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Radioisotope Gauge for Monitoring Suspended Sediment in Rivers and Streams

C. A. ZIEGLER, J. PAPADOPOULOS and BACH SELLERS
Parametrics Inc., Waltham, Massachusetts

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The problem of determining the amount of water carried suspended sediment is of increasing importance in areas such as agriculture, navigation and water conservation. Conventional point sampling methods have proved inadequate to meet current hydrology planning needs because short term concentration excursions cannot be monitored. To satisfy the need for a self-powered, continuous monitoring system, a gauge based on the use of radiation from a radioisotope source, having the capability of continuously measuring sediment concentration over a concentration range of 1000–50,000 ppm was designed, developed and tested. The system is capable of operating and recording data unattended for a period of 7-1/2 days on internal power, thus constituting a completely automatic monitoring system.

The theory of operation, error analysis, calibration methods, operating procedures, and test results, are presented.

UNE JAUGE RADIOISOTOPIQUE POUR LA MESURE DU SÉDIMENT SUSPENDU DANS LES FLEUVES ET RIVIÈRES

La question de la mesure de la quantité de sédiment suspendu dans l'eau possède une importance croissante en rapport aux sujets tels que l'agriculture, la navigation et la conservation de l'eau. Les méthodes conventionnelles de faire les échantillons d'un point à l'autre se sont montrées insuffisantes à satisfaire les besoins courants de dressage des plans hydrologiques puisqu'il est impossible de suivre les excursions de concentration de petite période. Afin de satisfaire le besoin pour un système de dosage continu ayant sa propre source d'énergie on a dessiné, mis à point et éprouvé une jauge qui emploie le rayonnement d'une source radioisotopique, capable de mesurer continûment la concentration du sédiment par une gamme de 1·000 à 50·000 ppm. Le système est capable de fonctionner et d'enregistrer les données sans attention durant une période de 7½ jours sur sa source d'énergie intérieure, ce qui donne un système de mesure tout-à-fait automatique.

On présente la théorie de fonctionnement, l'analyse des erreurs, les méthodes d'étalonnage, les façons d'emploi et les résultats des essais.

РАДИОИЗОТОПНОЕ УСТРОЙСТВО ДЛЯ ИЗМЕРЕНИЯ СУСПЕНЗИРОВАННЫХ ОСАДКОВ В РЕКАХ И ТЕЧЕНИЯХ

Проблема определения количества суспензированных осадков, переносимых водой, имеет все увеличивающееся значение в таких отраслях как навигация, сельское хозяйство, хранение воды. Обычные методы взятия образцов из разных точек не могут удовлетворить современные методы гидрологического планирования, так как кратковременные изменения концентрации не могут быть замечены. Для удовлетворения этих нужд была разработана система с собственным источником питания использующая радиацию от радиоактивного источника и имеющая способность измерять концентрации в пределе от 1.000 до 50.000 $\times 10^{-6}$. Система была развита и проверена. Она способна делать и записывать измерения в течении 7.5 дней, используя внутреннюю энергию, что превращает ее в автоматическую измерающую систему.

Теория действия, анализ ошибок, методы калибровки, упраление прибором и результаты испытаний представлены в статье.

RADIOISOTOPENMESSGERÄT ZUR KONTROLLE VON SCHWEBEGUT IN FLÜSSEN UND STRÖMEN

Die Frage Bestimmung des Betrages des vom Wasser mitgeführten schwebegutes wird immer wichtiger in Gebieten wie z.B. im Ackerbau, in der Schiffahrt und in der Wasserwirtschaft. Die üblichen punktweisen Probeentnahmen waren unzureichend für die Zwecke der neuzeitlichen wasserwirtschaftlichen Planung, weil kurzzeitige Abschweifungen in der Anreicherung nicht kontrolliert werden können. Um den Bedarf für ein selbststänges ununterbrochen arbeitendes System zu decken wurde ein auf der Verwendung der Strahlung von einer Radioisotopenquelle beruhendes Messgerät, das ununterbrochen den Schwebegutgehalt über einen Anreicherungsbereich von 1000 bis 50,000 T.p. Mill. messen kann, konstruiert, entwickelt und geprüft. Das System kann ohne Wartung arbeiten und Daten registrieren über einen Zeitraum von $7\frac{1}{2}$ Tagen und hat eine eingebaute Kraftversorgung, sodass es ein vollkommen automatisches Kontrollsystem darstellt.

