TEMPERATURE SENSITIVITY OF MERCURY-MANOMETER BUBBLE GAGES

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
foot (ft)	0.3048	meter

Temperature in °C (degrees Celsius) can be converted to °F (degree Fahrenheit) as follows:

$$°F = (1.8)(°C) + 32$$

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD) of 1929)--a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

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ABSTRACT

Elementary hydrostatic analysis shows that water-level measurements made with mercury manometers are subject to errors of approximately 0.02 percent per degree Celsius due to uncorrected variations in the temperature of the mercury. Normal diurnal variations in air temperature if uncorrected are sufficient to cause errors of ±0.15 percent or more. Errors of this magnitude would exceed the U.S. Geological Survey's pre-1989 tolerance of ±0.05 percent of full scale for stage-measurement instrumentation if the water levels measured were above one-third of full scale. Under the current (1991) more stringent tolerance of 0.02 percent of full scale, errors of this magnitude would exceed the tolerance at almost any water level. An informal survey conducted in 1986 indicated that most Geological Survey manometers do in fact operate at less than one-third of full scale for all but a few days per year, and that temperature sensitivity is relatively unimportant in comparison to other sources of error in measurements of high-water levels at stream-gaging stations.

INTRODUCTION

Gas-purged servomechanism-controlled manometers, or "bubble gages", are widely used to measure water levels at U.S. Geological Survey (USGS) stream-gaging stations. Descriptions of these devices have been given in various degrees of detail by the USGS (Research Section, Columbus, Ohio, written communication, 1962), Barron (1963), Buchanan and Somers (1968), Rantz and others (1982), Craig (1983), and Herschy (1985). Winchell Smith (USGS, written commun., 1974) discusses errors affecting high-head manometer installations. Beck and Goodwin (1970) discuss the dynamic response of the bubble gage to transient water level changes and oscillations. Nonetheless, there appears to be no readily accessible reference giving a straightforward general derivation of the mathematical equations governing the hydrostatic operation of the bubble gage manometer. Such a derivation is needed as a basis for analysis and discussion of various static errors that may affect the manometer.

This report presents a derivation of the general hydrostatic equations governing bubble-gage manometers and demonstrates how to use these equations to assess the magnitude and field significance of any errors resulting from temperature sensitivity of the bubble gage manometer. The report is in four parts. First is a review of the physics and functional operation of the manometer. Second

[Corrections made 9/12/91]

is an analysis of the pressures resulting from the weights of the gas columns in the purge-gas tube (bubble tube) and in the atmosphere between the gage instrument and the water surface. Third is a theoretical analysis of the effect of temperature on the manometer. Fourth is an assessment of the significance of the theoretical errors in field installations of the manometer.

Most bubble gages used by the USGS are deployed at stream-side installations where there is a range of less than 35 feet between high water and low water and where the manometer is located less than 100 feet above the water surface. The scope of this report therefore is limited to the analysis of the order of magnitude of static errors in such low-head installations. Dynamic errors such as failure to track rapidly rising stages (lag) or inability to properly register oscillating water surfaces are not considered. Some of the physical assumptions and mathematical approximations made in this report might not be appropriate for installations with water-level ranges of several hundred feet or instrument shelters located several hundred feet above the water. Similarly, the assumptions and approximations made are adequate to illustrate the general order of magnitude of possible errors, but may not be adequate for deriving high-precision corrections to the simple manometer equations. Derivation of appropriate equations for high-head installations or high-precision applications would require additional analyses, including variables and physical processes not considered here and more precise mathematical analysis.

MANOMETER PHYSICS AND OPERATION

The essential functional elements of a gas-purge manometer installation (bubble gage) are illustrated in figure 1 and explained as follows. A gas-purge system discharges a stream of gas bubbles through an orifice into the water body whose stage is being measured. At the orifice, the gas pressure is equal to the water pressure. This pressure is transmitted to the manometer pressure reservoir, where it is balanced by the weight of the mercury column. Consideration of the mercury and gas pressures in the pressure reservoir leads to the following equation:

$$p_{am} + \rho_m g h_m = p_{aw} + \rho_w g h_w + p_s + p_f + p_c - \rho_t g h_t \qquad (1)$$

in which p_{am} and p_{aw} denote the atmospheric pressures at the mercury and water surfaces, respectively, ρ_m and ρ_w denote the densities of mercury and water, h_m and h_w denote the heights of the mercury and water columns, g denotes the acceleration of gravity, p_s denotes the flow-stagnation pressure in the water at the orifice, p_f denotes the pressure drop due to gas-flow friction

