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CANAL DISCHARGE MEASUREMENTS WITH RADIOISOTOPES

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ABSTRACT

A study using radioisotopes--a part of the USBR continuing program to improve water measurement practices--provided useful information for developing radioisotope techniques in open channel discharge measurements and data for establishing minimum mixing lengths. Half-capacity tests in Feb 1962 and full-capacity tests in June 1963 using Gold-198 were made in a straight section of a concrete-lined irrigation canal with a design discharge of 620 cfs. The pulse or total-count radioisotope method was used for 65 discharge measurements. Consistency of the radioisotope method was evaluated by using up to 4 portable Geiger counting systems. Conclusions were: / (1) With adequate mixing of radioisotope and canal water; accuracy of 97% or greater is possible when compared with current meter discharge measurements. (2) In a canal with hydraulic characteristics similar to the one tested, a 2,500- to 3,000-ft mixing length is needed for 98 to 99% mixing. (3) Minimum mixing length may be computed for similar straight canals using a diffusion coefficient and time factor developed from these tests. (4) Simultaneous multiple injections of tracer will provide higher probability of uniform mixing in shorter lengths than will single injections and also result in higher diffusion coefficients. (5) With sufficient data from canals of various sizes mixing length equations can probably be derived for canals having a minimum of turbulence. / Further investigation is needed to refine the limits of variables that control mixing.

DESCRIPTORS: *discharge measurement/ *radioactive isotopes/ tracers/ dyes/ *mixing/ canals/ open channels/ *radiation measurement/ diffusion/ turbulent flow/ roughness coefficients/ current meters/ fluorescein/ shear/ counting method/ dispersion/ velocity/ prototype tests/ field tests/ concentration/ Geiger counters/ pulses/ open channel flow/ test procedures

IDENTIFIERS--*mixing length/ lined canals/ Yuma Mesa A Canal/ bifurcations/ Gila Project/ surface resistance coeffs/ diffusion coefficients/ dilution method/ Gold-198/ test reaches/ *total count method

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Introduction

The Bureau of Reclamation has an important responsibility for accurately measuring the water used for generation of electricity, irrigation of reclaimed land and other beneficial purposes. This responsibility is being met through an active laboratory and field program of study to develop, improve, and apply modern equipment and methods to the measuring of rates of flow. The overall plan of research and development includes radioisotope methods of measuring discharges in closed conduits as well as in open channels and is a joint program between the Hydraulics and Chemical Engineering Branches of the Division of Research. The emphasis in this report, however, is on a study of canal discharge measurements made with radioisotopes.

In the distribution of irrigation water, one of the most difficult problems is the measuring of discharges in large canals. Gated check structures in the canal or current meter gaging stations are often used as measuring devices in operating the canals to meet water demands. The calibration, or rating, of these devices is often difficult, and the ratings may change almost daily in some locations when there is scour or deposition of sediment, where the quantity of biological growth is great, or where the dimensions of a structure change with time. One relatively new method of water measurement, which shows promise, involves the use of radioisotopes. The method appears to combine convenience with accuracy, a desirable combination of characteristics for measuring discharges in canals.

Canal Description

The flow way selected for investigating the accuracy and for developing field techniques of the radioisotope method of discharge measurement was the concrete-lined Yuma-Mesa "A" Canal, near

Yuma, Arizona, Figure 1. The Gila Gravity Main Canal with headworks at Imperial Dam on the Colorado River supplies water to the Yuma-Mesa Canal through a pumping plant.

Immediately downstream from the pumping plant there is a short sinuous length of canal followed by a straight length approximately 9,700 feet long. This straight section contains one radial gate check structure but is free of other obstructions except for two bridge piers. At the end of the selected length, the Yuma-Mesa "A" canal branches into the "A" and "B" canals.

The concrete-lined "A" canal was designed for a discharge of 620 cubic feet per second at a depth of 10.1 feet, has an 8-foot bottom width, and 1-1/2:1 side slopes. The invert is constructed on a slope of 0.00007. The average water velocity is 2.7 feet per second.

The canal operates throughout the year, and discharges can be held constant over long periods of time. By working during selected times, different discharges could be measured: approximately one-half capacity in February 1962 and full capacity in June 1963. The second test series was more elaborate in concept and execution than the first series, and reflected the improved techniques which had been developed as a result of experience.

The two test series were made in accordance with Atomic Energy Commission regulations and license and with the permission of Health Authorities of the area.

Radioisotope Discharge Measuring Method

The radioisotope technique of discharge measurement is directly related to an older principle of measurement, the chemical dilution method. The dilution method of measuring discharges eliminates the need for knowing or determining the area of flow, the velocity of flow, the roughness of the flow boundary, the water stage, the head loss, or any of the other hydraulic quantities encountered when rating by usual methods. In the dilution method, a salt or chemical solution tracer, detectable by chemical or electrical means, of known concentration C_1 is introduced at a constant rate, q, into a flow, Q, containing natural amounts of tracer, C_o. At a cross section of the flow sufficiently far downstream from the place of injection to assure adequate transverse mixing of the tracer and flow, the concentration is then C_2. From the equation of continuity, where Q is the unknown discharge,

$$QC_o + q_1C_1 = (Q + q_1)C_2 \text{ or}$$

$$Q = q_1 \frac{C_1 - C_2}{C_2 - C_o} \qquad (1)$$

if C_o is negligible compared to C_2 and q_1 is negligible compared to Q

$$q_1C_1 = QC_2$$

then

$$Q = \frac{q_1C_1}{C_2}$$

An inspection of the terms in Equation (1) shows that no knowledge is required of the flow or cross-section geometry, the velocity, gradient, or other hydraulic characteristics normally associated with flow measurements. The discharge, Q, in the canal may be determined from the measured concentrations, C_o, C_1, C_2 and the injection rate, q_1.

In the pulse or total count method, a known amount of radiotracer, A, (C_1q_1) is introduced into the flow in a comparatively short time, producing a pulse of radioactivity in the flowing water. At the measurement cross section downstream, where the tracer is thoroughly mixed with the flowing water, the concentration of the tracer is determined from the gamma ray emissions detected and counted by a Geiger-Muller or scintillation detectors. However, where C_2 was a constant of concentration in the chemical dilution equation, the concentration of radioactivity in the pulse is variable with time. In this case, considering the conservation of matter,

$$A = C_1q_1 = Q\int C_2d_t \text{ or}$$

$$Q = \frac{C_1q_1}{\int C_2d_t} = \frac{A}{\int C_2d_t} \qquad (2)$$

where changes in concentration, C_2, are measured with respect to time. It should be noted that again the physical quantities to be measured to determine the discharge, Q, do not refer to the channel shape or the hydraulic characteristics of the flow. The discharge can be calculated from concentrations C_1 and C_2, which are determined in terms of parts per milliliter of radioactive solution by use of the Geiger or scintillation counting system, or by volumetric measurement.

Instruments and Procedures

Counting Systems

Portable gamma ray counting systems were used in the total count method of measuring canal discharges. A "system" included a battery-powered scaler for counting the electrical pulses received from the detectors, and a probe composed of four Geiger-Muller tubes encased in a transparent plastic or aluminum case. The scalers and probes of these systems had been newly developed for this measurement series and were also undergoing testing as the discharge measurement investigation progressed. Thus, the systems were not always reliable and occasionally measurements were lost because of water leakage into a probe or a failure of some mechanical or electrical component.

The counting systems were calibrated by determining the counting rate of the Geiger probe submerged in a large container filled with a mixture of water and radioisotope of known concentration. For best accuracy and consistency, the container volume is large enough that any further increase in volume would not change the counting rate. Determination of the counting rate in this manner simulates the action of the probe in a canal where the container is, in effect, infinite in size. Designating F as the calibration factor for a specific counting system or a specific probe, then the counting rate, R, for a solution concentration, C, is $\underline{R} = FC$, or $C = \underline{R}/F$, or from Equation (2):

$$Q = \frac{A}{\int (\underline{R}/F)\, d_t}$$

The total number of gamma rays, N, counted during the passage of pulse of tracer is $N = \int (R/F)\, d_t$. By substitution, the rate of flow (discharge) equation is

$$Q = \frac{FA}{N} \qquad (3)$$

in which

Q = volume per unit time (cubic feet per second)
F = counts per unit of radioactivity per unit of volume per unit of time (counts per second)/(millicuries per cubic foot)
A = total activity of radioactivity to be introduced for each discharge measurement (millicuries)
N = total counts

In preparing for a test, the total number of units of radioactivity, A, to be introduced into the canal for each discharge determination are measured by dividing a known measured quantity of isotope into parts, known as aliquots, in a field laboratory with a portable standardized counting system. These individual parts, A, usually contained in 1-pint plastic bottles, were then transported to the canal site in numbers sufficient for the discharge measurements.

Use of Fluorescein Dye

Fluorescein dye traces were used as an aid in selecting radioisotope injection points and the locations for the counting systems. The dye was added to the water and the action of the mixture of dye and water as it flowed downstream was used as an indicator of the canal length required for mixing of the dye throughout the cross section of the stream. This visual appraisal, using dye, resulted in a saving of time and radioactive material, and provided assurance that the selected sites were properly chosen.

After selection of the exact area where the counters are to be used, the counting probes are immersed in the canal flow, with a surrounding water volume equal to or greater than the volume of the container used in the calibration to establish the factor F. The scalers or count indicators are normally set on the canal banks, in an automobile on the canal banks, on a bridge, or in a boat in the canal according to the particular test conditions, Figures 2A and B.