Es wird die Theorie der Wirkungsweise, die Fehleranalyse, Eichmethoden, Arbeitsweisen und Prüfergebnisse dargelegt.

INTRODUCTION

The determination of the concentration of suspended sediment carried by natural and man-made waterways is of increasing importance to agencies concerned with water conservation and control. Conventional point sampling methods have proven unsuitable in areas where difficulty of access, or flash floods and subsequent large, short term concentration excursions preclude an adequate sampling program. In order to satisfy the need for a self-powered, continuous monitoring system a gauge based on the attenuation of radiation from a radioisotope source has been developed. Advantages of a radioisotope technique are first, because a beam of radiation is used as the sensing agent, the water and sediment are not perturbed, which permits greater accuracy than is obtainable using conventional mechanical sampling methods; and second, continuous sampling is possible with low power drain and high reliability. The latter is important inasmuch as the gauge must operate continuously and unattended for a week at a time.

In order to arrive at the most appropriate system design three areas were investigated in detail: (a) because long term, unattended operation was desired it was necessary to develop an operational theory in the context of a stable self-referenced system; (b) since the radiation energy is of prime importance in determining attenuation gauge characteristics, a study to ascertain the most appropriate radioisotope source was carried out; and (c) a geochemical survey of the concentration levels and composition variation of both dissolved and undissolved material at typical sites was made. This was necessary in order to predict gauge performance, because X- and gamma-ray absorption depends on both the density and composition of the attenuating medium. Reports covering the above research are available from the Office of Technical Services, Department of Commerce, Washington, D.C.(1,2,3) The sediment gauge described in the following sections constitutes the end result of these preliminary studies.

SYSTEM SPECIFICATIONS

The development program for this system was sponsored by the Division of Isotopes Development, U.S.A.E.C. with the cooperation of the Inter Agency Sedimentation Project representing members of thirteen U.S. Agencies interested in sediment measurement. Through the Technical Committee of the Sedimentation Project specifications were established representing the requirements of a gauge capable of widespread use within the continental U.S.

Concentration range. 1000–50,000 ppm of sediment of density averaging 2·65 g/cm^3.

Accuracy. Better than ±20% from 1000 to 50,000 ppm by weight.

Data retrieval. Data to be recorded permanently at 15 or 3 min intervals (real time) on tape capable of receiving data continuously over a $7\frac{1}{2}$ day period without replacement.

Environmental. Operational temperature-measuring head, 32–85°F; control unit, 20–120°F; survival temperature-measuring head and electronics −15–120°F.

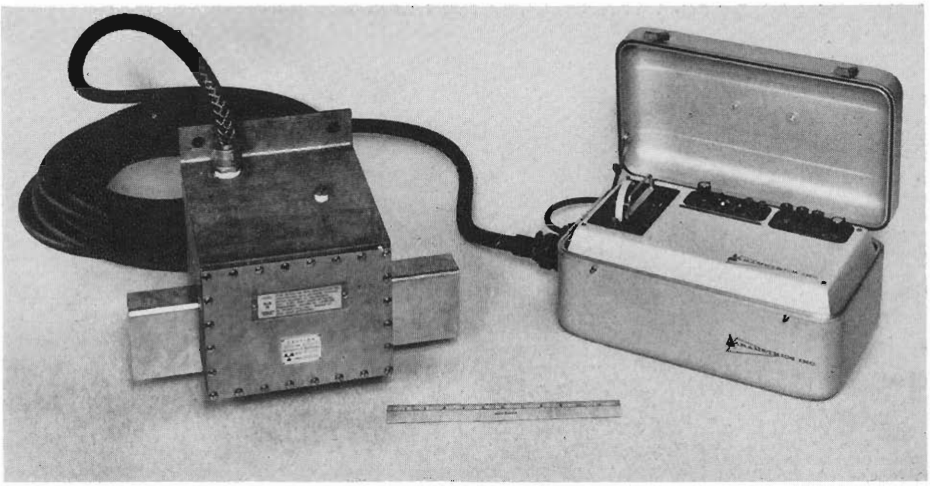

Fig. 1. Photograph of underwater measuring head and control unit. The channel extension shown on the head provides for a smooth flow of water through the test channel. No perturbation of sediment has been observed for flow rates up to 6 fps.