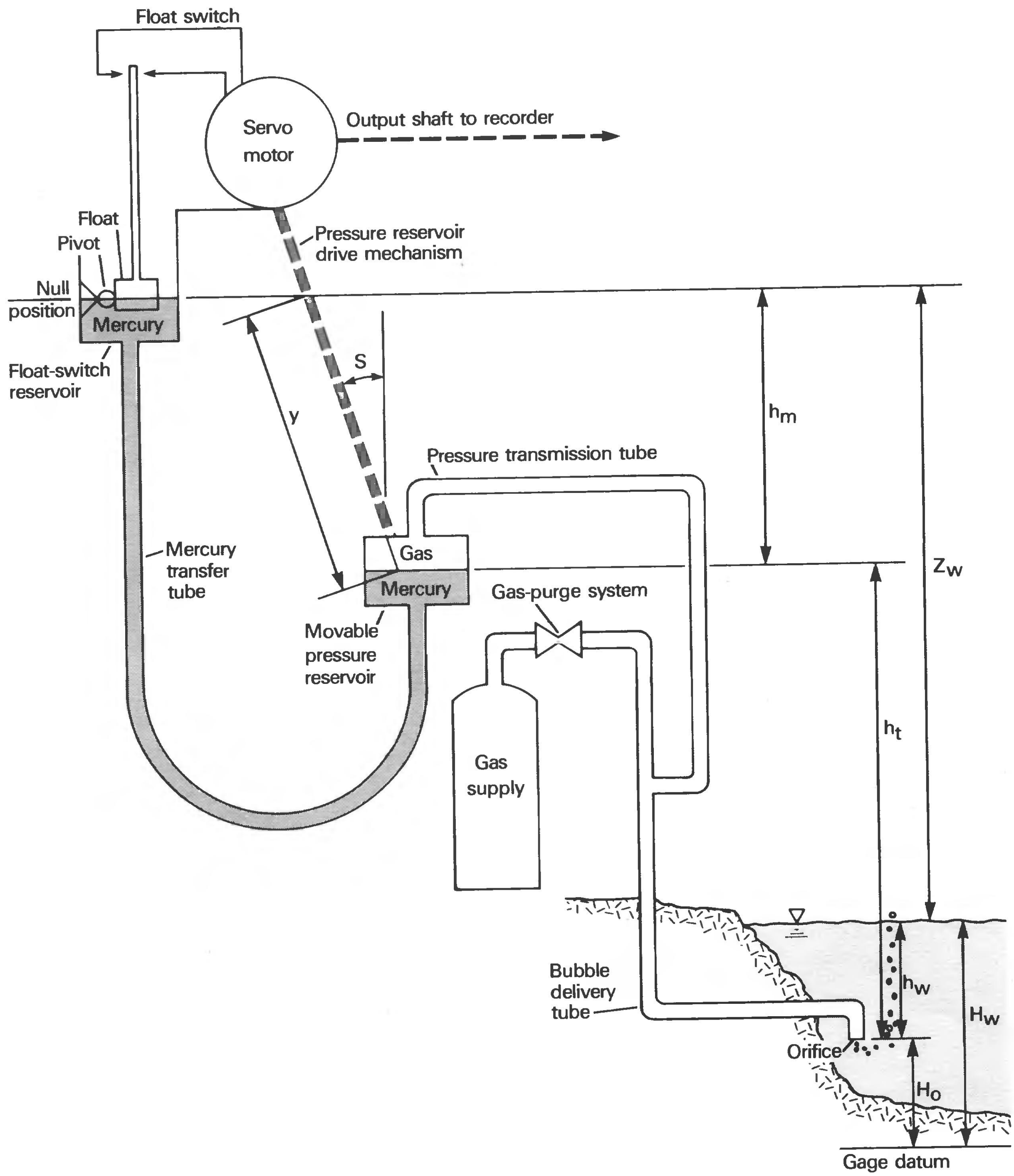

Figure 1. Schematic diagram of mercury-manometer bubble gage.

between the pressure takeoff and the orifice, p_c denotes the "capillarity" pressure needed to make the bubble break free from the orifice, ρ_t denotes the density of the gas in the bubble-delivery tube, and h_t denotes the height of the bubble-delivery tube. The quantity $\rho_t g h_t$ represents the pressure due to the weight of gas in the tubing between the pressure reservoir and the orifice. The difference in atmospheric pressures at the mercury and water surfaces may be expressed as

$$p_{aw} - p_{am} = \rho_a g Z_w \qquad (2)$$

in which ρ_a denotes the density of the air and Z_w denotes the height of the mercury above the water surface. It is assumed that ρ_a is essentially constant over the height range Z_w. By reference to the geometry of figure 1,

$$Z_w = h_t + h_m - h_w \qquad (3)$$

Substituting equations 2 and 3 into equation 1 and rearranging yields

$$\rho_m g h_m = \rho_w g h_w - \rho_t g h_t - \rho_a g h_w + \rho_a g (h_t + h_m) + p_s + p_f + p_c \qquad (4)$$

The term $\rho_a g h_w$ may be interpreted as the weight of air displaced by the water column over the orifice. Note that this term does not appear in isolation. It is coupled to $\rho_a g(h_t+h_m)$, which is the weight of the air column between the free mercury surface and the water.

This entire analysis is predicated on the hypothesis that the purge gas is bubbling freely out of the orifice. If the gas is not bubbling freely, then whatever is obstructing the flow also is introducing a pressure differential between the purge gas inside the bubble tube and the water body outside the tube. The magnitude of this pressure differential cannot be determined until the orifice is cleaned and the gas is bubbling freely again. Thus there is no definable relationship between water stage and manometer reading unless the purge gas is bubbling freely out of the orifice.