Radioisotope Introduction and Counting

In making a measurement, the radioisotope (in this test series Gold-198) was introduced into the canal flow by pouring it out of the plastic bottle onto the water surface, or by smashing a glass bottle in an impact device at a selected position below the water surface, Figures 3A and B. The radioisotope was then allowed to flow with the canal water through the test section.

To determine the total count, N, the counts received from natural radiation sources, called background, must be measured before and after the radioisotope-canal water mixture passes the measurement cross section. Therefore, the scalers were started well before the time of arrival of the radioisotope, and the counts accumulated on the register of the scaler were manually read and recorded (with uninterrupted counting and timing) throughout the prearrival period, the isotope passage period, and the postdeparture period. Recording of the count was stopped only when the background had receded to pretest levels. The total count, N, was taken as the gross number of counts recorded during the passage of the radioisotope minus the background count accumulated during the passage, Figure 4.

Radioisotope-Canal Water Mixing

Thorough transverse mixing of the radioisotope and canal water is necessary before accurate discharge measurements can be expected from the radioisotope method. The 2.7-feet-per-second average velocity in the Yuma-Mesa "A" Canal produces a minimum of turbulence to cause mixing of the isotope and water. (Natural streams contain much more turbulent energy, comparatively.) Since these studies were made to determine mixing characteristics, the natural turbulence in the canal flow was used for mixing, and no artifical means were used to induce greater turbulence.

To evaluate the thoroughness of the mixing of the radioisotope and canal water in this investigation, a criterion termed the degree of mixing was used.

$$\text{Percent mixing} = \left[\frac{1-(|N_R-N_M| + |N_C-N_M| + |N_L-N_M|)}{3N_M}\right]100 \quad (4)$$

where,

N_L, N_C and N_R are the total counts at the left, center, and right sides of the flow cross section and N_M is the arithmetic mean of N_L, N_C and N_R.

Ideally, N_L, N_C and N_R would be equal if complete transverse mixing of the radioisotope occurred in the canal cross section and if the counting systems were of the same sensitivity and were accurately calibrated. In most measurements, the ideal does not occur, and to assist in evaluating the measurement accuracy the mixing equation can be used to compute the degree of mixing uniformity.

Investigation of Discharge Measurements

Measurements at One-half Canal Capacity

Test program.--Tests consisting of three phases, each having several radioisotope introductions into the flow, were made in the first test series.

In Phase 1, four counting systems were located at four different stations along the canal to determine the minimum mixing length required for full dispersion of the isotope.

In Phase 2, three counting systems were spaced across the canal perpendicular to the canal centerline; the fourth system was located between the radioisotope introduction point and the row of systems. In this phase, the extent of lateral mixing at a chosen station was measured.

In Phase 3, the counting systems were used to investigate the principle of radioisotope measurement in divided streams whereby the total discharge of the main stream is determined by counting and measuring in one of the flowing fractions. When a stream containing a tracer is later divided into separate streams, each of the separated streams carries a fraction, x, of the total flow. The flow rate of the stream fraction will be xQ and the amount of tracer will be xA. Thus, the number of counts obtained in the flowing fraction of the main stream will be:

$$N = \frac{xAF}{xQ} = \frac{AF}{Q}$$

or theoretically the same number as would have been obtained in the main stream. A measurement of discharge in the main stream may therefore be made by placing the counting system downstream from a bifurcation.

Each completed phase of the program was accomplished by one or more introductions of radioisotope into the canal, on one or more days, for various locations of the counting systems in the canal.

<u>Longitudinal mixing tests.</u> --An investigation of the longitudinal mixing characteristics of the radioisotope was begun in the "A" canal after locating the counting systems as indicated in Figure 5, Phase 1A. The radioisotope was introduced into the canal flow at Station 5+00, Figure 5, and counted at Stations 18+50, 27+83, 42+60, and 85+45. Because of a malfunction of one of the scalers after Measurement 4, Phase 1 was continued without the counting system previously located on the bridge at Station 85+45, Measurements 5-10, Phase 1.

Phase 1 of the discharge measurements provided for mixing lengths of 850 to 8,045 feet. The discharges in Column 8 of Table 1A show that in Measurements 1-4 mixing may have been achieved in 1,350 feet; Measurements 5-10 indicate that nearly 3,300 feet may not have been a sufficient mixing length.

Transverse mixing tests.--Three counting systems were located at the bridge at Station 27+83 for Phase 2A of the investigation, Figure 5. The probes were immersed in the canal and spaced to divide the cross section into three flow areas, each conveying approximately one-third of the total canal discharge. To provide for an increased mixing length, the isotope introduction position was moved from Station 10 back to Station 5, Figure 5, Phase 2A.

Measurements 11-16, Columns 8 and 9, Table 1-B, indicated a nonuniform mixing possibly caused by canal sinuosity immediately upstream from the isotope injection point at Station 5+00.

Since the canal sinuosity was a suspected cause of the nonuniform mixing in Phase 2A, and possibly in Phase 1, the counting systems and injection point were relocated. To provide a uniform flow distribution at the injection point, Station 60+00 was selected and the three counting systems were placed at the bridge Station 85+45, Figure 5, Phase 2B.

Measurements 17-22, Table 1B, Columns 8 and 9, indicate that at a discharge equal to one-half the canal capacity, a length of 2,500 feet in a canal of this size may produce adequate mixing of the radioisotope.

Divided stream measurements.--Phase 3, Measurements 23-28, of the program used three counting systems to investigate the accuracy of determining the discharge of the main stream by measuring a flowing fraction of the stream. One counting system was located at the bridge Station 85+45 of the "A" canal, Figure 5. A second counting system was placed at the entrance to the highway culvert of the "A" canal at Station 104+24, 223 feet downstream from the bifurcation of the "A" canal, and the third system in the "B" canal approximately 300 feet downstream from the bifurcation point.

Discharge measurements of Phases 1 and 2 had indicated that about 2,500 feet of length would produce satisfactory mixing. Since the investigation of the divided stream measurements was dependent on uniform mixing in the canal at the first counting system, Station 85+45, the radioisotope was introduced at Station 60+00, Figure 5, Phase 3.

Measurements 23-28 demonstrated the probable soundness of the divided flow principle. Discharges measured upstream from the bifurcation in the "A" canal agreed with those measured downstream, within the accuracy to be expected from two sets of measurements. This series also indicated that a 2,500-foot length of this canal was sufficient to produce satisfactory radioisotope and canal water mixing.

Interpretation of Results

Good agreement was obtained between the discharges measured with radioisotopes and those previously measured by current meter rating. For measurements 17-22 where mixing of 99 and 98 percent occurred, the smallest discharge of 292 cubic feet per second, as measured by radioisotopes, was 4.5 percent below the operational discharge1/ of 305 cubic feet per second, Table 1B. This is considered good agreement because the operational discharge may be subject to a plus or minus 5 percent variation. Excellent agreement was also obtained between the measurement of the total discharge in the Yuma-Mesa "A" Canal, and that indicated by a measurement in each of the branches (Measurements 23-28). The computed maximum difference (Measurements 23 and 24) was 4.5 percent.

In a canal the size of the Yuma-Mesa, flowing at one-half capacity but near design depth, the required length to produce satisfactory mixing of the radioisotope-canal water mixture is about 2,500 feet for injections made near the canal centerline. This length varies considerably depending upon conditions upstream from the point of injection.

The results of this test series indicated that the discharge can be accurately measured by counters immersed in the flowing uniform mixture of radioisotope and canal water where the bottom or sides of the canal do not interfere with the radioisotope emission. The results of the measurements also indicated that the total discharge

1/Operational discharge is the pumping plant rating established from current meter discharge measurements at Station 18+50 of the Yuma-Mesa "A" Canal.

of a canal can be measured in a flowing fraction of the discharge if the radioisotope was uniformly mixed in the main stream.

Measurement at Canal Capacity

Test program.--A second series of measurements was made on the Yuma-Mesa "A" Canal in June 1963, 16 months after the first test series. These measurements were performed to investigate the mixing lengths required to provide an accurate discharge measurement with the canal flowing near the design capacity of 620 cubic feet per second. Three phases, each having several isotope injections were scheduled for this test series.

Phase 1, single injection mixing tests, fixed counter distance.--Mixing length experiments utilizing a single introduction of radioisotope were made to determine where in the canal cross section a single injection of radioisotope would provide the best transverse mixing in a length selected to be appreciably shorter than that required for uniform mixing. The isotope was introduced into the flow at the centroid or at the surface above the centroid of equal flow areas estimated from current meter velocity distributions. Three counters were located at Station 60 or 1,000 feet downstream from the injection station for Phase 1. Five equal quantities of radiotracer (Gold-198) were injected at different times at four different points in the cross section of flow at Station 50: (1) centerline surface, (2) centerline centroid, (3) surface above left centroid, and (4) left centroid, Figure 6 and Table 2A.

The mixing percentages achieved by each set of three measurements were given a preliminary evaluation at the conclusion of the series from the mixing equation (4). Results of the preliminary evaluation based on three operating counting systems, Tests 1, 2, 4, and 5, Table 2A, showed that the highest percentage of mixing was achieved for an isotope injection at the center centroid.

A minimum of two additional injections of isotope would have been desirable, one at the surface above the right centroid and one at the right centroid, to determine if flow asymmetry existed between the injection and counting stations. There was evidence during this phase of the measurements to indicate asymmetrical flow, because a higher total count was registered by the system on the right side of the canal in Tests 1, 2, and 3 when the isotope was injected at the center. Reasoning would lead to the belief that for center injection in a symmetrical velocity distribution, a higher total count should occur at the center counting system with lesser counts at both sides if 100 percent mixing is not achieved.

