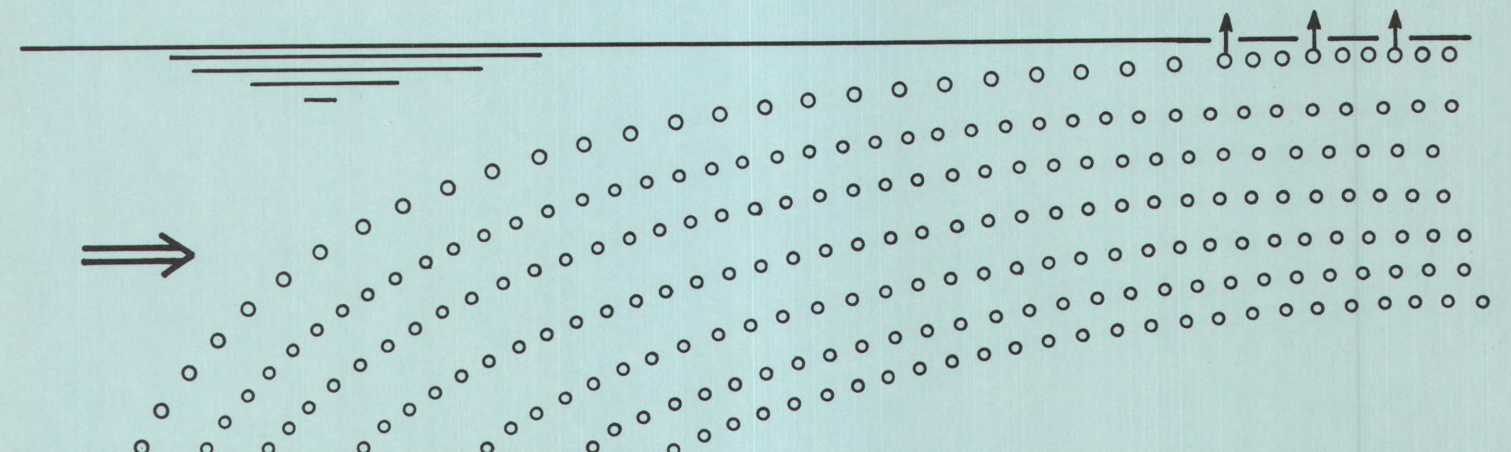
DETERMINATION OF STREAM REAERATION COEFFICIENTS BY USE OF TRACERS



U.S. DEPARTMENT OF THE INTERIOR
March 3, 1849

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DETERMINATION OF STREAM REAERATION COEFFICIENTS BY USE OF TRACERS

by F.A. Kilpatrick, R.E. Rathbun, N. Yotsukura, G.W. Parker, and L.L. DeLong

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UNIT CONVERSION

Multiply inch-pound unit	by	To obtain metric unit
inch (in.)	25.40	millimeter (mm)
foot (ft)	.3048	meter (m)
mile (mi)	1.609	kilometer (km)
pound (lb)	453.6	gram (g)
gallon (gal)	3.785	liter (L)
gallon (gal)	3785	milliliters (mL)
cubic foot (ft^3)	.02832	cubic meter (m^3)
foot per second (ft/s)	0.3048	meter per second (m/s)
square foot per second (ft^2/s)	.09294	square meter per second (m^2/s)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
degree Fahrenheit (°F)	°C = 5/9 (°F-32)	degree Celsius (°C)