In equation 4, the stagnation pressure p_s can be expressed as a stagnation head, $h_s = p_s/\rho_w g$. This head may be expected to be proportional to the velocity head prevailing at the orifice, with the proportionality coefficient reflecting the orientation of the orifice relative to the velocity vector. A coefficient of +1 would be expected if the orifice were aimed directly into the current. A negative coefficient, reflecting drawdown, would be expected if the orifice were aimed downstream. A coefficient of 0 would represent a perfect installation of the orifice. Because the velocities and configuration of the streamlines near the orifice may be expected to change with stage or discharge, the stagnation head h_s also may be expected to vary with stage. For purposes of discussion, therefore, it is assumed that the stagnation head can be expressed as $h_s = c_s h_w$, where c_s is a coefficient that itself may vary with stage. The nature of any such relationship would depend strongly on the stream hydraulics and orifice configuration at any particular site. Because the stagnation head is a function of the orifice installation and not an inherent characteristic of the manometer, it is not discussed or evaluated further, but is retained in the equation for generality.

The friction pressure p_f also can be expressed as a friction head, $h_f = p_f/\rho_w g$. This term represents the pressure needed to force the purge gas to flow through the bubble-delivery tube. Because the gas flow rates are low, typically 15-80 bubbles/minute, Poiseuille's equation applies, and the friction head varies linearly with the bubble-delivery tube length and the bubble rate. Rantz and others (1982, p. 71-72) present results that imply that bubble gages typically are designed so that friction heads, h_f, are less than 0.01 foot.

The capillary pressure, p_c, represents the pressure needed to overcome surface tension at the orifice and allow the gas bubble to break free from the orifice and enter the free water body. The magnitude of the surface-tension effect, expressed as a capillarity head, $h_c = p_c/\rho_w g$, may be of the order of 0.03 ft (U.S. Geological Survey, Research Section, Columbus, Ohio, written communication, 1962).

The foregoing errors are inherent in the design of the gas-purge bubbler system. Actual field installations are subject to additional errors, including orifice fouling by chemical and biological action, burial of the orifice by sediment, and obstruction of the bubble tube by droplets of water or oil. Gas leaks in the gas-purge system and bubble tube have the effect of reducing the bubble rate at the orifice, thereby introducing lag errors in tracking rapidly rising stages. Vertical movement of the orifice itself introduces an additional error into measurement of water level relative to the gage datum. For purposes of mathematical error analysis, these and any other errors related to the orifice and bubble tube will be lumped together with the friction and capillarity errors h_f and h_c; the combined error will be denoted as h_x.

The dominant terms of equation 4 are $\rho_w g h_w$ and $\rho_m g h_m$. The density of the atmosphere, ρ_a, is about 0.001 times that of water and about 0.0001 that of mercury. The term $\rho_a g h_m$ therefore is adequately approximated by $\rho_a g h_w \rho_w / \rho_m$.

Upon making the substitutions discussed above and rearranging, equation 4 becomes:

$$h_m = \frac{\rho_w}{\rho_m} h_w \left[1 - \frac{(\rho_t - \rho_a) h_t}{\rho_w h_w} - \frac{\rho_a}{\rho_w}\left(1 - \frac{\rho_w}{\rho_m}\right) + c_s + \frac{h_x}{h_w}\right] \tag{5}$$

The terms involving ρ_t and ρ_a are called the gas-weight correction terms. Note that there are two of these terms. The first gas-weight term represents the effect of the weight of gas in the bubble-delivery tube between the orifice and the instrument. The second term represents the effect of the weight of gas in the atmospheric column between the water surface and the instrument. Together, they represent the net effect of the weights of the bubble-gas and atmospheric columns between the gage instrument and the water surface.

In applications, the manometer is connected to a servomechanism and recorder that automatically measure the mercury-column height and compute and record the water-column depth. As indicated in figure 1, the upper (float-switch) reservoir is set at a fixed position and the lower (pressure) reservoir is driven along an inclined track by a servo-motor mechanism. When the water level in the stream rises, the pressure in the tubing and pressure reservoir increases, forcing the mercury in the upper reservoir to rise and the float switch to activate the drive mechanism. The drive mechanism lowers the pressure reservoir (and attached mercury transfer tube) with the result that the mercury level falls in the upper reservoir. When the level falls to the null point, the float switch opens and the drive mechanism stops. The change in height of the pressure reservoir now equals the change in the height of the mercury column. A reverse sequence of actions occurs when the water level falls.

The motion of the pressure reservoir along its inclined track is expressed as a shaft rotation in the drive mechanism. It is this shaft rotation that is recorded by the attached output devices. The recorded water level, h_r, thus is given by

$$h_r = Gy + b \tag{6}$$

where y is the position of the pressure reservoir along the inclined track relative to the position of the null point of the float switch, G is a proportionality constant defined by gear ratios and mechanical linkages in the drive and recorder mechanisms, and b is a bias or zero-setting adjustment in the recorder mechanism. The inclined distance y is related to the vertical mercury-column length by

$$h_m = y \cos S \tag{7}$$

where S is the slant angle of the track, measured from the vertical. The value of b can be adjusted by the hydrographer to make the recorded water level h_r agree with the actual water level h_w existing at the time of adjustment.

