubbler gauge provides a practical alternative for automated long-term monitoring of water density and/or salinity. It measures the vertically averaged water density with an uncertainty of less than 0.0005 g/cc in the laboratory tests, less than 0.003 g/cc in the high wave energy experimental station, and less than 0.0015 g/cc in the low wave energy field station compared to hydrometer measurements, which are normally used in NOS field stations.

c. Measurement errors have been identified and quantified. In typical measurement stations total water level error is less than 1 cm. Corrections can be implemented easily because of the linear nature of these corrections.

ACKNOWLEDGMENT

The authors wish to thank Philip Libraro for setting up the pressure transmitter-DCP interface and preparing the data collection and telemetry software, Jim Sprenke for electronic support, and other colleagues at NOS who successfully fabricated and installed these gauges in a less than comfortable environment.

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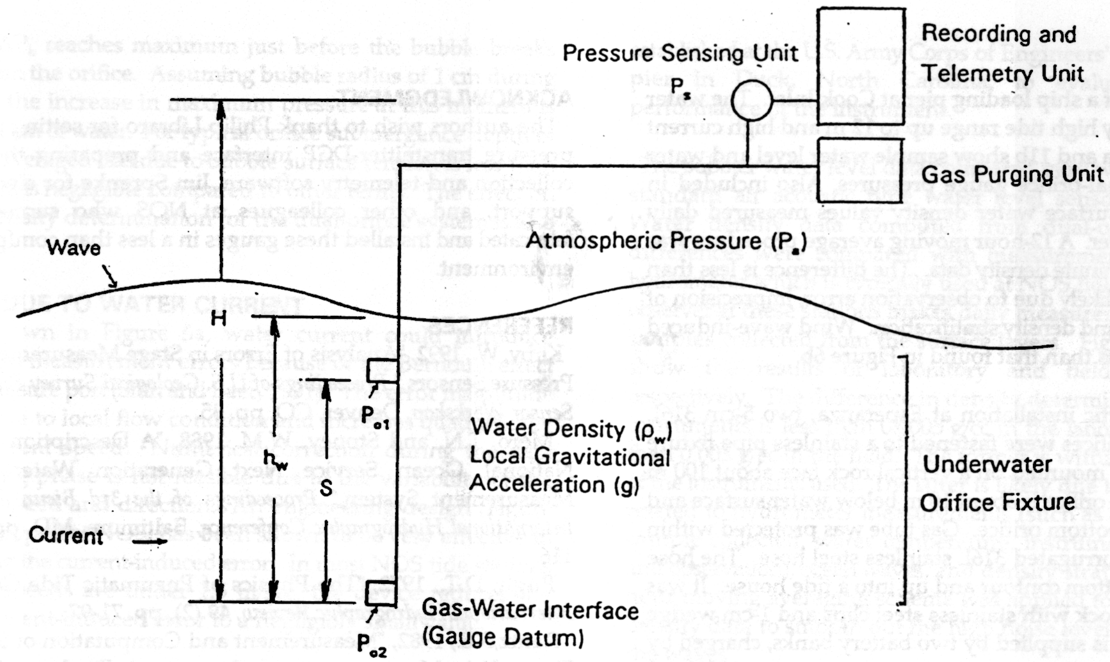