Power. Operable either from 115 V. a.c. power source, or from four automobile type batteries capable of supplying all system requirements for 7½ days of continuous operation.

DESCRIPTION OF GAUGE

The gauge consists of two units connected by up to 125 ft of flexible cable: a weatherproof shore based control unit; and a submersible measuring head. Figure 1 is a photograph of both units. The shore unit is an aluminum box 16 in × 9 in × 8 in, weighing 17 lb, containing a digital printer, the various counting electronics, a timer and the necessary low voltage power supplies. A switch on the control unit allows selection of a 15- or a 3-min readout period. Since readings are printed out in digital form on paper tape at accurately timed intervals their sequential position indicates the time of reading if the starting time is known.

The measuring head is brass, weighs 50 lb, and is 7½ in. 9½ × 11 in. It contains the radioactive source, the source switching mechanism, the X-ray detector and preamplifier, and the high voltage supply for the X-ray detector. External brackets are provided for mounting on the side of a wall or pier.

Basically, the gauge observes the ratio of X-ray transmission through ambient water containing suspended sediment and a reference liquid such as distilled water. This ratio is a function of the ratio of the X-ray attenuation in the two liquids and, therefore, in the absence of an appreciable amount of dissolved material, the ratio is a function of the concentration of suspended sediment in the ambient water. This mode of operation eliminates errors that would otherwise be introduced due to the decay of the radioactive source, secular drifts in the X-ray detector response and in the electronics, and changes in the liquid density due to temperature.

The radioactive source is Cd^{109} in the form of metallic cadmium plated on a copper substrate. This source has a half-life of 470 days and emits an electron capture X-ray of 22 keV energy. It also emits an 87 keV gamma ray about 4% of the time. Gauge operation depends on the attenuation of the 22 keV X-ray (the 87 keV gamma-ray forms an undesirable radiation component since it is relatively unattenuated in traversing the water path). The radioactive source has an initial strength of about 1·3 mc and is designed to operate the gauge for over one year.

The X-ray Detector is a square cross section side window proportional counter filled with two atmospheres of 90% krypton–10% methane. The window is 5 mil beryllium, and there is a two-inch path length for the detected X-rays, which results in an efficiency of 80% at 22 keV and 2% at 87 keV. Thus, the probability of detecting the unwanted gamma at 87 keV is small. The shape of the observed spectrum after transmission of the X-rays through 8 cm of distilled water is shown in Fig. 2. The peak below the 22 keV peak is the result of escape of the krypton K X-ray after detection of the 22 keV X-ray. As a result of the very high signal to noise ratio inherent in this type detector it is possible to use an integral electronic discriminator set at about 4 keV.

The gauge has been designed and constructed to insure compliance with the most stringent safety requirements. The radioisotope used emits primarily a low energy X-ray which is almost completely absorbed in the housing of the gauge. Moreover, because the source material is electroplated metallic cadmium the possibility of leakage of source material is remote. The external radiation levels at exterior surfaces of the gauge are low (less than 0·1 mr/hr) and the unit may be handled without the necessity of monitoring external radiation.

THEORY OF OPERATION

The radioactive source is cycled mechanically between two positions to provide attenuation measurements sequentially on known and unknown media. The dual cell arrangement is shown in Fig. 3. For theoretical purposes it is considered that the reference cell contains distilled water which assumes the same temperature as ambient water. The X-ray absorption equation for the reference cell is described by

$$N_w = N_1 e^{-\alpha_w \rho_w x} \tag{1}$$

where N_w is the number of counts due to source X-rays that are detected per sec, x is the X-ray path length in the reference cell, α_w and ρ_w are the mass absorption coefficient and density of