Here and in subsequent discussion, water levels h_r and h_w, referenced to the orifice rather than to gage datum, will be used. The water levels over the orifice are the ones that are relevant to discussion of bubble gage performance. Water levels h_r and h_w referenced to the orifice can be converted to water levels relative to gage datum by adding H_0, the elevation of the orifice relative to gage datum.

Combining equations 5 through 7 yields the following expression for the recorded water level h_r in terms of the actual depth h_w:

$$h_r = G \frac{1}{\operatorname{Cos} S} \frac{\rho_w}{\rho_m} h_w \left[1 + c_s - \frac{(\rho_t - \rho_a)}{\rho_w} \frac{h_t}{h_w} - \frac{\rho_a}{\rho_w}\left(1 - \frac{\rho_w}{\rho_m}\right) + \frac{h_x}{h_w} \right] + b \tag{8}$$

It can be seen that by proper adjustment of the slant angle S and bias setting b, the manometer can be made to record the water level h_w directly. Before this can be done, however, the gas-correction terms must be evaluated.

EVALUATION OF GAS-CORRECTION TERMS

For purposes of this discussion, the gas-weight correction may be analyzed by assuming that the bubble gas is air at atmospheric temperature. Boyle's law then implies that the bubble-gas density, ρ_t, is proportional to the absolute pressure. When the water depth is h_w, the pressure is $p_a + \rho_w g h_w$ (assuming that the stagnation pressure has negligible effect on the bubble gas density). The proportionality factor can be evaluated by noting that when the water barely covers the orifice and capillarity pressure is negligible, the pressure in the bubble tube is practically equal to atmospheric and the bubble gas density also is practically equal to atmospheric. Boyle's law then gives the bubble gas density as

$$\rho_t = \rho_a \left[1 + \frac{h_w}{h_a}\right] \tag{9}$$

where h_a (= $p_a/\rho_w g$) is the height of the water column supported by atmospheric pressure at the gage. If the bubble gas is not air, the above value of ρ_t must be adjusted in proportion to the ratio of molecular weights of bubble gas and air, m/m_a. For nitrogen, the ratio is 28/29; for carbon dioxide, 44/29. Substituting equation 9, the gas-correction term thus becomes

$$\frac{(\rho_t - \rho_a)}{\rho_w} \frac{h_t}{h_w} = \left[\frac{m}{m_a}\left(1 + \frac{h_w}{h_a}\right) - 1\right] \frac{\rho_a}{\rho_w} \frac{h_t}{h_w} \tag{10}$$

Smith (Geological Survey, written commun., 1974) gives a more detailed evaluation of the gas correction term. The two evaluations give equivalent results for pressure-tube heights h_t less than about 350 feet (275 ft for CO_2).

After substitution of equation 10, the manometer equation 8 becomes

$$h_r = \frac{G}{\cos S} \frac{\rho_w}{\rho_m} \left\{h_w \left[1 + c_s - \frac{\rho_a}{\rho_w}\left(1 + \frac{m\, h_t}{m_a h_a}\right) + \frac{\rho_a}{\rho_m}\right] + h_x + \frac{\rho_a}{\rho_w}\left(1 - \frac{m}{m_a}\right) h_t\right\} + b \tag{11}$$

The value of h_a varies approximately linearly with altitude from about 34 feet at sea level to about 28 feet at 5,000 feet above sea level. Under standard atmospheric conditions, ρ_a/ρ_w is approximately 0.00124 at sea level and 0.00106 at 5,000 feet. The value of h_t is not fixed, as can be seen from figure 1, but the range of variation of h_t is less than 1/10 of the range of h_w and this magnitude of variation of h_t has little effect on the recorded values h_r in equation 11.

For a given manometer installation the value of G is fixed and, for purposes of error analysis, h_t also may be considered constant. For given water and air (mercury) temperatures, T_w* and T_m*, the corresponding densities ρ_w* and ρ_m* are fixed. The manometer scale factor may be made equal to unity by adjusting the slant angle S such that

$$\cos S = G \frac{\rho_w^*}{\rho_m^*} \left[1 + c_s - \frac{\rho_a}{\rho_w^*} \left(1 + \frac{m\, h_t}{m_a h_a}\right) + \frac{\rho_a}{\rho_m^*}\right] \qquad (12)$$

If c_s varies with stage, an approximate average value would be used to obtain a scale factor that was approximately equal to unity. After the scale factor is set, the index adjustment can be set to make the recorded stage, h_r, agree with the actual water level, h_w. It is seen that gas weight is only one of several factors that affect the scale factor and index adjustment of a bubble gage. The gas-weight terms are the ones containing ρ_a in equations 11 and 12 above. The gas-weight effect on the scale factor is most significant when the water level is high, and has little effect when the depth over the orifice (h_w) is near zero. It is also noted that the gas-correction terms are proportional to the bubble-tube height, h_t, so that the correction is more important for gages set high above the water than for ones set at lower heights.