FIGURE 1. SCHEMATIC DIAGRAM OF BUBBLER GAUGE AND ITS PRINCIPLE SYSTEM PARAMETERS

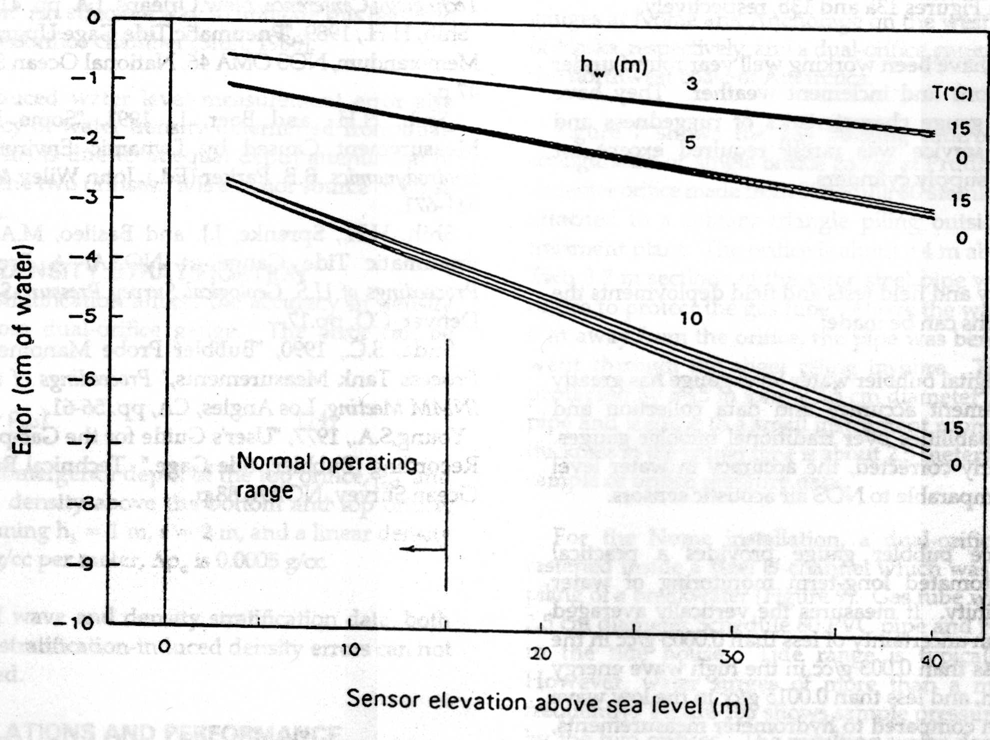


FIGURE 2. WATER LEVEL MEASUREMENT ERROR DUE TO AIR AND GAS WEIGHTS AT VARIOUS SENSOR ELEVATIONS, ORIFICE SUBMERGENCE DEPTHS, AND GAS TEMPERATURE (GAS: NITROGEN, WATER DENSITY: 1.025 G/CC)

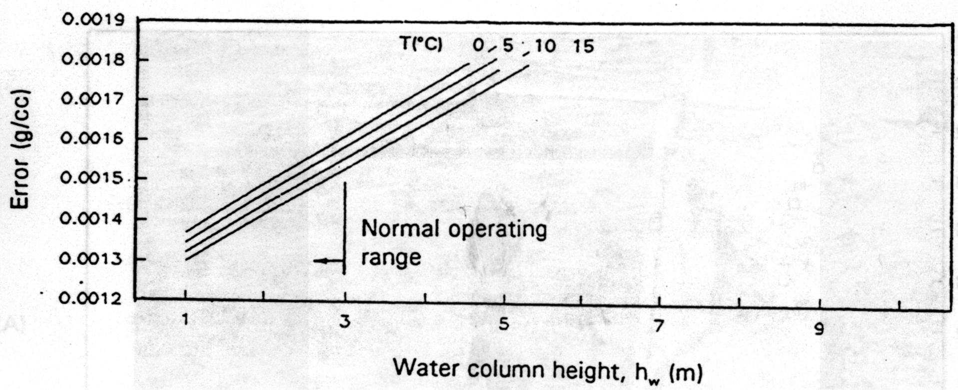


FIGURE 3. WATER DENSITY MEASUREMENT ERROR DUE TO GAS WEIGHT AT VARIOUS ORIFICE SUBMERGENCES AND GAS TEMPERATURES (GAS: NITROGEN, WATER DENSITY: 1.025 G/CC)

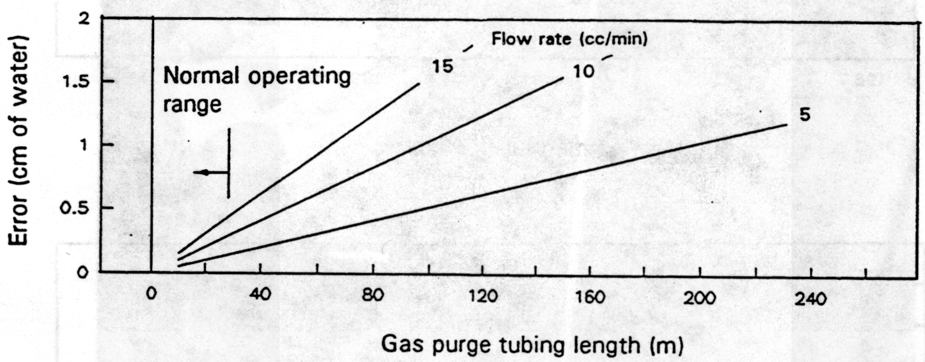


FIGURE 4. WATER LEVEL MEASUREMENT ERROR DUE TO PRESSURE DROP AT VARIOUS FLOW RATES AND TUBE LENGTH (TUBE I.D.: 0.32 CM, GAS: NITROGEN, WATER DENSITY: 1.025 G/CC)