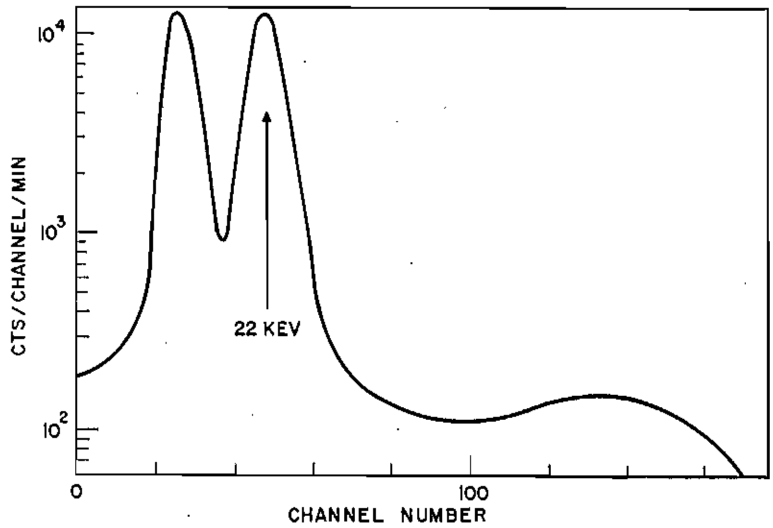

FIG. 2. Differential pulse height spectrum of C^{109} source observed by proportional counter.

the distilled water and N_1 is the number of counts per unit time that would be detected if there were no water in the reference cell. The count rate recorded in a similar cell containing the suspended sediment is

$$N_m = N_2 e^{-[(\alpha_s - \alpha_w)f + \alpha_w]\rho_m x} \tag{2}$$

where N_2 is the number of counts that would be recorded if there were no water in the sediment cell, and where α_s is the absorption coefficient for the sediment, f is the fractional weight occupied by the sediment and ρ_m is the density of the sediment-water mixture.

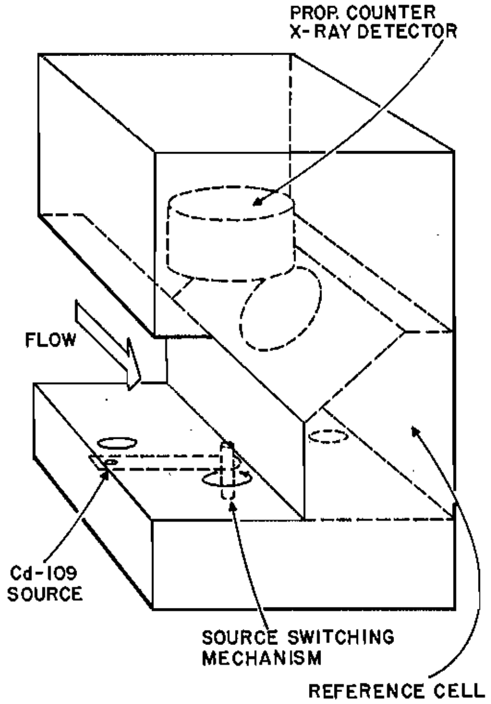

FIG. 3. Schematic view of measuring head.

$$\rho_m = \frac{\rho_s \rho_w}{\rho_s - f(\rho_s - \rho_w)} \tag{3}$$

Here ρ_s is the sediment density.

For sediment concentrations no larger than $f = 0{\cdot}05$ (50,000 ppm), the maximum design limit, the second term in the denominator of (3) is small compared to the first. Then

$$\rho_m/\rho_w \approx 1 + f(\rho_s - \rho_w)/\rho_s \tag{4}$$

Division of (2) by (1), utilizing (4) and neglecting the very small term in f^2 yields the ratio R defined by

$$R \equiv N_m/N_w = Ce^{-f/S} \tag{5}$$

where $C = N_2/N_1$ is the value of R when $f = 0$ and is a constant for any gauge and reference liquid. Due to slight differences in mechanical alignment etc. it is not exactly unity even with a distilled water reference. This has no effect on system accuracy. S is a "stream constant" defined by

$$S = 1/\rho_w x(\alpha_s - \rho_w \alpha_w/\rho_s) \tag{6}$$

S can be written as a fraction, or it can be given the units of ppm if f is written in ppm. Solution of (5) for f yields

$$f = S \ln (CN_w/N_m) = S \ln (C/R) \tag{7}$$

Thus the first order correction to the change in mixture density with f, as given by (4), can be included, and attenuation of the radiation is described by the simple exponential form of (5). Use of this expression, rather than the more complicated one that results when (3) is used for ρ_m, introduces an error of only about 1% at 50,000 ppm. The error is actually somewhat less than this if S is defined experimentally rather than calculated from (6).