The actual effect of the gas-weight terms depends on how the manometer scale factor (slant angle) is set. If the scale factor is set according to some theoretical formula that does not include gas weight, then the scale factor will tend to be too small and the manometer will tend to under-register at high stages. In such cases the scale factor also will be in error by the magnitude of the stagnation coefficient c_s. This coefficient may either add to or offset the gas-weight error. On the other hand, if the scale factor is set by field calibration based on direct measurements over the range of high and low stages, then the gas-weight and stagnation terms both are automatically taken into account, and there is no gas-weight error. Such calibration might be accomplished either by adjustment of the manometer slant angle or by application of a calibration curve based on concurrent manometer readings and direct stage measurements. The bubble-gage manuals (USGS, written communication, 1962; Craig, 1983), W. Smith (USGS, written commun., 1974), and Rantz and others (1982) allude to the possibility of field calibration of the scale factor, and the 1962 manual gives detailed instructions. The index adjustment always is set in the field by comparison with a direct measurement of the water level. The gas-weight term that is independent of h_w thus is automatically taken into account in the index-adjustment setting, along with the error term h_x.

Sample computations of the gas-weight terms are shown in table 1. The ratio of atmospheric density to mercury density, ρ_a/ρ_m, is neglected in comparison to the other two gas-weight terms. The results for bubble tube height h_t of 230 ft may be compared with those of W. Smith (USGS, written commun., 1974). Note that the entries in this table represent errors only if the manometer scale factor and index adjustment are set by theoretical formulas that ignore gas weights; field calibration for high stages would automatically account for these terms.

TEMPERATURE SENSITIVITY

The main source of temperature sensitivity in the manometer is the temperature variation of the water and mercury densities ρ_w and ρ_m. Dimensional changes in the manometer itself may also be significant. Therefore, the following equations cannot be used by themselves to compute precise temperature corrections, although they do provide informative estimates of error magnitudes. The temperature variations of the water and mercury densities are illustrated in figures 2 and 3. (Data from Lange, 1944, p. 1376-77; the densities are taken relative to water at 4°C.).

The variation of density with temperature may be represented approximately by the following equations: for mercury,

$$\rho_m = 13.596 - 0.00246\ T_m \tag{13}$$

and for water

$$\rho_w = 1.00 - (6.20\times10^{-6})(T_w-4)^2 \tag{14}$$

where temperatures are expressed in degrees Celsius. In general, the water temperature T_w will be different from the mercury temperature T_m.

Table 1. -- *Gas-weight heads for selected station elevations, bubble-tube heights, water levels, and bubble gases.*

Elevation (feet)	Standard-Atmosphere Pressure Head h_a (feet H_2O)	Standard-Atmosphere Density ρ_a/ρ_w (--)	Bubble-tube Height h_t (feet)	Water Level h_w (feet)	$-\frac{\rho_a}{\rho_w}(1+\frac{m}{m_a}\frac{h_t}{h_a})h_w$ (feet)	$+\frac{\rho_a}{\rho_w}(1-\frac{m}{m_a})h_t$ (feet)	Total Gas-Weight Head (feet)
Bubble Gas: Nitrogen, m/m_a = 0.966							
0	34	0.00124	30	10	-0.023	0.001	-0.022
				30	-.069	.001	-.068
			100	10	-.048	.004	-.044
				30	-.143	.004	-.139
			230	50	-.467	.010	-.457
				150	-1.401	.010	-1.391
5000	28	0.00106	30	10	-.022	.001	-.021
				30	-.065	.001	-.064
			100	10	-.047	.004	-.043
				30	-.142	.004	-.138
Bubble Gas: Carbon Dioxide, m/m_a = 1.517							
0	34	0.00124	30	10	-.029	-.019	-.048
				30	-.087	-.019	-.106
			100	10	-.068	-.064	-.132
				30	-.203	-.064	-.267

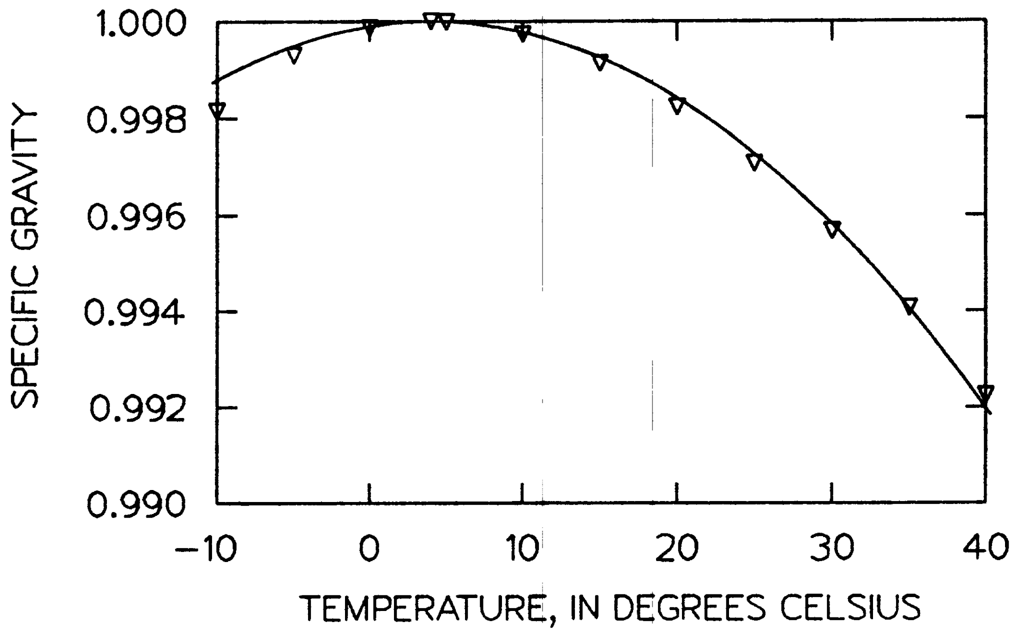

Figure 2. Density of water as a function of temperature. Density is expressed as specific gravity relative to water at 4°C.