SYMBOLS AND UNITS

Symbol	Explanation	Unit
A_c	Area of the observed dye concentration-time response curve	(μg/L)(min) or (μg/L)(h)
A_z	Area of the observed dye concentration-time response curve measured on a streamline z	(μg/L)(min) or (μg/L)(h)
A_g	Area of the gas concentration-time response curve	(μg/L)(min) or (μg/L)(h)
B	Average width of stream	ft
$\overline{c}$	Weighted or average plateau dye concentration	μg/L
$\overline{c}_g$	Weighted or average plateau gas concentration	μg/L
C	Concentration of injected dye solution	μg/L
C_d	Observed dye concentration	μg/L
C_g	Observed gas concentration	μg/L
C_p	Observed peak dye concentration	μg/L
C_s	Concentration of stock dye solution, generally as obtained from the manufacturer	μg/L
d	Mean depth of stream; also a subscript to denote downstream	ft
e	A constant, 2.72	----
E_z	Lateral or transverse mixing coefficient	ft^2/s
ΔH	Change in elevation in test reach	ft
J	Dye loss correction factor	----
K_2	Oxygen absorption or reaeration rate coefficient	h^{-1}
$K_{2_{20}}$	Oxygen absorption or reaeration rate coefficient at 20 °C	h^{-1}
K_e	Ethylene gas desorption rate coefficient	h^{-1}
K_p	Propane gas desorption rate coefficient	h^{-1}
K_{P_T}	Propane gas desorption rate coefficient at stream temperature T	h^{-1}
$K_{P_{20}}$	Propane gas desorption rate coefficient at 20°C	h^{-1}
K_T	Tracer gas desorption rate coefficient	h^{-1}
$K_{T_{20}}$	Tracer gas desorption rate coefficient at 20°C	h^{-1}
K_{T_T}	Tracer gas desorption rate coefficient at temperature T	h^{-1}
K_{T_z}	Tracer gas desorption rate coefficient along a streamline, z	h^{-1}
L	Length of measurement reach	ft
L_o	Channel length required for optimum mixing; usually corresponds to about 95 percent mixing	ft
M	Mass of tracer injected	g
$M_{1,2,3..n}$	Series of slug injections of equal mass	g
q	Rate of constant dye tracer injection	mL/min
q_g	Rate of constant gas tracer injection	ft^3/h or L/min or lbs/h

Symbol	Explanation	Unit
Q	Total stream discharge	ft^3/s
ΔQ_z	Portion of total stream discharge applicable to a streamline	ft^3/s
Q_z	Cumulative stream discharge laterally in the cross section at streamline z	ft^3/s
Q_m	Maximum discharge in test reach	ft^3/s
R_e	Ratio of oxygen reaeration rate coefficient to ethylene gas desorption rate coefficient	----
R_p	Ratio of oxygen reaeration rate coefficient to propane gas desorption rate coefficient	----
R_r	Dye recovery ratio	----
s	Water-surface slope	ft/ft
S_G	Specific gravity	
Δt	Numerical intergration interval	min or h
t	Elapsed time from start of injection	h
t_b	Interval of time for dye concentrations to build up from the leading edge to the peak	h
$t_{c,L,t,p}$	Traveltime of centroid, leading edge, trailing edge, and peak, respectively, of dye response curve	h
t_i	Elapsed time to point i on response curve	h
T	Stream temperature	°C
$T_{c,L,t,p}$	Elapsed time to centroid, leading edge, trailing edge and to peak, respectively, of dye response curve	h or min
T_d	Duration in time for dye cloud to pass at any one point in a section	h or min
T_D	Duration in time for entire tracer cloud to pass section	h or min
V_d	Volume of dye solution	mL
V_I	Volume of dye solution injected into stream	L or mL
V_s	Volume of stock dye solution	L or mL
u	A subscript denoting upstream	----
V_w	Volume of diluent, usually distilled water	mL
v	Mean stream velocity	ft/s
v_p	Velocity of peak	ft/s
W_d	Weight of dye injected	g
W_r	Weight of dye recovered	g
z	Streamline index expressed as a percentage of the total river discharge; $z = 100\ Q_z/Q$; also used as a subscript to denote a streamline	percent
ϕ	Mass distribution	----

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ABSTRACT

Stream reaeration is the physical absorption of oxygen from the atmosphere by a flowing stream. This is the primary process by which a stream replenishes the oxygen consumed in the biodegradation of organic wastes.

Prior to 1965, reaeration rate coefficients could be estimated only by indirect methods. In 1965, a direct method of measuring stream reaeration coefficients was developed in which a radioactive tracer gas was injected into a stream--the tracer gas being desorbed from the stream inversely to how oxygen would be absorbed. The technique has since been modified by substituting hydrocarbon gases for the radioactive tracer gas.

This manual describes the slug-injection and constant-rate injection methods of performing gas-tracer desorption measurements. Emphasis is on the use of rhodamine WT dye as a relatively conservative tracer and propane as the nonconservative gas tracer, on planning field tests, methods of injection, sampling and analysis, and computational techniques to compute desorption and reaeration coefficients.