A contributing possible cause of the asymmetric flow was found by the use of dye, to be caused by the openings of the check structure at Station 42+60. Since the radial gates and all check boards had been removed from the water to gain additional canal capacity, the natural unbalance and resulting periodicity of the flow through the remaining apertures affected the mixing characteristics of the test section. Additional measurements were not made because of time and radioisotope limitations, and because Tests 4 and 5 clearly indicated that with isotope injection on one side of the canal the isotope remained predominantly on that side.

Phase 2, single injection mixing tests, varied counter distances.--Mixing length experiments were continued with single injections of radioisotopes at the center centroid of the flow cross section at Station 50. The purpose was to determine the length of canal required to obtain uniform mixing for the center centroid injection which had shown the highest percent mixing in Phase 1.

One mixing length test of 1,000 feet (Station 60) had been made in Phase 1, Test 2. Since no high percentages of mixing had been obtained in a distance of 1,000 feet, a shorter distance was not desirable; therefore, the counting systems were moved to Station 65, an increase of 500 feet, Phase 2, Test 6, Table 2B. Two irregularities were readily apparent from this measurement: (1) 85 percent mixing was obtained in Test 2, for a 1,000-foot mixing length, and only 73 percent was obtained in Test 6 for a 1,500-foot mixing length, and (2) more of the isotope migrated to the left of the canal centerline instead of to the right, although the discharge, according to operating records, remained constant. The 500-foot increase in mixing length and an approximate 50 percent decrease in the isotope quantity were the only known differences between the two tests.

With a mixing length of 2,000 feet (Station 70) for Test 7, 81 percent mixing was obtained but a greater quantity of radioisotope was counted on the right side of the canal than on the left. A comparison of Tests 2, 6, and 7, Phases 1 and 2, implies (1) the possibility of sinuosity or vorticity in the canal flow as suspected from Phase 1, and (2) a possible relation between the mixing length and the quantity of isotope. In Test 6, at a point 1,500 feet downstream from the injection point, a larger count had been obtained on the left; in Test 7, at 2,000 feet the larger count occurred on the right. For Test 2, 85 percent mixing had been achieved in 1,000 feet for a single isotope injection of 269 mc; for Test 7, 81 percent mixing was achieved in 2,000 feet for an injection of 122 mc. A ratio of the N/F2/ values between left, center, and right counting systems for Tests 7 and 2 shows a distribution percentage of 45, 41, and 49, respectively. Thus, the lateral distribution of the radioisotope at the counting probes was essentially the same for the two tests but there may be an implication of some unknown relationship between the isotope quantity, counting system sensitivity, and mixing length.

Mixing lengths for Tests 8 and 9 were increased to 2,500 and 3,000 feet, resulting in 94 and 98 percent mixing, respectively. Test 8 showed a higher total count on the right side of the canal as did Test 7; Test 9 showed almost equal total counts at the left and center. Thus, as the test length was increased, a more uniform mixture was obtained.

After completing Phase 2, analysis of the data showed that 98 percent mixing for a single injection of radioisotope had occurred 3,000 feet (Station 80) downstream from the injection station. The results also showed the possibility of obtaining a high percentage of mixing in a distance of 2,500 feet. Because the next series of measurements was designed to provide information on both accuracy of measurement and percent mixing for the simultaneous injection of multiple quantities of radioisotope, a length of 2,000 feet (Station 70) was chosen for the location of the counting systems. Thus, if multiple injections resulted in improved mixing and discharge measurement accuracy, the effect could best be shown at a canal cross section where there was incomplete mixing.

Phase 3, multiple injections, fixed counter distance.--Four introductions of the isotope divided into two or three parts were used in Phase 3 Table 2C. The quantity of isotope was about 55 percent greater than for Phase 2, and 30 percent less than for Phase 1.

A quantity of radioisotope, divided into two parts and introduced at the left and right surface above the centroids of the flow areas at Station 50, resulted in 99 percent mixing at Station 70, Table 2C, Test 10. This result was unexpected and surprising when compared to the percent mixing obtained from nine previous tests.

2/N/F is a parameter independent of individual instrument calibration directly related to the total number of counts. The parameter is used to compute percent mixing when instruments having different sensitivities are used for discharge measurements.

Mixing percentages for Tests 10, 11, 12, and 13, were 99, 92, 94, and 93 percent, respectively. Test 10 was surprisingly high when compared to Tests 12 and 13, Table 2C. Reasoning during the planning of the tests indicated that for uniform conditions of flow a greater initial dispersion of the isotope at the time of injection should produce a greater percentage of mixing. With the exception of Test 10, the number of injections seemed to have little effect. The differences in mixing percent noted in individual tests are easily accounted for in the flow irregularities noted from Phases 1 and 2 and from the possible variation in computing the total counts for the individual counting systems. In Test 11, water seeped into a connector on the counter probe, voiding the measurement on the left side of the canal. A different percentage of mixing would probably have been obtained had a measurement been available from this portion of the flow. Larger variations in percent of mixing were expected in this test series; those obtained do not permit any definite conclusions.

Interpretation of Results

A review of each test series shows an apparent consistency in the measurements for a fixed mixing length. In Phase 1 with one exception, the mixing percentage was 80 to 85 percent, and Phase 3, 92 to 99 percent, ranges of 5 and 7 percent. Not as much benefit was realized from the multiple injections as was expected. However, for isotope quantities reduced from about 270 mc in Phase 1 to 190 mc in Phase 2, an increase of about 10 percent in the mixing quality was achieved in an additional 1,000 feet of length by the use of multiple injections.

In Phase 2, a centerline centroid injection of isotope, Tests 7 and 8, produced 81 percent mixing in 2,000 feet and 94 percent in 2,500 feet. Multiple injections at the three centroids for a 2,000-foot mixing length, Test 13, produced about 93 percent mixing to indicate some improvement over the single injection.

Phase 2 was satisfactory in providing an indication of the change in the degree of mixing with changes in test length over a distance of 3,000 feet. Another series of measurements with several injections of single isotope quantities for each mixing length would provide statistical data valuable for defining a mixing length equation.

Each test series performed on the Yuma-Mesa "A" Canal provided information on the intended purpose, but an insufficient number of measurements were made to provide adequate statistical data on the mixing characteristics. The results of the tests show, as in previous studies, that:

1. Simultaneous multiple injections of radioisotope will provide a higher probability of uniform mixing in shorter lengths than will single injections.

2. The effect of the multiple injections may not be as great as anticipated.

3. Replication of individual tests within the series designed for the Yuma-Mesa experiments would probably produce statistical data for defining a mixing length equation for a straight section of canal the size of the Yuma-Mesa "A".

4. The length required in the Yuma-Mesa "A" Canal for 98 to 99 percent mixing is about 2,500 to 3,000 feet.

Radioisotope Diffusion

Although there were an insufficient number of measurements available to satisfactorily explain the mixing characteristics of the flow on the Yuma-Mesa Canal, the data were used to compute approximate values of a diffusion coefficient. The diffusion coefficient expresses the rate of dispersion of the radioisotope both longtudinally and transversely in the canal water. Two methods of computations were available: the first relates the dispersion of matter to the boundary shear and the rate of energy dissipation in the flow system, and the second relates the dispersion to the concentration of matter with time.

Diffusion Coefficients from Shear Velocity and Energy Dissipation

The theory of turbulent diffusion has an ever widening attraction for study by physicists, mathematicians and engineers. A study possibly most closely related to the Yuma-Mesa tests was the work of Sir Geoffrey Taylor[3] later reviewed by F. L. Parker.[4]

3/Taylor, Sir Geoffrey, "The Dispersion of Matter in Turbulent Flow Through a Pipe," Proceedings Royal Society of London, Series A., April-May 1954, Vol. 223, p 446.
4/Parker, F. L., "Eddy Diffusion in Reservoirs and Pipelines," Jour. Hydraulics Division, Proceedings of the ASCE, May 1961, HY3, Vol. 87.

Sir Geoffrey Taylor presents the equation for a virtual coefficient of diffusion in a pipe as

$$K = 10.1(a\nu_*) \qquad (5)$$

K = virtual coefficient of diffusion (square feet per second, ft^2/sec)
a = pipe radius (feet, ft)
ν_* = shear velocity (feet per second, fps)

For open channel flow and Taylor's equation, the average shear velocity

$$\nu \text{ ave} = \sqrt{\frac{\tau}{\rho}} = \sqrt{\frac{\gamma RS}{\rho}}$$

was substituted for the shear velocity

$$K = 10.1a\sqrt{\frac{\gamma RS}{\rho}}$$

substitution of $\frac{D}{2}$ for a, g for $\frac{\gamma}{\rho}$ and four times the hydraulic radius (4R) for D leads to the relationship

$$K = 14.3\ R^{3/2}\ \sqrt{2gS} \qquad (6)$$

where S is the slope of the energy gradient of the open channel, R is the hydraulic radius, and g is the acceleration of gravity.

Using Equation (6) and the resistance coefficient data measured on the Yuma-Mesa "A" Canal, Table 3, resulted in two quite different diffusion coefficients. In 1962 for a discharge of 295 cubic feet per second, K was computed to be 8.4 ft^2/sec and in 1963 for 630 cubic feet per second, K was 13.9 ft^2/sec.

The diffusion coefficient has been shown by Orlob5/ to be proportional to the one-third power of the rate of energy dissipation per unit mass and the four-thirds power of the scale of the eddies participating in the diffusion, or

$$D_{Z(\infty)} = (\text{constant})\ (E^{1/3})\ (La^{4/3})$$

where

$$D_{Z(\infty)} = \text{ultimate diffusion coefficient}$$

5/Orlob, G. T., "Eddy Diffusion in Homogeneous Turbulence," Jour. Hydraulics Division, Proceedings of the ASCE, September 1959, Vol. 85, HY9, p 75.