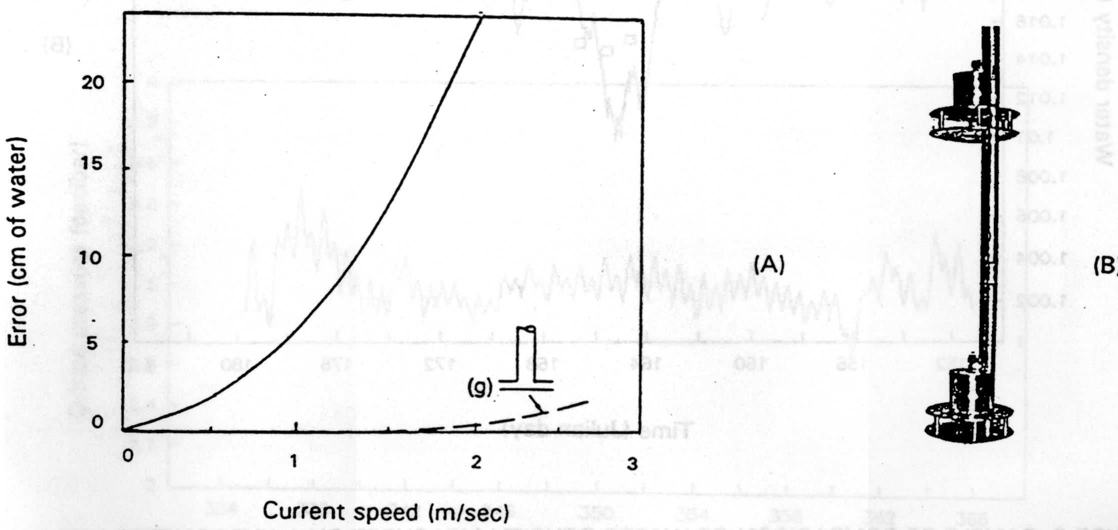
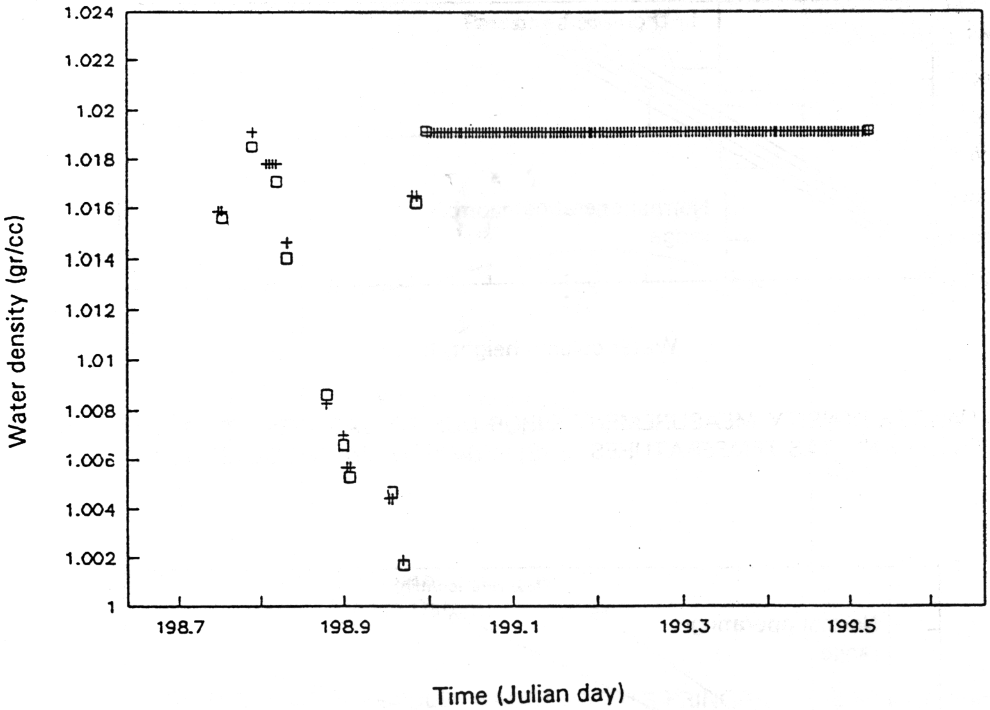
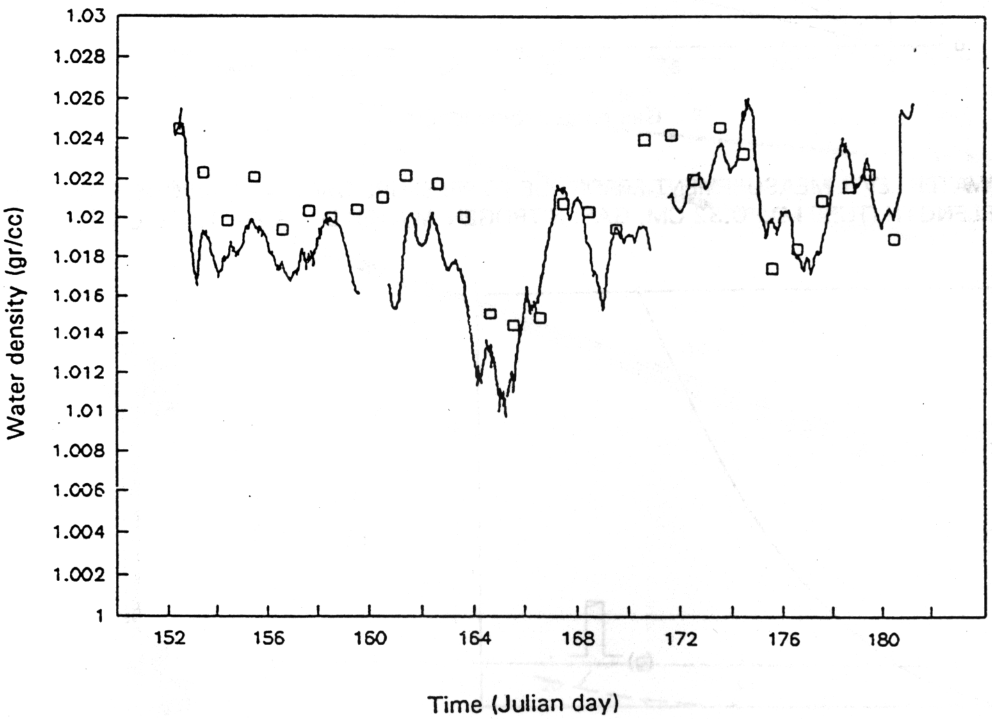