Although equation (5) was derived under the assumption that distilled water is used in the Reference Cell, it is equally applicable for other reference liquids. Both C and S depend on the reference used, thus equation (6) can only be used to estimate S for distilled water.

System operation can be understood with reference to the block diagram of Fig. 4. The objective of the counting system is to measure the ratio of counting rates of source X-rays transmitted alternately through the Reference and Sediment Water Cells. This is accomplished by accumulating counts in the Reference Counter for the time required to reach a

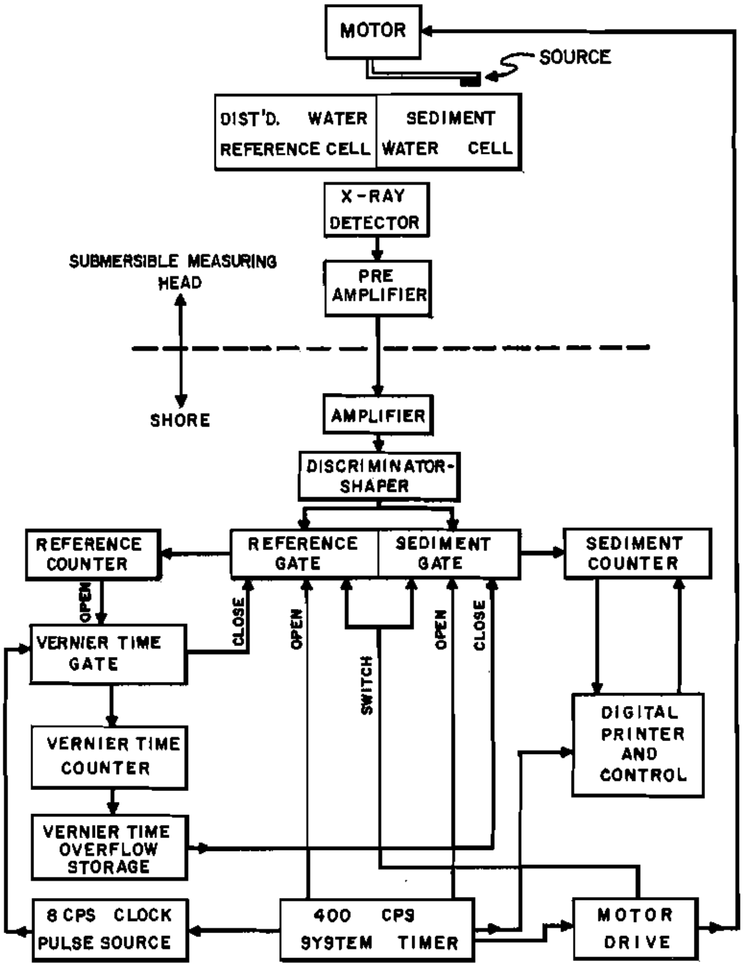

FIG. 4. Counting logic block diagram.

selected capacity, and then the number of counts accumulated in the Sediment Counter during an equal amount of time is printed out. In this way the Sediment Count reading is proportional to the ratio N_m/N_w. The length of time required for the Reference Counter to reach the preset value increases over a period of several months as the source intensity decreases. However, the statistical accuracy is the same throughout the life of the source since during this period the same preset number of counts N_w is always accumulated.

A description of the counting system operation is as follows. Initially, a switch selected choice is made between ratio printouts every 3 or 15 min, corresponding to 160,000 or 800,000 accumulated counts, respectively, in the Reference Counter. Once the unit is placed in operation the sequencing of all events is controlled by the 400 c/s System Timer. At the beginning of each measurement interval the Reference and Sediment Gates receive a signal that allows them, subsequently, to be switched open or closed by signals from the Motor Drive unit.