The rate of energy dissipation per unit mass of fluid in a broad channel is defined as

$$E = UgS$$

where U is the mean velocity, g is the acceleration of gravity and S is the slope of the energy gradient.

In the Yuma-Mesa tests, Table 3, the volume of water for energy dissipation for a given mixing length increased by only 13 percent between the 1962 and 1963 series (depth change 10.5 to 11.3 feet) while the energy slope increased nearly 2.4 times (0.0000283 to 0.0000666). The change in the rate of energy dissipation per unit volume of water (that is, in E and the size of the eddies) between 1962 and 1963 is believed to be in part reflected in the increase from 8.4 to 13.9 ft^2/sec in the values of the diffusion coefficients.

Diffusion Coefficients from Concentration Distribution

A second method of computing the diffusion coefficient, K, was also available from Taylor's work. 3/ If it is assumed for a straight open channel, as with a pipe, that the concentration of dissolved material at time t and distance X is equal to

$$C = \frac{M}{2} r^{-2} \pi^{3/2} (K)^{1/2} t^{1/2} e^{-(X-ut)^2/4Kt} \qquad (7)$$

then at any time after the introduction of the tracer, the concentration distribution can be assumed to have nearly a gaussian or normal distribution. According to Taylor, Equation (7) may be solved to obtain the relationship

$$K = \frac{\bar{U}^3 \quad (t_{0.5})^2}{4 X \ln 2} \qquad (8)$$

from which numerical values of the diffusion coefficient may be computed. In relationship (8) $t_{0.5}$ is equal to one-half the time that the tracer concentration is above 50 percent of the maximum concentration; X is the distance from the introduction point to the measuring station of the tracer.

Diffusion coefficients (K in Equation 8) were computed from all available data in the 1963 test series using the curves drawn to show the concentration of radioisotope with time (counts per second vs accumulated time). The curve for Test 10 and left side counting system Table 2C has been reproduced to show the slight asymmetry encountered with all of the concentration curves and the way in which the values were used to compute $t_{0.5}$, Figure 7. From each of the concentration curves, the time, $t_{0.5}$, was computed with an accuracy commensurate with the amount and frequency of the data defining the curve. The scaled time, $t_{0.5}$, along with the mixing length distance, was used to compute the diffusion coefficients, Table 4. Values ranged from 0.7 to 15 ft^2/sec.

A frequency distribution curve of the diffusion coefficients for all of the 1963 tests shows 68 percent of the total K values to lie between 2.9 and 8.6 ft^2/sec, with a mean value of about 5.6. In general, the indicated diffusion coefficients were lower for the shorter mixing distances than for the longer distances. The mean of the diffusion coefficients for the multiple injections. Tests 10 to 13, was higher than for single injections.

The mean diffusion coefficient 5.6 ft^2/sec computed by the concentration method was approximately four-tenths of the 13.9 ft^2/sec computed from the measured energy slope in 1963 and about two-thirds of the 1962 coefficient of 8.4 ft^2/sec. No comparison was possible for coefficients computed by the concentration method in 1962 because the radioisotope was introduced into the canal flow over an extended period of time in 1962, which produced a marked asymmetry in the concentration-time curve. In 1963, the isotope was introduced almost instaneously to disperse from nearly a point source with respect to the area of the canal cross section. The 1963 method of introduction thus produced a reasonably well defined concentration curve.

Conclusions

The half-capacity and full-capacity tests performed on the Yuma-Mesa "A" Canal provided information useful in developing techniques for using radioisotopes in open channel discharge measurements and produced data useful in establishing minimum mixing lengths. However, analysis of the data showed that each test series was limited in scope and that an insufficient number of measurements had been made to provide firm statistical data on mixing characteristics. The results of the tests show:

1. That with adequate mixing of the radioisotope and canal water, discharge measurement accuracy of about 97 percent or greater is possible when compared to current meter discharge measurements.

2. A distance of approximately 2,500 to 3,000 feet is necessary to produce 98 to 99 percent mixing in a canal having the hydraulic operating characteristics of the Yuma-Mesa Canal.

3. The use of a diffusion coefficient value of about 6.5 ft^2/sec and a time factor of $t_{0.5}$ = 65 seconds in the equation

$$K = \frac{\bar{U}^3 \quad (t_{0.5})^2}{4 X \ln 2}$$

will give the minimum mixing length, X, for a straight section of canal the size and slope of the Yuma-Mesa.

4. Simultaneous multiple injections of tracer will provide a higher probability of uniform mixing in shorter lengths than will single injections.

5. Higher diffusion coefficients will result from multiple simultaneous injections of radioisotope than from single injections, although the increase resulting from double or triple injections may not be as great as might be anticipated.

6. Despite the difficulties encountered in determining the mixing length and discharge measuring accuracy, the Yuma-Mesa tests show that, with sufficient data from tests on canals of various sizes, mixing length equations can probably be derived for canals having a minimum of turbulence.

Acknowledgment

The investigations reported herein were a cooperative effort of many persons. The contributions of each are gratefully acknowledged, including Messrs. C. L. Sweet and M. M. Hastings of the Bureau of Reclamation Regional Office at Boulder City, Nevada, who provided the facilities for the field work, and to R. L. Hansen of the Chemical Engineering Branch of the Research Division, Denver, who helped develop techniques for the use of radioisotopes, participated in all of the experiments, and helped analyze the data.

REFERENCE

Timblin, L. O. and Peterka, A. J., Open Channel Flow Measurements, Proceedings of the Symposium on the Application of Radioisotopes in Hydrology, Radioisotopes in Hydrology, International Atomic Energy Agency, Tokyo, March 1963 (37-57)

APPENDIX

APPENDIX
(Notations)

The following symbols have been adopted for use in this paper:

A = quantity of radioisotope

A_c = area of canal

a = pipe radius

C = concentration of tracer

cfs = cubic feet per second

D = diameter

D = ultimate diffusion coefficient

E = rate of energy dissipation per unit mass of fluid

F = calibration factor

fps = feet per second

g = acceleration of gravity

H_L = head loss

K = virtual coefficient of diffusion

L = length

La = Lagangian eddy size

M = mass of tracer

mc = millicurie

N = total count

n = Manning resistance coefficient

P = wetted perimeter

APPENDIX--Continued

Q = discharge

q = volume of radioisotope

R = hydraulic radius

$\underline{R}$ = counting rate

S = slope of the energy gradient

t = time

U = average velocity

u = instantaneous velocity

X = mixing length

x = fractional part

γ = specific weight of water

ν_* = shear velocity

ρ = mass density

τ = boundary shear stress

Table 1A

SUMMARY OF RESULTS
Total Count Flow Measurements
Yuma-Mesa "A" Canal
Phase 1
February 6-8, 1962

Measurement No.	Counter No.	Location	Injection-to-counter distance (feet)	Total count "N"	Isotope activity "A"	Ratio* A/N	Indicated discharge cfs	Percent mixing
1	USBR No. 1	Station 18+50	1,350	15,665	287.6 mc	0.0184	325	
2	LRS No. 1	Station 27+83	2,283	16,200	286.7 mc	.0177	319	
3	USBR No. 2	Station 42+60	3,760	15,500	285.5 mc	.0184	334	
4	LRS No. 2	Station 85+45	8,045	15,500	283.1 mc	.0183	324	
5	USBR No. 1	Station 18+50	850	6,830	295.0 mc	.0334	593	
6	LRS No. 2	Station 27+83	1,760	18,350	294.4 mc	.0160	284	
7	LRS No. 1	Station 42+60	3,260	17,110	293.5 mc	.0172	309	
8	USBR No. 1	Station 18+50	850	10,280	405.5 mc	.0394	699	
9	LRS No. 2	Station 27+83	1,760	26,190	404.3 mc	.0154	273	
10	LRS No. 1	Station 42+60	3,260	24,070	403.9 mc	.0168	303	

*From the equation $Q = \frac{FA}{N}$ the calibration factor F is constant for a particular counting system. Therefore, Q is proportional to the ratio A/N. F = 17.74 (USBR No. 1), 18.14 (USBR No. 2), 18.01 (LRS No. 1), 17.71 (LRS No. 2).

Table 1B

SUMMARY OF RESULTS
Total Count Flow Measurements
Yuma-Mesa "A" Canal
Phase 2
February 6-8, 1962

Measurement No.	Counter No.	Location	Injection-to-counter distance (feet)	Total count "N"	Isotope activity "A"	Ratio* A/N	Indicated discharge cfs	Percent mixing
						Operational discharge:	330	
11	USBR No. 2	Station 27+83 left	2,283	15,780	244.2 mc	.0155	281	
12	LRS No. 2	Station 27+83 center	2,283	12,040	244.2 mc	.0203	360	87
13	LRS No. 1	Station 27+83 right	2,283	11,630	244.2 mc	.0210	378	
						Operational discharge:	330	
14	USBR No. 1	Station 27+83 left	2,283	18,790	300.9 mc	.0160	284	
15	LRS No. 2	Station 27+83 center	2,283	15,760	300.9 mc	.0191	338	91
16	LRS No. 1	Station 27+83 right	2,283	15,120	300.9 mc	.0199	358	
						Operational discharge:	305	
17	LRS No. 1	Station 85+45 left	2,545	12,460	208.7 mc	.0168	302	
18	USBR No. 1	Station 85+45 center	2,545	12,280	208.7 mc	.0170	301	99
19	LRS No. 2	Station 85+45 right	2,545	12,440	208.7 mc	.0168	297	
						Operational discharge:	305	
20	LRS No. 1	Station 85+45 left	2,545	12,280	200.2 mc	.0163	294	
21	USBR No. 1	Station 85+45 center	2,545	12,180	200.2 mc	.0164	292	98
22	LRS No. 2	Station 85+45 right	2,545	11,660	200.2 mc	.0172	304	