FIGURE 5. EFFECT OF WATER CURRENT: (A) WATER LEVEL MEASUREMENT ERROR VS. CURRENT SPEED, (B) USE OF CIRCULAR END PLATES TO REDUCE CURRENT EFFECT (SHIH ET AL. 1992).



(A)



(B)

FIGURE 6. SAMPLE OF COMPARISON OF WATER DENSITY MEASURED BY A HYDROMETER AND A DUAL-ORIFICE GAUGE: (A) LABORATORY EXPERIMENT (7/92, □ : HYDROMETER, +: DUAL-ORIFICE GAUGE), (B) FIELD EXPERIMENT (DUCK, NC, 6/93, □ : HYDROMETER, +: DUAL-ORIFICE GAUGE).

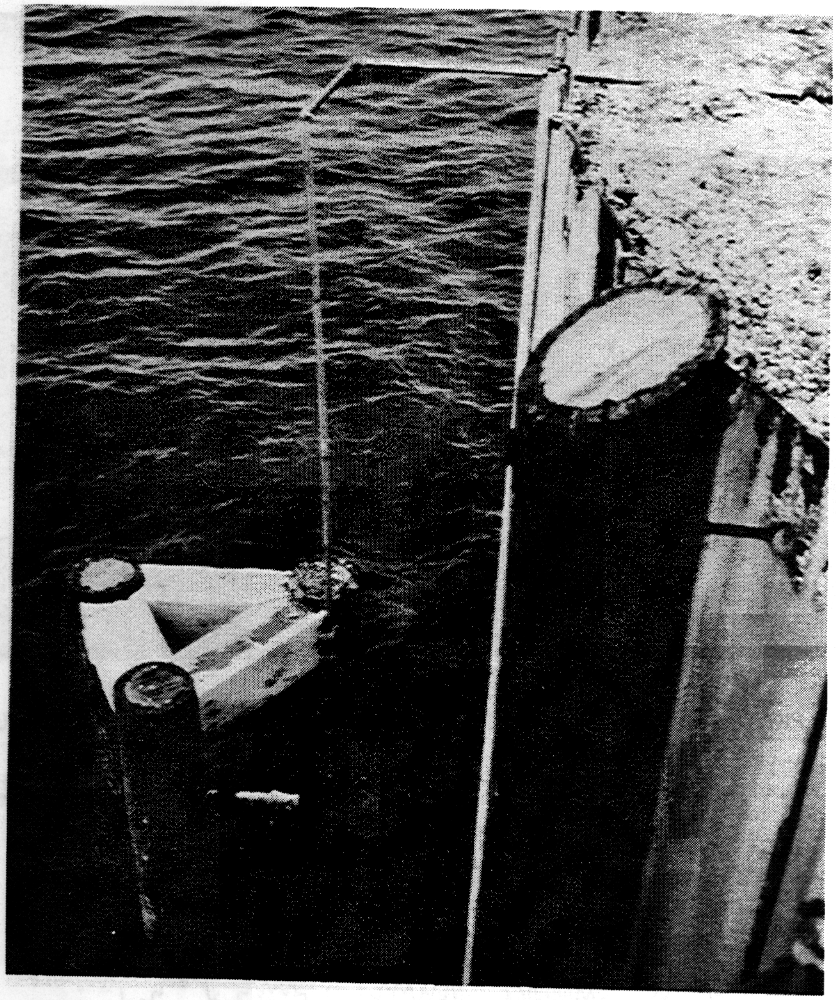


FIGURE 7. PICTURE OF UNDERWATER ORIFICE FIXTURE INSTALLED AT PRUDHOE BAY, ALASKA.