The X-ray Detector pulses, processed by a Pre-amplifier, Amplifier and Discriminator-Shaper, are routed to both the Reference and Sediment Gates simultaneously. Only one of these gates is open at any time, however, as controlled by the Motor Drive which is actuated by the System Timer. The source is switched, and at the same tlme these gates are opened and closed, once every twelve seconds until the capacity selected is reached by the Reference Counter. The relatively rapid switching minimizes effects of temperature changes, etc. during the measurement interval. During the first second after each switching operation the system is allowed to stabilize, and the counts are recorded for the last eleven seconds. At some point in the cycle, after the source has been switched a large number of times, the Reference Counter overflows producing an output signal. This closes the Reference Gates for the remainder of the selected measurement interval and brings into operation the vernier time system. This system determines the portion of the final 11-sec required by the Reference Counter to overflow and allows the Sediment Counter to accumulate counts for this short additional period. Its use increases the accuracy of the measurement considerably over that which would be obtained without it. The vernier system quantizes each 11-sec counting period into 88 segments 0·125 sec long by use of an 8 c/s Clock Pulse Source derived from the System Timer. The overflow signal from the Reference Counter opens the Vernier Time Gate and allows the clock pulses to be accumulated in the Vernier Time Counter (a pulse scaler). Thus, some portion of the total of eighty-eight pulses generated in 11-sec will be accumulated before the source is switched to the Sediment Cell. This directly measures the portion of the final 11-sec *not* used by the Reference Counter. When eighty-eight pulses are accumulated the Vernier Time Counter produces an overflow signal that is stored in the Vernier Time Overflow Storage and which closes the Sediment Gate for the remainder of the measurement interval. The pulse scaling portion of the unit is then dormant until the System Timer actuates the Digital Printer and Control either 14⅘ min or 2⅘ minutes, after the beginning of the measurement interval, depending on whether a 15 min or 3 min print rate has been selected. The Control queries the Sediment Counter and the four most significant digits of the ratio R are then printed serially in digital form. The entire process is again initiated when the Counters have been cleared and the Gates are opened by the System Timer.

CALIBRATION AND GEOCHEMICAL CONSIDERATIONS

Calibration procedures. The gauge can be tested in the laboratory using materials which simulate sediment. Both sodium sulfate and aluminum sulfate are suitable for this purpose, since they contain typical sediment elements and are in the correct density range.

The gauge is supplied with a curve obtained with simulated sediment and an accurate reading of the ratio output with distilled water in each cell. This defines C of equation (5) for a distilled water reference. Since the response is linear on log paper, the user can obtain a complete calibration curve for a particular stream simply by obtaining one or more point sample measurements of f and plotting them on the log paper against the ratio indicated by the gauge. A straight line is then drawn through

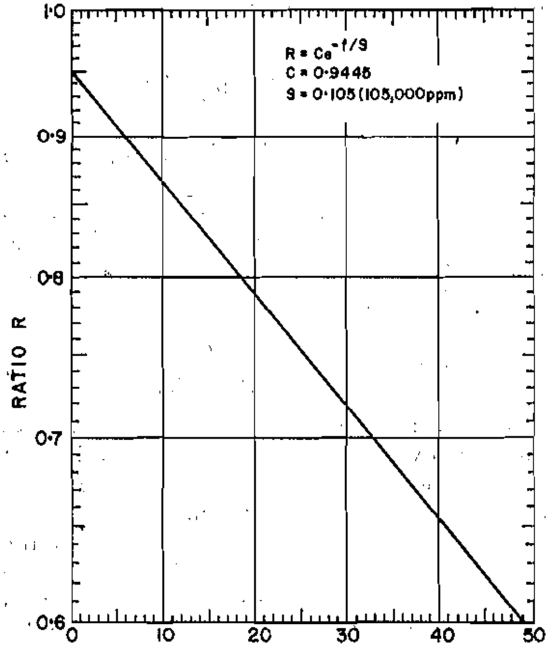

Fig. 5. Typical calibration curve obtained using sodium sulfate and distilled water reference.

these points and that corresponding to $f = 0$. A typical curve is shown in Fig. 5.

In practice it is necessary to carry out this calibration procedure whenever the user has reason to believe that a significant change in sediment composition has occurred. This means that recalibration is necessary at suitable intervals if the gauge is left in one location, or if it is moved to a new location.