Table 1C

SUMMARY OF RESULTS
Total Count Flow Measurements
Yuma-Mesa "A" Canal
Phase 3
February 6-8, 1962

Measurement No.	Counter No.	Location	Injection-to-counter distance (feet)	Total count "N"	Isotope activity "A"	Ratio* A/N	Indicated discharge cfs	Percent mixing
23	LRS No. 2	"A" Canal, Sta 85+45	2,545	14,010	228.7 mc	.0163	289	
24	LRS No. 1	"A" Canal, Sta 104+24	4,424	13,580	227.5 mc	.0168	302	
25	USBR No. 1	"B" Canal, Sta 3+00	4,500	13,950	227.5 mc	.0163	289	
26	LRS No. 2	"A" Canal, Sta 85+45	2,545	14,060	231.2 mc	.0164	291	
27	LRS No. 1	"A" Canal, Sta 104+24	4,424	14,160	230.8 mc	.0163	294	
28	USBR No. 1	"B" Canal, Sta 3+00	4,500	13,870	230.5 mc	.0166	295	

Table 2A

RADIOISOTOPE MIXING INVESTIGATIONS--YUMA-MESA "A" CANAL, YUMA, ARIZONA--JUNE 10-14, 1963
Phase 1

Date	Type of injection (Station 50)	Test No.	Counter location	Mixing distance (ft)	A (mc)	N/F* Left	N/F* Center	N/F* Right	Discharge* Q cfs Left	Discharge* Q cfs Center	Discharge* Q cfs Right	% Mixing
June 12	℄ surface	1	Sta 60	1,000	276.1	325.8	480.6	596.4	847	574	463	80
	℄ centroid	2	Sta 60	1,000	268.6	389.3	520.8	584.2	690	516	460	85
	℄ surface	3	Sta 60	1,000	259.4	345.8	--	488.0	750	--	532	83
	Left centroid surface	4	Sta 60	1,000	257.7	550.7	421.4	357.1	468	612	722	83
	Left centroid	5	Sta 60	1,000	256.0	762.1	365.3	143.1	336	701	1789	46

$*Q = \frac{AF}{N}$

Calibration Factor F

Left	Center	Right
30.9	30.3	30.8

CANAL DISCHARGE:

	Operations	Current Meter
June 12	640 cfs	--
June 13	642 cfs	--
June 14	642 cfs	630 cfs

Table 2B

RADIOISOTOPE MIXING INVESTIGATIONS--YUMA-MESA "A" CANAL, YUMA, ARIZONA--JUNE 10-14, 1963
Phase 2

Date	Type of injection (Station 50)	Test No.	Counter location	Mixing distance (ft)	A (mc)	N/F* Left	N/F* Center	N/F* Right	Discharge* Q cfs Left	Discharge* Q cfs Center	Discharge* Q cfs Right	% Mixing
June 13	℄ centroid	6	Sta 65	1,500	125.9	257.2	226.2	120.6	490	557	1044	73
	℄ centroid	7	Sta 70	2,000	122.4	174.2	211.9	288.4	703	578	424	81
	℄ centroid	8	Sta 75	2,500	120.8	208.3	206.2	225.3	580	586	536	94
	℄ centroid	9	Sta 80	3,000	120.0	210.7	211.2	204.4	570	568	587	98

Table 2C

RADIOISOTOPE MIXING INVESTIGATIONS--YUMA-MESA "A" CANAL, YUMA, ARIZONA--JUNE 10-14, 1963
Phase 3

Date	Type of injection (Station 50)	Test No.	Counter location	Mixing distance (ft)	A (mc)	N/F* Left	N/F* Center	N/F* Right	Discharge* Q cfs Left	Discharge* Q cfs Center	Discharge* Q cfs Right	% Mixing
June 14	Left and right surface above centroid	10	Sta 70	2,000	197.4	349.2	338.8	345.3	565	583	572	99
	Left and right centroids	11	Sta 70	2,000	195.0	--	320.0	375.4	--	609	519	92
	Surface above three centroids	12	Sta 70	2,000	186.8	312.6	325.6	361.8	598	573	516	94
	At three centroids	13	Sta 70	2,000	184.4	376.4	336.1	307.3	490	549	600	93

Table 3

RESISTANCE COEFFICIENTS
RADIOISOTOPES MIXING INVESTIGATIONS
YUMA-MESA "A" CANAL

Date	Station	Elevation	H_L	L	S	Q	U	R	n
	27+83	216.069							
1962			.163	5762	.0000283	295	1.182	5.44	.021
	85+45	215.906							
	27+83	216.98							
1963			.384	5762	.0000666	630	2.233	5.68	.017
	85+45	216.596							

$$n = \frac{1.49}{U} R^{2/3} S^{1/2}$$

1962

Depth = 10.5 ft
A_C = 249.3 ft^2
P = 45.8 ft
$R^{2/3}$ = 3.085
$S^{1/2}$ = .00532

1963

Depth = 11.3 ft
A_C = 281.9 ft^2
P = 49.6 ft
$R^{2/3}$ = 3.181
$S^{1/2}$ = .00816

Water Temperature 78° F

Table 4

RADIOISOTOPE DISCHARGE MEASUREMENTS
DIFFUSION COEFFICIENTS
YUMA-MESA "A" CANAL

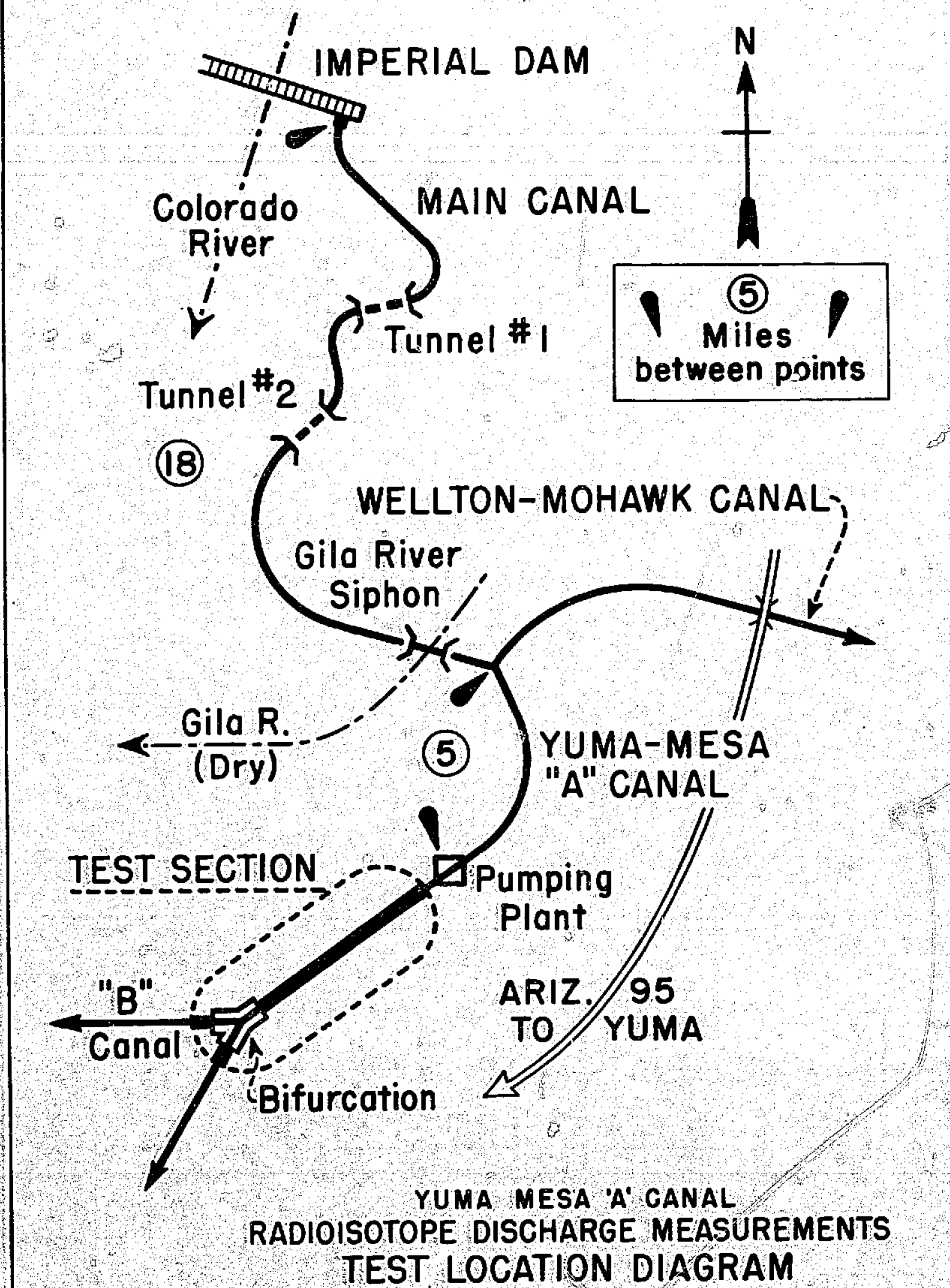
Diffusion coefficient $K = \frac{\overline{U}^3 (t_{0.5})^2}{4 X \ln 2}$