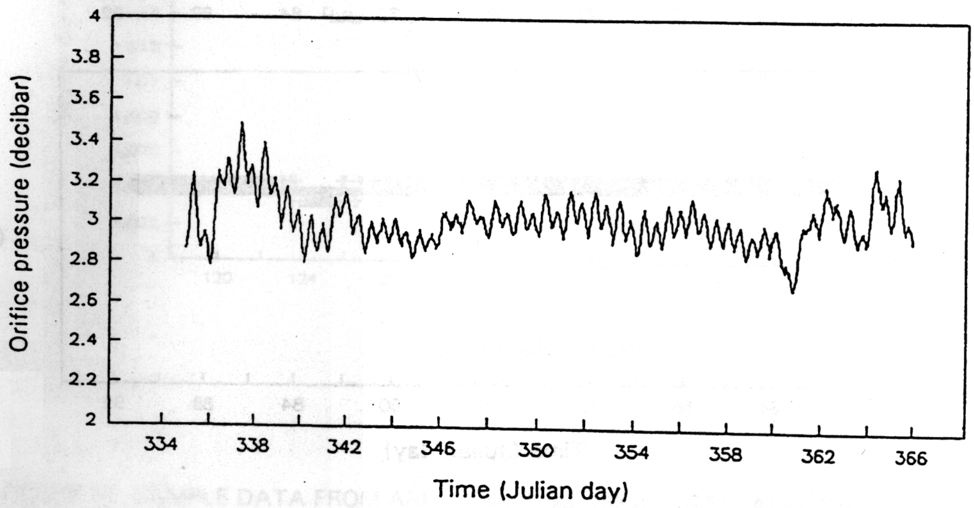


FIGURE 8. SAMPLE DATA OF ORIFICE PRESSURE FROM PRUDHOE BAY (12/94).

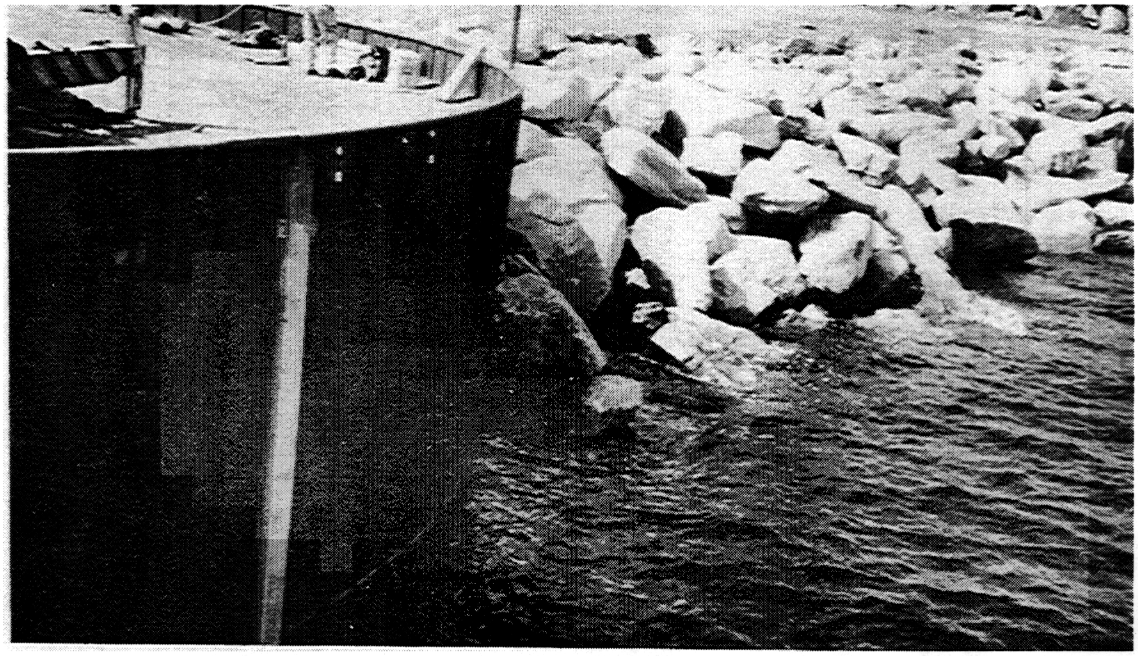


FIGURE 9. PICTURE OF UNDERWATER ORIFICE FIXTURE INSTALLED AT NOME, ALASKA.