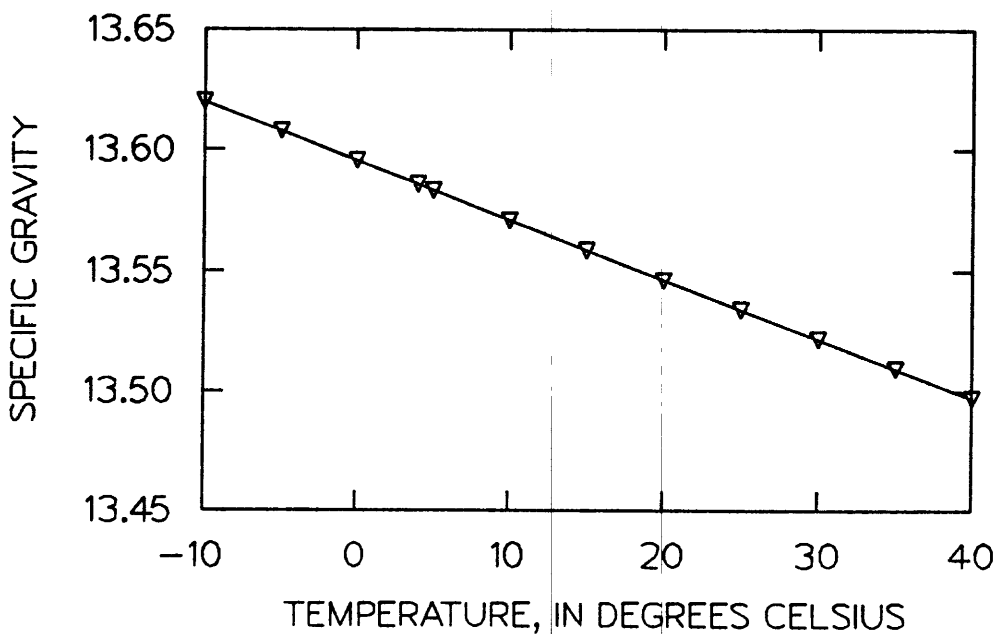

Figure 3. Density of mercury as a function of temperature. Density is expressed as specific gravity relative to water at 4°C.

For given water and mercury temperatures T_w^* and T_m^* (and corresponding densities ρ_w^* and ρ_m^*), the slant angle and index adjustment of a given manometer installation can be set so that the recorded stages, h_r, equal the actual water levels, h_w, above the orifice. For other temperatures and densities, the manometer equation becomes, approximately,

$$h_r = \frac{\rho_w}{\rho_w^*} \frac{\rho_m^*}{\rho_m} h_w \tag{15}$$

For temperature variations that are not too large, the density variations may be approximated by the derivatives of equations 13 and 14, as follows:

$$\rho_m = \rho_m^* - 0.00246(T_m - T_m^*) \tag{16}$$

$$\rho_w = \rho_w^* - (12.40\text{x}10^{-6})(T_w^*-4)(T_w-T_w^*) \tag{17}$$

Equation 15 then becomes

$$h_r = \frac{1 - (12.40\text{x}10^{-6})(T_w^* - 4)(T_w - T_w^*)}{1 - 0.000181\ (T_m - T_m^*)} h_w \tag{18}$$

in which values of $\rho_m^* = 13.6$ and $\rho_w^* = 1.00$ have been used. The fraction term in equation 18 is of the form (1 - a)/(1 - b), with a and b both much less than 1. This ratio is approximately equal to 1 + b - a. Making this substitution and rearranging equation 18 yields the following expression for the relative error due to temperature variations:

$$(h_r - h_w)/h_w = 0.000181\ (T_m-T_m^*) - (12.40\text{x}10^{-6})(T_w^*-4)(T_w-T_w^*) \tag{19}$$

Equation 19 indicates that the percentage error in h_r is roughly 0.02 percent per degree Celsius mercury temperature error, with a smaller variable compensating effect for water temperature error. This result is consistent with Craig (1983, p. 4).

Diurnal air temperature variations commonly are of the order of 5 to 10°C (U.S. Geological Survey, 1970, pp. 102-107). The diurnal variations are superimposed on seasonal variations that can add several Celsius degrees to the anticipated range of air temperature fluctuations between hydrographer's visits to a gage. Finally, it is well known that temperatures in enclosed spaces exposed to the sun are substantially higher than ambient air temperatures; many gage shelters are thus affected. It would seem, therefore, that gage-house temperatures of 10°C above and 5°C below any seasonal mean temperature would occur with significant frequency and that substantially larger deviations (for intervals of several hours during at least several days per month) could possibly occur.