$\overline{U} = \frac{630}{271} = 2.22$ ft/sec

$\ln 2 = 0.693$

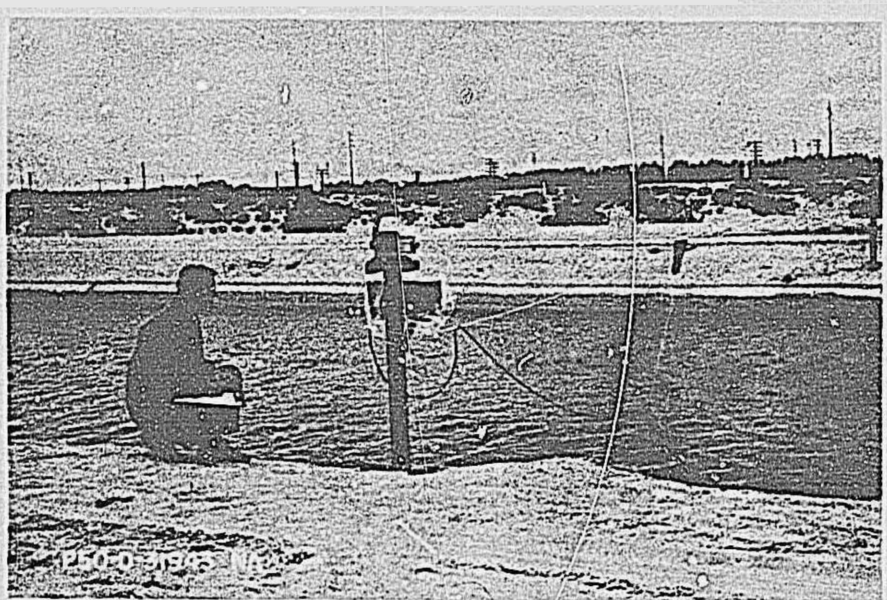
$$K = \frac{\overline{2.22}^3 (t_{0.5})^2}{4 \ln 2 X} = 4.13 \frac{(t_{0.5})^2}{X}$$

Test No. Table 2	Concentration time: $t_{0.5}$ Left	Center	Right	Mixing length: X	Diffusion Coefficient K Left	Center	Right
1	31.1	27.1	--	1,000	4.0	3.0	--
2	23.3	32.9	60.4	1,000	2.3	4.5	15.0
3	32.8	--	13.2	1,000	4.5	--	0.7
4	31.2	28.8	30.7	1,000	4.0	3.4	3.9
5	30.2	36.2	38.3	1,000	3.8	5.4	6.1
6	19.2	37.8	47.5	1,500	1.0	3.9	6.2
7	57.3	--	55.2	2,000	6.8	--	6.3
8	66.5	63.4	63.8	2,500	7.2	6.6	6.8
9	71.8	71.3	68.5	3,000	7.1	7.0	6.5
10	67.6	22.8	49.1	2,000	9.3	1.1	5.0
11	--	57.3	68.7	2,000	—	6.8	9.8
12	61.4	68.1	65.0	2,000	7.8	9.6	8.7
13	49.2	50.1	51.9	2,000	5.0	5.2	5.6



YUMA MESA 'A' CANAL
RADIOISOTOPE DISCHARGE MEASUREMENTS
TEST LOCATION DIAGRAM

Figure 2
Report No. Hyd-527



A. Counting system for radioisotopes at current meter cableway, Canal Station 18+50, counter probe suspended from cableway pulley, scaler on post.

B. Assembled counting systems on canal roadway and in boat, Canal Station 80.

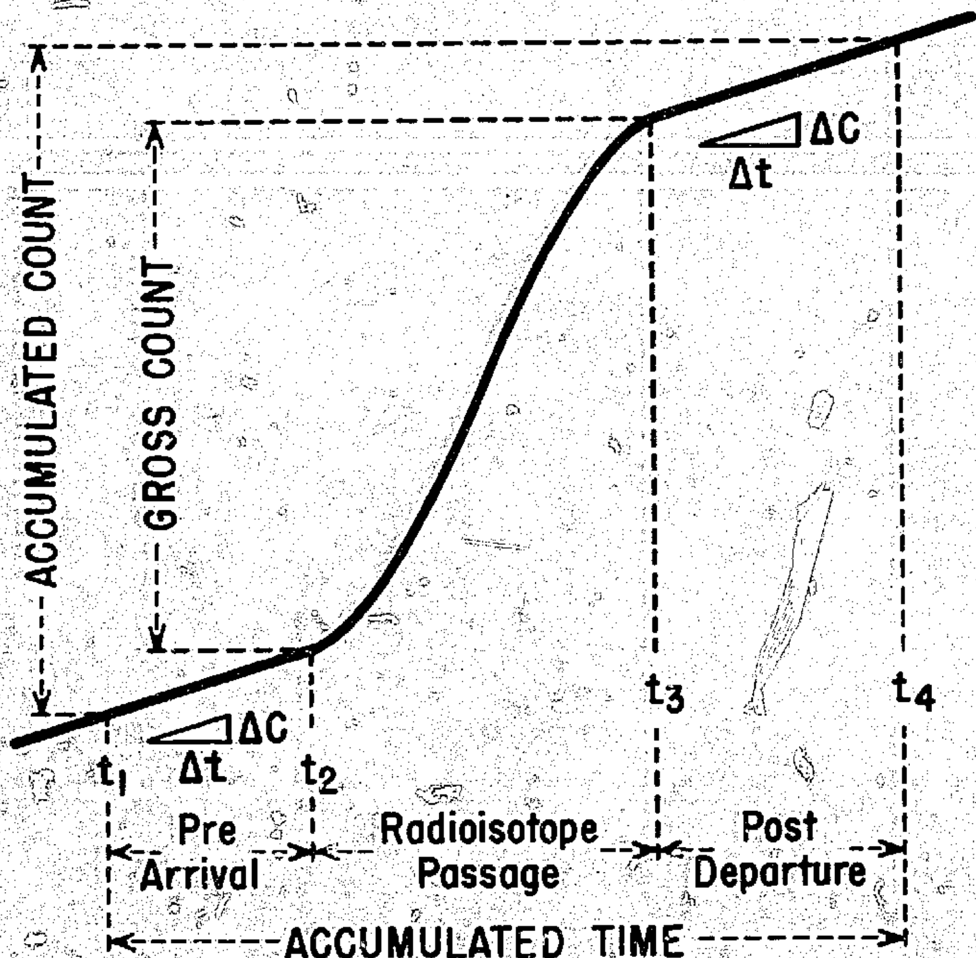
YUMA-MESA CANAL
RADIOISOTOPE DISCHARGE MEASUREMENTS
METHODS OF USING COUNTING SYSTEMS

A. Pouring method of introducing radioisotope into canal flow.

B. Impact method of introducing radioisotope. (Chamber near water surface was immersed and bottle inside was crushed to introduce isotope.)

YUMA-MESA CANAL
RADIOISOTOPE DISCHARGE MEASUREMENTS
METHODS OF INTRODUCING RADIOISOTOPE INTO CANAL FLOW

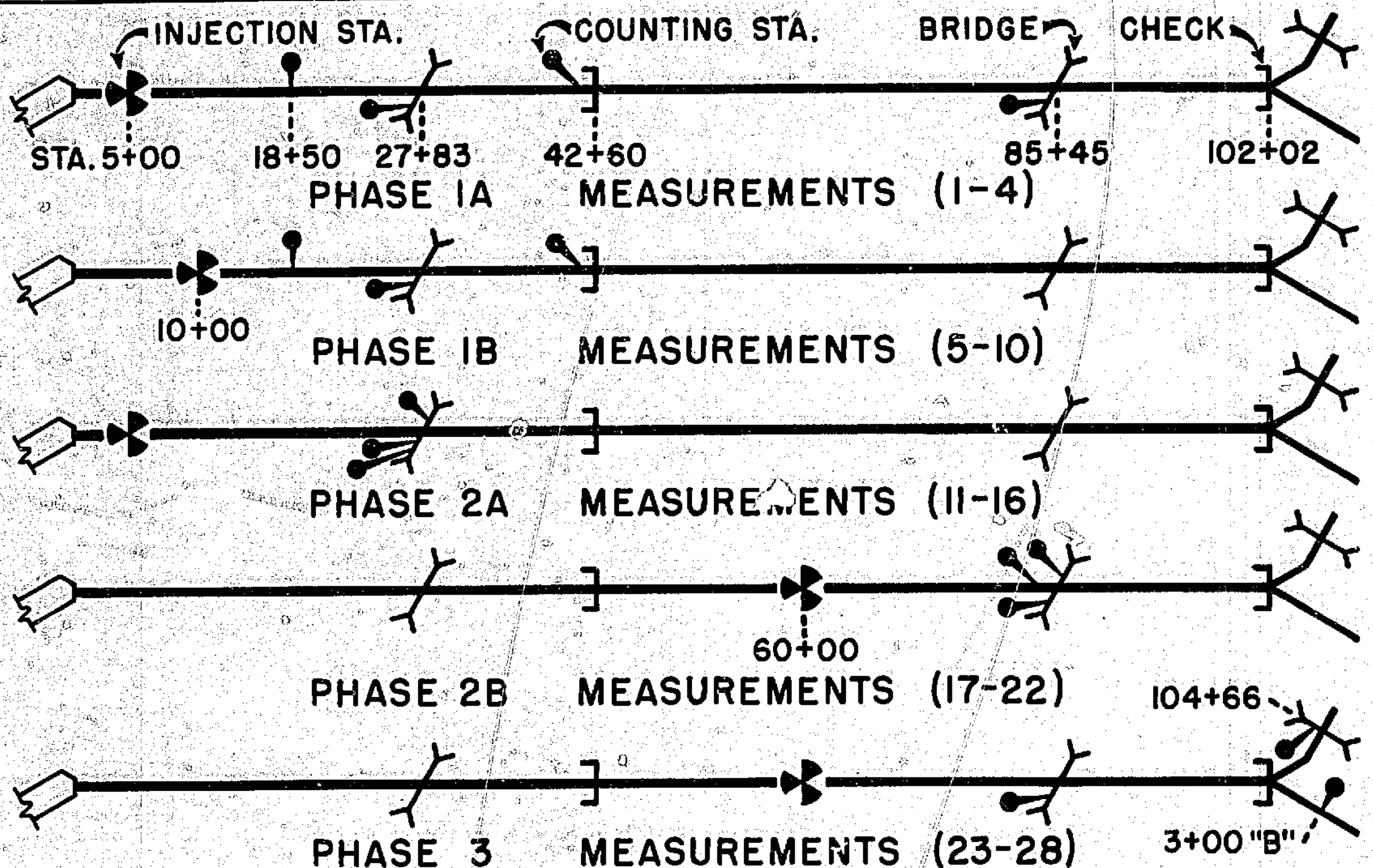
FIGURE 4
REPORT HYD-527



$$\left(\frac{\Delta C}{\Delta t}\right)_{AV.}\left(t_3 - t_2\right) = \text{Accumulated Background}$$