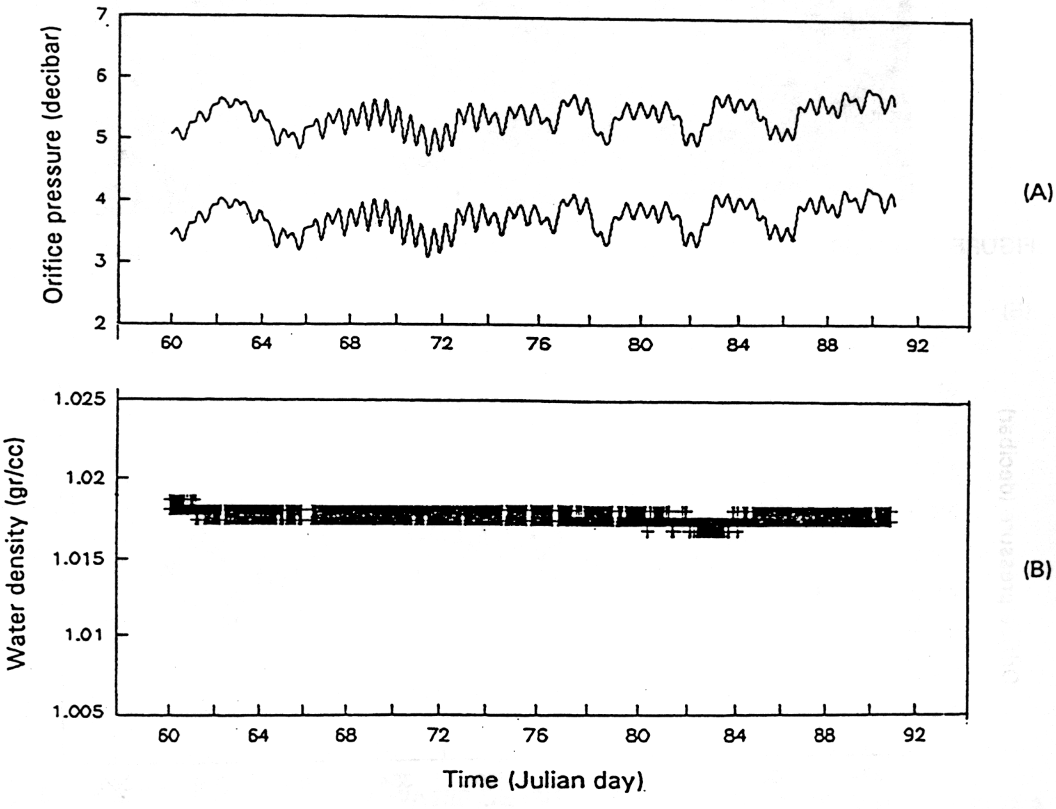


FIGURE 10. SAMPLE DATA FROM NOME, ALASKA (3/93): (A) ORIFICE PRESSURES, (B) WATER DENSITY.