Information on diurnal and short-term water-temperature fluctuations is less well known. Water-temperature fluctuations would be expected to be smaller and more site-dependent than air-temperature variations. For purposes of discussion, water-temperature deviations of 3°C above and below a seasonal mean will be considered.

The water-level errors resulting from various temperature fluctuations around various seasonal mean temperatures are shown in table 2. The errors are computed from equation 19 and are expressed in percent. It is apparent that relative errors of 0.1 to 0.2 percent must be expected with significant frequency. In 1989 and prior years, the USGS had published error tolerances for water-level measurements (Olive, 1989, Rapp, 1982) that were based on ±0.050 percent error for full-scale measurements. The resultant absolute error (for example, ±0.018 feet for a 35-foot scale) was used as the tolerance for all measurements on the scale. Thus the tolerable relative error was larger for small measured values than for large ones. For measurements of 1/10 full scale, for example, the tolerable relative error was 0.50 percent.

During 1989, the tolerance for stage-measurement errors by pressure sensors (including manometers) was lowered from ±0.05 percent of full scale to ±0.02 percent of full scale and the full-scale length was established at 50 feet (USGS, written communication HIF-S-02, 1989). This change in tolerance was made after the analysis presented in this report had been performed. For clarity, the tolerance in effect at the time of the analysis is referred to as the pre-1989 tolerance in the remainder of this report.

Table 2.-- *Relative error of recorded water-column height as function of temperature deviations from seasonal mean. [°C, degree Celsius; % percent]*

Seasonal mean temperature T_m^*, T_w^* (°C)	Mercury temperature T_m (°C)	Water temperature T_w (°C)	Relative error: Mercury component %	Relative error: Water component %	Relative error: Total %	Relative error: Ratio to pre-1989 tolerance (0.05%)
0	-5	-3	-0.090	-0.015	-0.105	-2.1
		+3		+.015	-.075	-1.5
	+10	-3	+.181	-.015	+.166	+3.3
		+3		+.015	+.196	+3.9
15	10	12	-.090	+.041	-.049	-1.0
		18		-.041	-.131	-2.6
	25	12	+.181	+.041	+.222	4.4
		18		-.041	+.140	2.8
30	25	27	-.090	+.097	+.007	+0.1
		33		-.097	-.187	-3.7
	40	27	+.181	+.097	+.278	5.6
		33		-.097	+.084	1.7

The ratio of computed temperature error to pre-1989 USGS full-scale tolerable error (0.05 percent) is tabulated in the last column of table 2. This ratio represents the multiplicative factor by which a full-scale reading would be out of tolerance. Conversely, the reciprocal represents the fraction of full scale for which readings would be within the absolute pre-1989 tolerance. A ratio of 2 implies, for example, that only readings on the lower half of the scale would be within the pre-1989 tolerance. It is apparent that under reasonably frequently occurring temperature conditions only a small fraction of the low end of the manometer range can give readings that are within the pre-1989 tolerance. The current tolerance would be met only in an even smaller fraction of the low end of the range.

FIELD SIGNIFICANCE OF TEMPERATURE SENSITIVITY

The significance of this theoretical finding must now be evaluated. It is well known that water levels in streams and rivers are quite low for most of the year. During a few days or weeks per year the water level approaches bank-full. On relatively rare occasions, roughly every other year on average, a flood peak briefly exceeds bank-full level. Because of their infrequent occurrence, flows at or above bank-full level contribute only a small part of the total volume of water delivered by the stream. Most of the water is delivered by flows that are well below bank-full.

Automatic-recording manometers are used primarily to measure the relatively low water levels that occur on most days of the year and that contribute the bulk of the water delivered by the stream. Stage measurements at near-bank-full and overbank levels are complicated by hydraulic conditions in the fast-flowing water. These conditions affect all types of stage-measurement instruments. They are related not to the physical characteristics of manometers (or other pressure-sensing instruments) but to the actual pressures and water levels in the stream at the point or points that are sensed by the instrument. The actual pressures or water levels at the point sensed may not always be representative of the water level in the stream cross section as a whole. For this reason various means are used to determine water levels at near-bank-full and overbank levels. These methods include use of crest-stage gages and observation and surveying of high-water marks in addition to the manometer record. The accuracy of high-water-level measurements thus does not depend solely on manometer accuracy.

At lower water levels, more reliance, of necessity, is placed on the manometer record. Even at low stages, however, the manometer reading is checked against an outside reference-gage reading each time the gaging station is inspected. If necessary, the manometer readings are corrected and the manometer reset to agree with the reference-gage reading. These adjustments, however, are related to the datum or origin of the manometer readings, whereas the temperature sensitivity is related to the scale factor. Nonetheless, adjustment of the manometer readings to conform to reference-gage readings does help to minimize the effects of any scale-factor errors. Moreover, as noted above and in table 2, the effects of scale-factor errors are reduced when the manometer readings are confined to the low end of the scale.

A critical question thus is how much of the non-flood discharge record is collected with the aid of manometers operating in the high-stage ranges where temperature sensitivity is important. Alternatively, what is the normal range of non-flood stages at which manometers are operated? To answer this question, an informal survey of USGS manometer installations was conducted in 1986.