Geochemical considerations. In general, X- and gamma-ray absorption depends on both the density and composition of the attenuating medium. Therefore, a valid correlation between gauge response and suspended sediment concentration requires that certain criteria be satisfied. First, the dissolved material must either make a negligibly small contribution to the density, or its concentration must be measured separately (e.g. by a conductivity cell) and an appropriate correction made. Second, variations in the composition of dissolved and undissolved material must have an acceptably small effect on gauge accuracy. Regarding the first of these factors, it was found that in the continental U.S. many sites exist where the concentration of dissolved salts in the water is sufficiently low to have a negligible effect on gauge response. Also, experiments carried out using a conductivity gauge to determine the concentration of dissolved salts demonstrated that the output of the radiation gauge could be suitably corrected so as to allow operation in water having a high concentration of dissolved material(1). With regard to the second factor, the proper selection of radiation energy is of chief importance in minimizing effects due to variation in the composition of suspended sediment. The intermediate 22 keV energy photons emitted by Cd^{109} appeared to offer the possibility of a compromise by providing reasonable gauge geometry as well as relative freedom from composition effects. In order to establish this, a geochemical survey was carried out in which the elemental variation of undissolved solids at a number of sites in the U.S. was determined. The results of this survey were then used as the basis for predicting gauge response under typical sediment composition variations.(1,2)

SYSTEM ACCURACY

The gauge performance is influenced by several sources of errors and the joint effect of all simultaneous, but independent fluctuations is considered here. The errors involved in any measurement may be broadly classified into systematic and random. The systematic errors are primarily due to composition variations in the suspended sediment, and possible long-term temperature variations. Random sources or errors are predominantly due to the statistical nature of emission of radiation, and, to a lesser extent, the reproducibility of source positioning. Effects of composition variation and statistical errors are amenable to analytical treatment and are examined in that manner here The effects of other sources of errors were deduced from experimental observations performed under controlled conditions.

At concentrations of only a few thousand ppm the principal source of errors is due to the statistical nature of emission of radiation and it is thus appropriate to consider its effect first.

Statistical uncertainty of emission of radiation. The statistical uncertainty in sediment concentration,

Δf, can be related to the uncertainties of accumulated counts N_m and N_w by

$$\Delta f = \left[\left(\frac{\partial f}{\partial N_m}\right)^2 (\Delta N_m)^2 + \left(\frac{\partial f}{\partial N_w}\right)^2 (\Delta N_w)^2\right]^{1/2} \tag{8}$$

Using (7) and noting that on a one sigma basis

$$\Delta N_m = \sqrt{N_m}; \quad \Delta N_w = \sqrt{N_m} \tag{9}$$

yields the fractional standard deviation error in f

$$\delta f \equiv \frac{\Delta f}{f} = \frac{1}{\sqrt{N_w}} \frac{\sqrt{(1 + N_w/N_m)}}{\ln(CN_w/N_m)} \tag{10}$$

or, alternatively, from (5) and (7),

$$\delta f = \frac{1}{\sqrt{N_w}} \frac{S}{f} \sqrt{\left(1 + \frac{e^{f/S}}{C}\right)} \tag{11}$$

Since N_w is constant in this system, the statistical error associated with any sediment concentration f can be readily computed from (11) once C and the stream constant S have been determined; i.e. once a calibration curve has been obtained. Equation (11) shows the dependence of statistical uncertainty on stream constant and sediment concentration. To obtain an estimate of this uncertainty consider the approximately worst cases anticipated: $f = 0{\cdot}001$ (1000 ppm), $S = 0{\cdot}100$, and $C = 1$. Then the statistical uncertainty on a one standard deviation basis is:

$$\begin{aligned} &\text{3-min readout:} \quad \delta f = \pm 35{\cdot}5\,\% \\ &\text{15-min readout:} \quad \delta f = \pm 15{\cdot}9\,\% \end{aligned} \tag{12}$$

Effects of composition variation. It is evident from equation (7) that a fractional deviation in f is equal in magnitude to an identical fractional deviation in the stream constant S. Thus

$$(\delta f)_{\text{comp}} \equiv \left(\frac{\Delta f}{f}\right)_{\text{comp}} = \delta S \equiv \frac{\Delta S}{S} \tag{13}$$