Total Count N = Gross Count − Accumulated Background

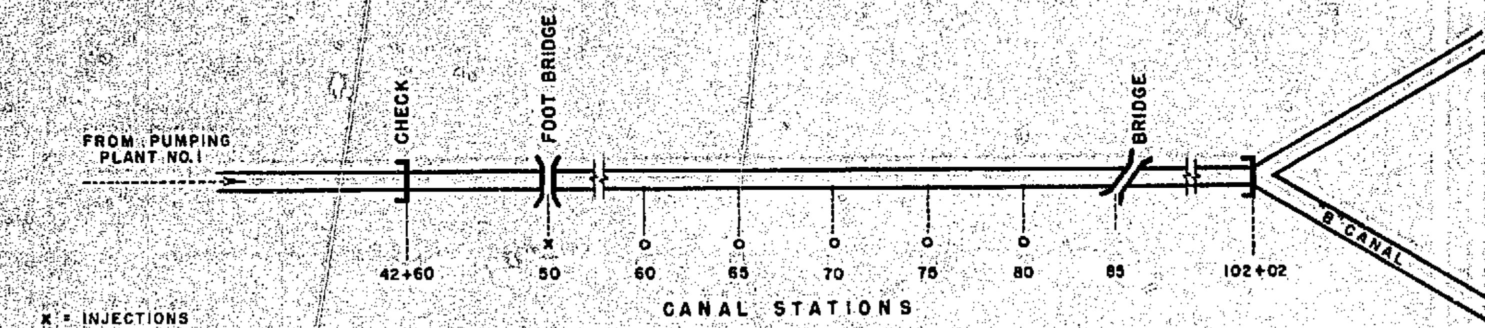
YUMA MESA 'A' CANAL
RADIOISOTOPE DISCHARGE MEASUREMENTS
GRAPHICAL PRESENTATION
CALCULATION OF TOTAL COUNT N



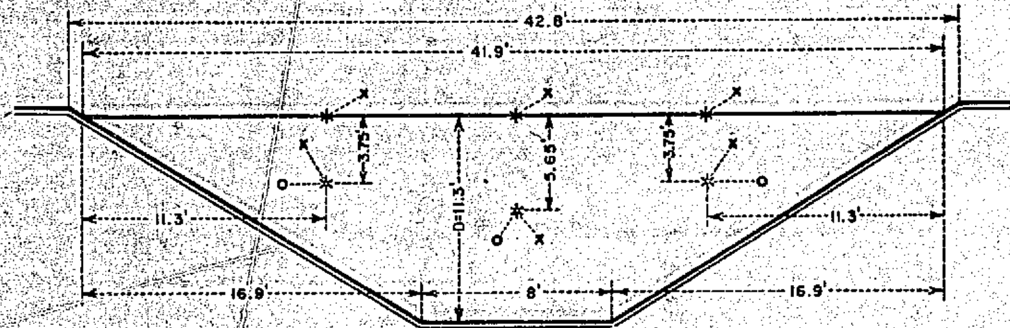
YUMA MESA 'A' CANAL
RADIOSOTOPE SCALER AND COUNTER LOCATIONS
FEBRUARY 6-8, 1962

FIGURE 5
REPORT HYD-527

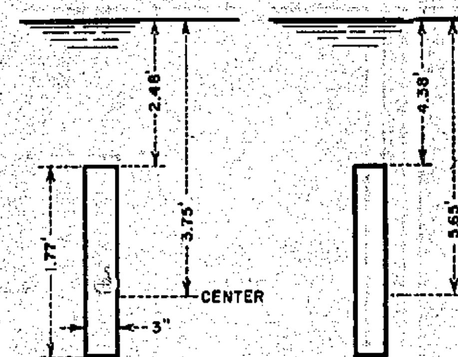
FIGURE 6
REPORT HYD-527



INJECTION AND COUNTER LOCATIONS



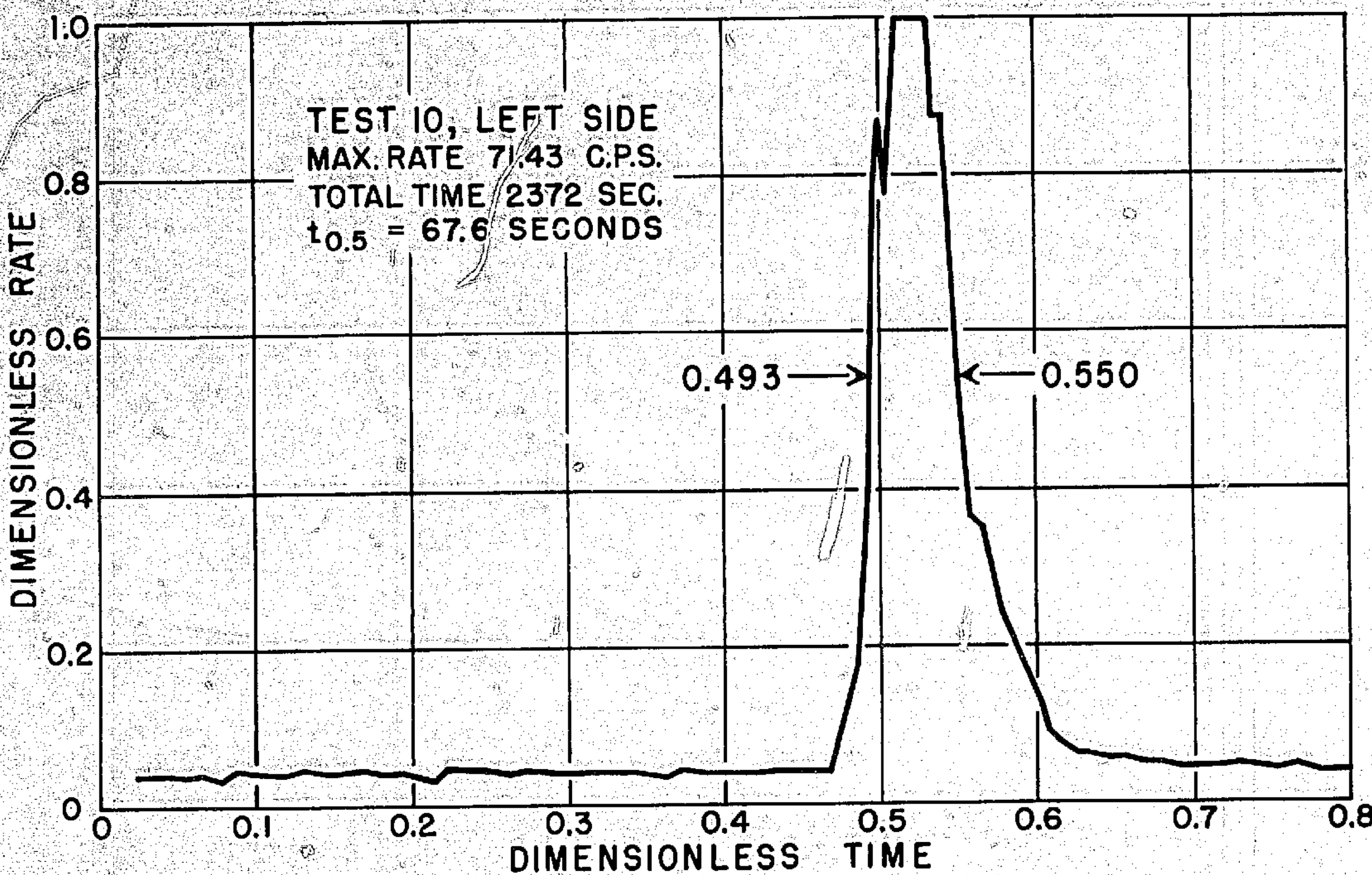
INJECTION AND COUNTER LOCATIONS IN CANAL CROSS SECTION



COUNTER PROBES

YUMA MESA "A" CANAL
INVESTIGATION OF RADIOISOTOPE MIXING CHARACTERISTICS
JUNE 10-14, 1963
YUMA PROJECT - ARIZONA

690



YUMA MESA 'A' CANAL
RADIOISOTOPE DISCHARGE MEASUREMENTS
CONCENTRATION CURVE

CONVERSION FACTORS—BRITISH TO METRIC UNITS OF MEASUREMENT

The following conversion factors adopted by the Bureau of Reclamation are those published by the American Society for Testing and Materials (ASTM Metric Practice Guide, January 1964) except that additional factors (*) commonly used in the Bureau have been added. Further discussion of definitions of quantities and units is given on pages 10-11 of the ASTM Metric Practice Guide.