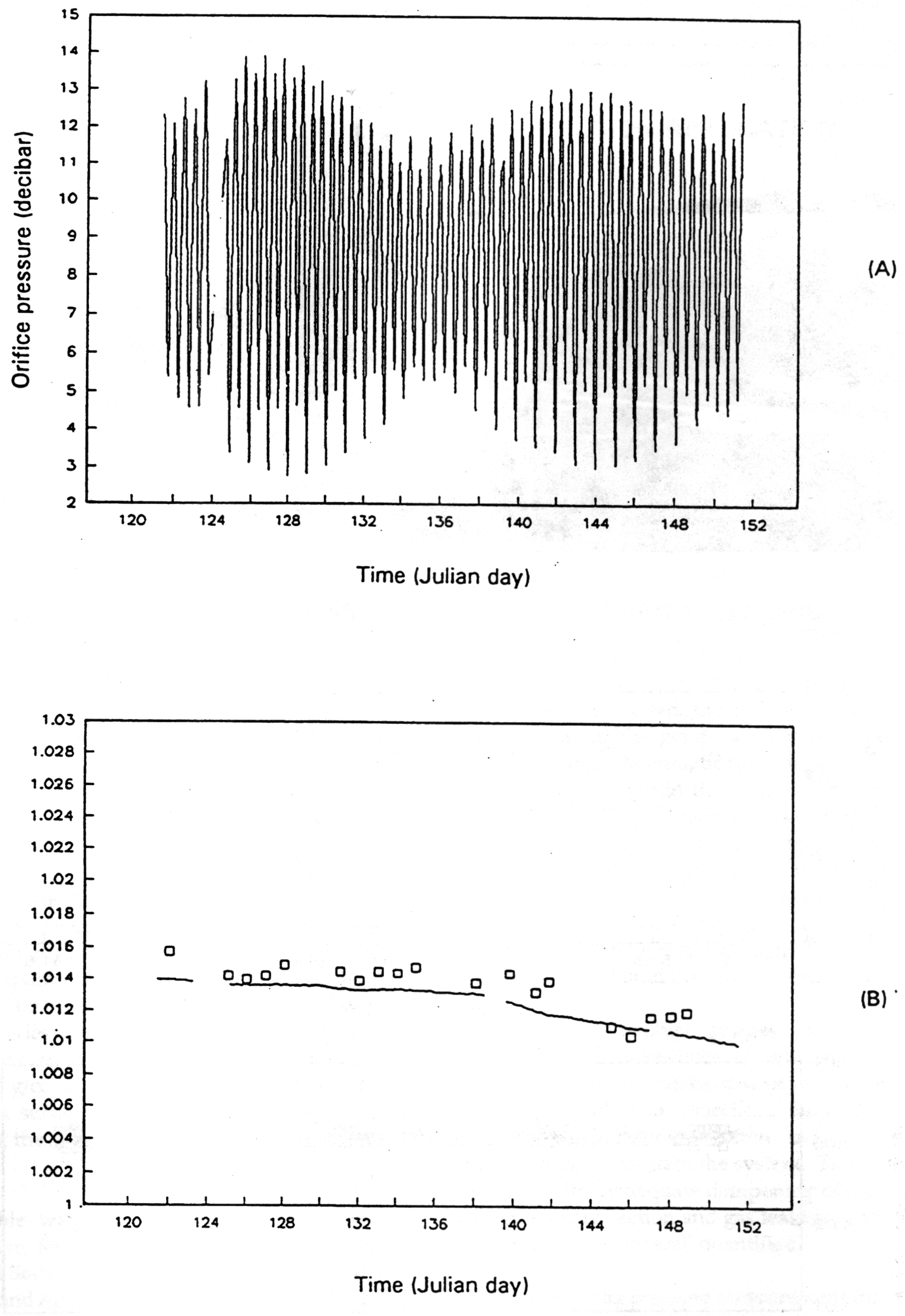
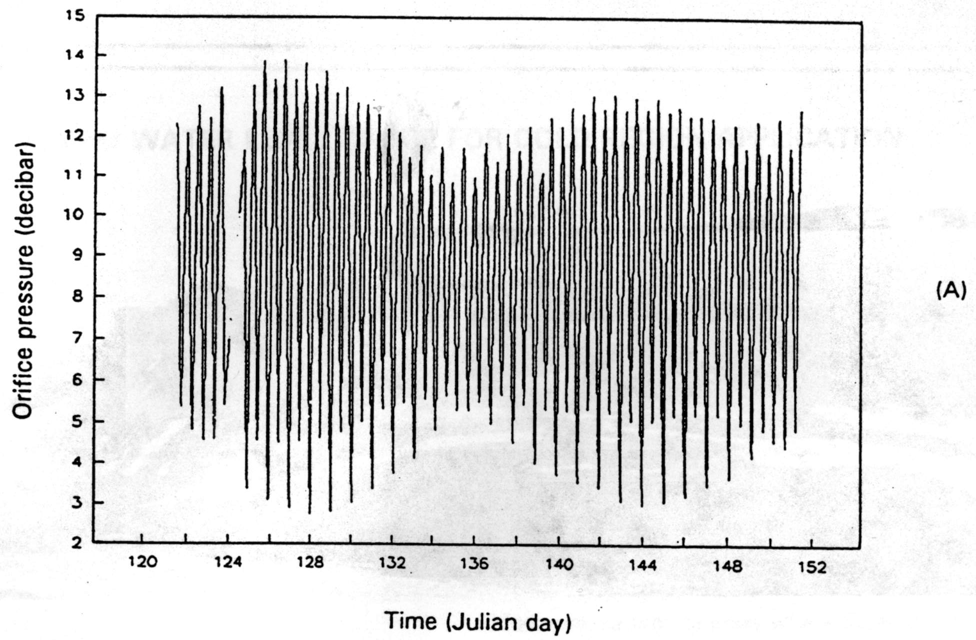


FIGURE 11. SAMPLE DATA FROM ANCHORAGE, ALASKA (5/93): (A) BOTTOM ORIFICE PRESSURE, (B) WATER DENSITY (□ : HYDROMETER, — : DUAL-ORIFICE GAUGE)