δS can be obtained either experimentally, from calibration curves of two materials with known differences in density and absorption coefficient, or analytically from equation (6) which has been shown to agree reasonably well with observed data, and should thus give an adequate estimate of the errors involved. The desired expression can be derived as follows:

$$\begin{aligned} \Delta S &= \left|\frac{\partial S}{\partial \alpha_s}\right| \Delta\alpha_s + \left|\frac{\partial S}{\partial \rho_s}\right| \Delta\rho_s \\ &= \left(\Delta\alpha_s + \frac{\rho_w \alpha_w}{\rho_s^{\,2}} \Delta\rho_s\right) S^2 \rho_w x \end{aligned} \tag{14}$$

From equations (6), (13) and (14) the fractional change in sediment concentration f can be related to fractional composition changes $\delta\alpha_s$ and $\delta\rho_s$ by

$$(\delta f)_{\text{comp}} = \frac{\alpha_s \rho_s \delta\alpha_s + \alpha_w \rho_w \delta\rho_s}{\alpha_s \rho_s - \alpha_w \rho_w} \tag{15}$$

Based on geochemical survey data(1) it was found that variations in sediment composition at a specific location introduces a variation in the absorption coefficient of sediment, for 22-keV X-rays, of about 3% and a variation in the sediment density of about 2%. Their combined effect, according to (15), introduces an error in sediment concentration of about 3·5%.

Experimental tests. The foregoing discussion on the statistical uncertainty provided a measure of the distribution of individual measurements about a mean, as described by the Poisson distribution. The distribution of the calculated statistical fluctuations, about a mean, was one

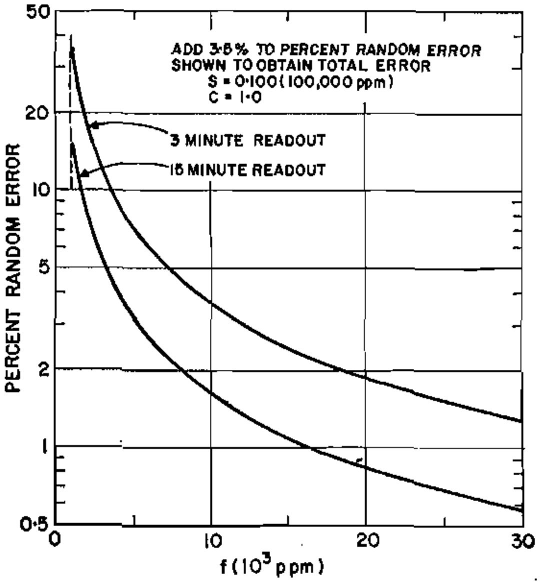

Fig. 6. Typical variation of random error with concentration.

which would be observed with an ideal counting apparatus (a system with no drifts or noise counts, and a counter with no dead-time losses). In practice the finite resolving power of the counter will tend to *reduce* the true dispersion of counts. Additionally, spurious periodic discharges of the counter and linear amplifier may also distort the true randomness of incident radiation.

Accordingly, tests were conducted in order to determine the magnitude of these effects at room temperature, and for typical temperatures in the high and low regions of the operating range of the shore base control unit which contains the counting circuitry.

As a further verification of the assumed distribution a statistical test for "goodness of fit" between the observed data and the assumed spread of Poisson distribution was examined. The chi-square test was employed for this purpose. The result of this test was satisfactory and it indicated that the apparatus behaved properly and that the assumed Poisson distribution was correct. The 3-min readout option was tested in a similar fashion and the agreement between observed and expected performance was likewise satisfactory.

It was concluded, therefore, that the only two significant errors are the random statistical error, given by equation (11), and the systematic composition variation error given by equation (15). The total error may be evaluated with the aid of Fig. 6, which shows the variation of per cent random error with concentration for both the 3-min and 15-min readout options. This was calculated using assumed values of $C = 1{\cdot}0$ and $S = 100{,}000$ ppm, which are typical of those expected. It is seen that with the 15-min readout the sum of random and systematic errors (3·5% due to composition variations) amounts to 19·5% at 1000 ppm. With the 3-min readout the total error (random + systematic) becomes less than 20% for concentrations greater than about 2200 ppm.

OPERATIONAL USE

Eleven gauges have been placed in operation at various sites within the continental U.S. These sites were selected to provide wide variations in climate and geochemistry. Field data obtained over approximately a one year period is being evaluated by the U.S. Inter-Agency Sedimentation Project.

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