The metric units and conversion factors adopted by the ASTM are based on the "International System of Units" (designated SI for Systeme International d'Unites), fixed by the International Committee for Weights and Measures; this system is also known as the Giorgi or MKSA (meter-kilogram (mass)-second-ampere) system. This system has been adopted by the International Organization for Standardization in ISO Recommendation R-31.

The metric technical unit of force is the kilogram-force; this is the force which, when applied to a body having a mass of 1 kg, gives it an acceleration of 9.80665 m/sec/sec, the standard acceleration of free fall toward the earth's center for sea level at 45 deg latitude. The metric unit of force in SI units is the newton (N), which is defined as that force which, when applied to a body having a mass of 1 kg, gives it an acceleration of 1 m/sec/sec. These units must be distinguished from the (inconstant) local weight of a body having a mass of 1 kg; that is, the weight of a body is that force with which a body is attracted to the earth and is equal to the mass of a body multiplied by the acceleration due to gravity. However, because it is general practice to use "pound" rather than the technically correct term "pound-force," the term "kilogram" (or derived mass unit) has been used in this guide instead of "kilogram-force" in expressing the conversion factors for forces. The newton unit of force will find increasing use, and is essential in SI units.

Table 1

QUANTITIES AND UNITS OF SPACE

Multiply	By	To obtain
	LENGTH	
Mil	25.4 (exactly)	Micron
Inches	25.4 (exactly)	Millimeters
	2.54 (exactly)*	Centimeters
Feet	30.48 (exactly)	Centimeters
	0.3048 (exactly)*	Meters
	0.0003048 (exactly)*	Kilometers
Yards	0.9144 (exactly)	Meters
Miles (statute)	1,609.344 (exactly)*	Meters
	1.609344 (exactly)	Kilometers
	AREA	
Square inches	6.4516 (exactly)	Square centimeters
Square feet	929.03 (exactly)*	Square centimeters
	0.092903 (exactly)	Square meters
Square yards	0.836127	Square meters
Acres	0.40469*	Hectares
	4,046.9*	Square meters
	0.0040469*	Square kilometers
Square miles	2.58999	Square kilometers
	VOLUME	
Cubic inches	16.3871	Cubic centimeters
Cubic feet	0.0283168	Cubic meters
Cubic yards	0.764555	Cubic meters
	CAPACITY	
Fluid ounces (U.S.)	29.5737	Cubic centimeters
	29.5729	Milliliters
Liquid pints (U.S.)	0.473179	Cubic decimeters
	0.473166	Liters
Quarts (U.S.)	9,463.58	Cubic centimeters
	0.946358	Liters
Gallons (U.S.)	3,785.43*	Cubic centimeters
	3.78543	Cubic decimeters
	3.78533	Liters
	0.00378543*	Cubic meters
Gallons (U.K.)	4.54609	Cubic decimeters
	4.54596	Liters
Cubic feet	28.3160	Liters
Cubic yards	764.55*	Liters
Acre-feet	1,233.5*	Cubic meters
	1,233,500*	Liters

Table II

QUANTITIES AND UNITS OF MECHANICS

Multiply	By	To obtain
MASS		
Grains (1/7,000 lb)	64.79891 (exactly)	Milligrams
Troy ounces (480 grains)	31.1035	Grams
Ounces (avdp)	28.3495	Grams
Pounds (avdp)	0.45359237 (exactly)	Kilograms
Short tons (2,000 lb)	907.185	Kilograms
	0.907185	Metric tons
Long tons (2,240 lb)	1,016.05	Kilograms
FORCE/AREA		
Pounds per square inch	0.070307	Kilograms per square centimeter
	0.689476	Newtons per square centimeter
Pounds per square foot	4.88243	Kilograms per square meter
	47.8803	Newtons per square meter
MASS/VOLUME (DENSITY)		
Ounces per cubic inch	1.72999	Grams per cubic centimeter
Pounds per cubic foot	16.0185	Kilograms per cubic meter
	0.0160185	Grams per cubic centimeter
Tons (long) per cubic yard	1.32894	Grams per cubic centimeter
MASS/CAPACITY		
Ounces per gallon (U.S.)	7.4893	Grams per liter
Ounces per gallon (U.K.)	6.2362	Grams per liter
Pounds per gallon (U.S.)	119.829	Grams per liter
Pounds per gallon (U.K.)	99.779	Grams per liter
BENDING MOMENT OR TORQUE		
Inch-pounds	0.011521	Meter-kilograms
	1.12985×10^6	Centimeter-dynes
Foot-pounds	0.138255	Meter-kilograms
	1.35582×10^7	Centimeter-dynes
Foot-pounds per inch	5.4431	Centimeter-kilograms per centimeter
Ounce-inches	72.008	Gram-centimeters
VELOCITY		
Feet per second	30.48 (exactly)	Centimeters per second
	0.3048 (exactly)*	Meters per second
Feet per year	0.965873×10^{-6}*	Centimeters per second
Miles per hour	1.609344 (exactly)	Kilometers per hour
	0.44704 (exactly)	Meters per second
ACCELERATION*		
Feet per second^2	0.3048*	Meters per second^2
FLOW		
Cubic feet per second (second-feet)	0.028317*	Cubic meters per second
Cubic feet per minute	0.4719	Liters per second
Gallons (U.S.) per minute	0.06309	Liters per second
FORCE*		
Pounds	0.453592*	Kilograms
	4.4482*	Newtons
	4.4482×10^{-5}*	Dynes
WORK AND ENERGY*		
British thermal units (Btu)	0.252*	Kilogram calories
	1,055.06	Joules
Btu per pound	2.326 (exactly)	Joules per gram
Foot-pounds	1.35582*	Joules
POWER		
Horsepower	745.700	Watts
Btu per hour	0.293071	Watts
Foot-pounds per second	1.35582	Watts
HEAT TRANSFER		
Btu in./hr ft^2 deg F (k, thermal conductivity)	1.442	Milliwatts/cm deg C
	0.1240	Kg cal/hr m deg C
Btu ft/hr ft^2 deg F	1.4880*	Kg cal m/hr m^2 deg C
Btu/hr ft^2 deg F (C, thermal conductance)	0.568	Milliwatts/cm^2 deg C
	4.882	Kg cal/hr m^2 deg C
Deg F hr ft^2/Btu (R, thermal resistance)	1.761	Deg C cm^2/milliwatt
Btu/lb deg F (c, heat capacity)	4.1868	J/g deg C
Btu/lb deg F	1.000*	Cal/gram deg C
Ft^2/hr (thermal diffusivity)	0.2581	Cm^2/sec
	0.09290*	M^2/hr
WATER VAPOR TRANSMISSION		
Grains/hr ft^2 (water vapor transmission)	16.7	Grams/24 hr m^2
Perms (permeance)	0.659	Metric perms
Perm-inches (permeability)	1.67	Metric perm-centimeters

Table III

OTHER QUANTITIES AND UNITS

Multiply	By	To obtain
Cubic feet per square foot per day (seepage)	304.8*	Liters per square meter per day
Pound-seconds per square foot (viscosity)	4.8824*	Kilogram second per square meter
Square feet per second (viscosity)	0.02903* (exactly)	Square meters per second
Fahrenheit degrees (change)*	5/9 exactly	Celsius or Kelvin degrees (change)*
Volts per mil	0.03937	Kilovolts per millimeter
Lumens per square foot (foot-candles)	10.764	Lumens per square meter
Ohm-circular mils per foot	0.001662	Ohm-square millimeters per meter
Millicuries per cubic foot	35.3147*	Millicuries per cubic meter
Milliamps per square foot	10.7639*	Milliamps per square meter
Gallons per square yard	4.527219*	Liters per square meter
Pounds per inch	0.17858*	Kilograms per centimeter

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ABSTRACT

A study using radioisotopes--a part of the USBR continuing program to improve water measurement practices--provided useful information for developing radioisotope techniques in open channel discharge measurements and data for establishing minimum mixing lengths. Half-capacity tests in Feb 1962 and full-capacity tests in June 1963 using Gold-198 were made in a straight section of a concrete-lined irrigation canal with a design discharge of 620 cfs. The pulse or total-count radioisotope method was used for 65 discharge measurements. Consistency of the radioisotope method was evaluated by using up to 4 portable Geiger counting systems. Conclusions were: / (1) With adequate mixing of radioisotope and canal water; accuracy of 97% or greater is possible when compared with current meter discharge measurements. (2) In a canal with hydraulic characteristics similar to the one tested, a 2,500- to 3,000-ft mixing length is needed for 98 to 99% mixing. (3) Minimum mixing length may be computed for similar straight canals using a diffusion coefficient and time factor developed from these tests. (4) Simultaneous multiple injections of tracer will provide higher probability of uniform mixing in shorter lengths than will single injections and also result in higher diffusion coefficients. (5) With sufficient data from canals of various sizes mixing length equations can probably be derived for canals having a minimum of turbulence. / Further investigation is needed to refine the limits of variables that control mixing.

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DESCRIPTORS: *discharge measurement/ *radioactive isotopes/ tracers/ dyes/ *mixing/ canals/ open channels/ *radiation measurement/ diffusion/ turbulent flow/ roughness coefficients/ current meters/ fluorescein/ shear/ counting method/ dispersion/ velocity/ prototype tests/ field tests/ concentration/ Geiger counters/ pulses/ open channel flow/ test procedures

IDENTIFIERS--*mixing length/ lined canals/ Yuma Mesa A Canal/ bifurcations/ Gila Project/ surface resistance coeffs/ diffusion coefficients/ dilution method/ Gold-198/ test reaches/ *total count method

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