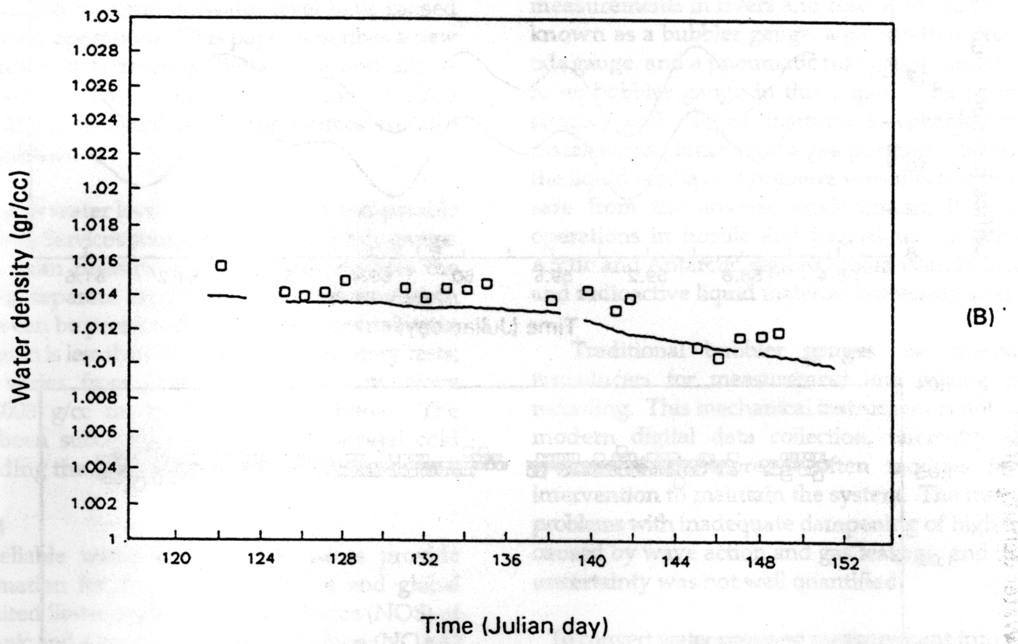


FIGURE 11. SAMPLE DATA FROM ANCHORAGE, ALASKA (5/93): (A) BOTTOM ORIFICE PRESSURE, (B) WATER DENSITY (□ : HYDROMETER, — : DUAL-ORIFICE GAUGE)

FIGURE 12. PICTURE OF WATER LEVEL STATION AT ESPERANZA, ANTARCTICA.

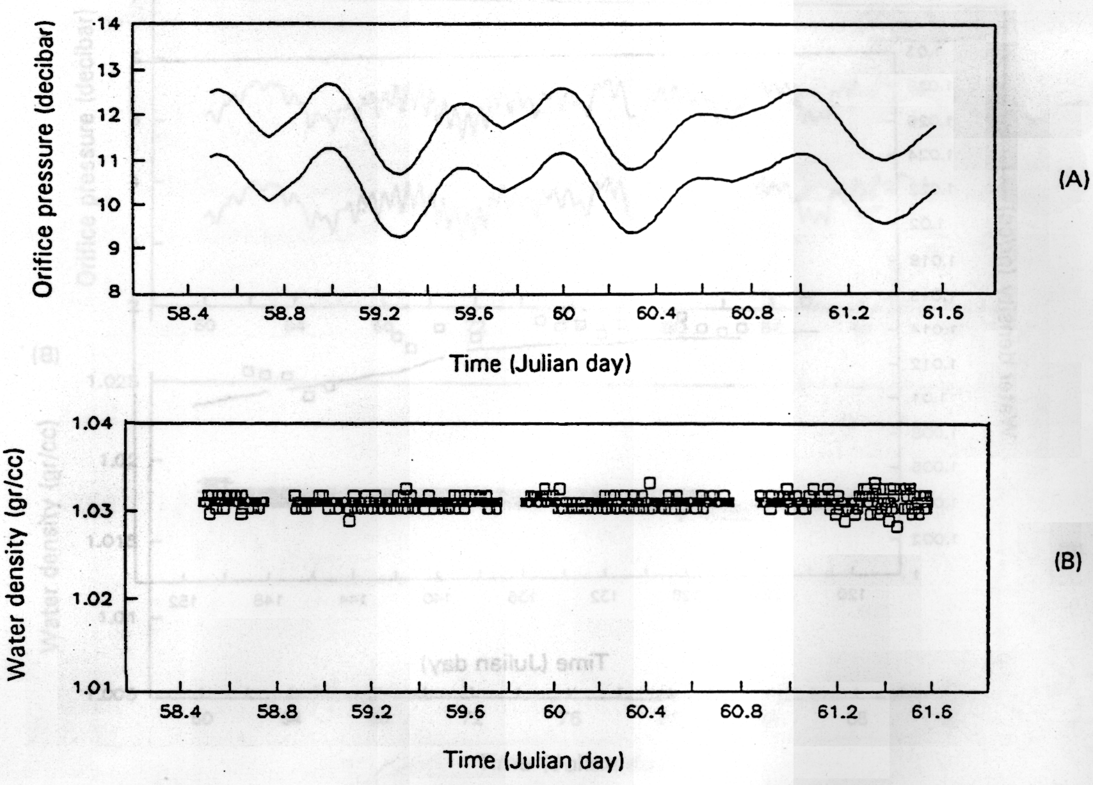


FIGURE 13. SAMPLE DATA FROM ESPERANZA, ANTARCTICA (2/27-3/4/93): (A) ORIFICE PRESSURES, (B) WATER DENSITY.