The USGS in 1987 collected continuous records of stage at about 8,200 sites, including about 780 sites on lakes and reservoirs (Condes de la Torre, 1987; figures for 1986 are not readily available.) About 2,700 manometers were used in 1986 to collect continuous records of stage, and about 2,840 in 1990 (J.C. Futrell, USGS, written communication, 1990). Most of the manometers at discharge-record stations (as opposed to lake-level stations) have a 35-foot measurement range. Because temperature sensitivity begins to become important relative to the pre-1989 USGS stage-measurement specification at about one-fourth of full scale (table 2), USGS District offices were asked to identify manometers at which stages in excess of 8-10 feet were likely to occur. For these stations, the Districts were asked to estimate the stages corresponding to the partial-duration flood base, the mean annual flood, and several points on the daily-mean flow-duration curve. Because the Districts were asked to supply only the most readily available information, the responses are not all directly comparable. They furnish a general indication of bubble-gage operating conditions, but not a comprehensive inventory or statistical sample. Therefore, only a general summary of the results will be given.

Responses were received from 26 District offices, representing a total of about 3,800 sites at which continuous records of discharge are collected. About 770 sites were identified as manometers subject to occasional occurrence of stages (depth over orifice) exceeding 8-10 feet. At a significant fraction of these sites, however, only relatively rare floods, with return periods much greater than 2 years, exceeded the 8-10 feet stage. At approximately 530 sites, flood-peak stages exceeded 8 feet with frequencies ranging from several per year to one per several years. At approximately 270 of these sites the flood- peak stages exceeded 12 feet at this frequency. Thus, at about 10-15 percent of the sites in the Districts responding, there is a significant frequency of occurrence of flood-peak stages at which manometer temperature sensitivity might lead to manometer-recording errors exceeding the pre-1989 published tolerances. (Under the current tolerance, a greater number of sites would be so affected.) As explained above, however, a number of other factors contribute even larger errors to flood-peak stage measurements. Because of these potential errors, peak stage measurements, especially the highest and most significant ones, typically are corroborated, and corrected, if necessary, by independent observation of high-water marks. Thus it is expected that manometer temperature sensitivity would not likely be a major source of error in actual published flood-peak stage determinations.

On all but the largest rivers, daily-mean discharges tend to be considerably smaller than instantaneous peak discharges. At the sites surveyed, Districts were asked to report equivalent stages corresponding to daily-mean discharges that were exceeded on several (3-10) days per year. At approximately 400 stations, daily-equivalent stages in excess of 8 feet occurred on 3-10 days per year. At about 200 stations the daily-equivalent stages exceeded 12 feet with this frequency. Thus at about 5-10 percent of all stations in the Districts responding, there is a significant number of days per year (3-10) at which the daily-mean flow occurs at stages at which manometer temperature sensitivity might exceed the pre-1989 tolerance. (Under the current tolerance, a larger percentage of stations would be so affected.) Many respondents pointed out, however, that in their opinion various other error sources, primarily drawdown, were more important sources of error in manometer reading at these stages.

In addition to information on stages, information on the existence of temperature data was requested from the District offices. Water temperatures are measured and recorded continuously along with other water-quality parameters at a few sites, but gage-house air temperature-variation effects are not generally measured. Only 7 out of the 770 manometers identified by the survey were equipped with the optional temperature-compensation servomechanism. One respondent pointed out that quasi-gage-house temperatures could be obtained from temperature sensors in some data-collection platforms (DCP's), provided that the DCP's were programmed to transmit the data, data-channel transmission capacity were allocated to transmit the data, and appropriate software were provided to make use of the data.

It is of some interest that more than half the high-stage manometers in this survey were reported by a single District, in which the great majority of all gages were manometers subject to high stages. Almost one-fourth of the remaining manometers were reported by just two other Districts. These three Districts accounted for approximately 90 percent of the manometers at which stages exceeded 8 and 12 feet with significant frequency. Further investigation revealed that these Districts have many streams with deeply incised main channels, little or no active flood-plain storage, and low channel slopes. Responses from other Districts indicated that although maximum stages of record may have exceeded 8 feet, 2-year-flood stages typically were well under 8 feet and stages that were exceeded a few days per year were even lower. These Districts had many streams with non-incised channels, active flood plains, and steep channel slopes. Thus, it appears that high-stage manometer records might be confined to a few Districts or to identifiable physiographic regions or channel morphologies.

A recurrent theme in the responses to the survey was that a variety of environmental factors influence the relation between the water stage and the gas pressure that is recorded by the manometer. At data-collection sites where stream stage and discharge are determined, these factors include velocity drawdown or stagnation effects, effects of sediment and dissolved solids concentrations on water density, deposition of silt over the orifice, fouling of the orifice itself by scale or other deposits, and movement of the orifice. To monitor these factors, manometer readings are regularly compared with independent readings of outside reference gages. Discrepancies of the order of several hundredths to several tenths of a foot commonly are observed. The manometers are reset and the readings corrected as necessary to eliminate these discrepancies. Even after allowance for these corrections, however, the residual uncertainties in the manometer record generally are believed to be substantially greater than the errors attributable to temperature variations. For this reason it appears to be superfluous to attempt to provide temperature-variation adjustments to manometer records of stage in streams.

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