INTRODUCTION

Stream reaeration is the physical absorption of oxygen from the atmosphere by a flowing stream. This is the primary process by which a stream replenishes the oxygen consumed in the biodegradation of organic wastes.

The primary use of reaeration coefficients is to quantify the process of reaeration in dissolved oxygen (DO) water-quality models. The reaeration coefficient is the rate constant for the absorption of oxygen from the atmosphere. These models which simulate the exchange of DO, are used to calculate waste-load allocations for the stream so that the DO concentration standards are not violated. If the reaeration coefficient used in a model is smaller than the actual coefficient of the stream, then the required degree of waste treatment indicated by the model results will be too large, and the expenditure of funds will be greater than needed (St. John and others, 1984). Conversely, if the reaeration coefficient used in the model is larger than the actual coefficient of the stream, then the degree of waste treatment determined from the model results will be insufficient, and the DO standards may be violated. Management of the DO resources of the stream can be done either by increasing the degree of treatment of the wastes discharged into the stream or by reducing the quantity of waste discharged into the stream. In either case, the reaeration coefficient must be known accurately if the DO resources of the stream are to be managed properly.

Prior to 1965, reaeration-rate coefficients could be estimated only by indirect methods (Bennett and Rathbun, 1972), which were subject to significant errors. In 1965, Tsivoglou and others developed a direct method of measuring stream-reaeration coefficients employing the radioactive tracer gas krypton-85. Tsivoglou's method is based on the principle that a gas tracer injected into a stream would be desorbed from the stream inversely to how oxygen would be absorbed. This provided the first direct means of measuring stream reaeration capacity.

Unfortunately, the radioactive tracer technique has disadvantages. The primary disadvantage is the potential for radiation exposure by the personnel conducting the study and by the public along the stream. Tsivoglou (1967) reported that radiation exposure could be eliminated with a minimum of trouble for discharges less than 200 ft^3/s (cubic feet per second). For larger flows, however, more stringent precautions are required because of the larger amounts of tracer necessary. Another disadvantage of using radioactive tracers is that the process for obtaining a license to use radioactive material in a public waterway may be quite involved.

In the early 1970's, Rathbun (Rathbun and others, 1975; Rathbun and others, 1978) modified the technique (hence, it is frequently called the Modified Method) whereby a hydrocarbon gas such as ethylene or propane is substituted for radioactive krypton as the gas tracer. Theoretically, this method does not differ substantively from the krypton method; the only differences are in performance techniques.

The purpose of this manual is to provide the user an understanding of the principles and techniques of performing reaeration tests on streams through use of gas tracers. The basic technique applied by Tsivoglou and Rathbun involved the slug injection of the gas tracer into the stream and the subsequent measurement of its desorption as it moved and dispersed downstream. To be consistent with other tracer manuals and use in the U.S. Geological Survey (Kilpatrick and Cobb, 1985), the slug-injection method is referred to henceforth as the SI method. This distinguishes it from the steady-state method of Yotsukura and others (1983), which features the continuous injection of the gas tracer at a constant rate, and is hereafter referred to as the CRI method. The application of this method is also fully discussed in this manual.

Both the SI and CRI methods have been used primarily on small streams where complete vertical and lateral mixing in a cross section could be readily obtained. Preliminary tests have been performed and techniques developed (Yotsukura and others, 1984) to apply the CRI method to wide streams in which lateral mixing as well as longitudinally dispersion is not complete. Although preliminary, the field techniques and methods of analysis will be presented in this manual to encourage their use and further development.

Background Preparation

The reader is advised to become fully acquainted with the following Techniques of Water-Resources Investigations (TWRI) of the Geological Survey prior to using this manual and performing tracer reaeration tests:

1. Fluorometric Procedures for Dye Tracing
   By J. F. Wilson, Jr., E. D. Cobb, and F. A. Kilpatrick
   TWRI, Book 3, Chapter A12, 1986

2. Measurement of Time of Travel and Dispersion in Streams by Dye Tracing
   By E. F. Hubbard, F. A. Kilpatrick, L. A. Martens, and J. F. Wilson, Jr.
   TWRI, Book 3, Chapter A9, 1982

3. Measurement of Discharge Using Tracers
   By F. A. Kilpatrick and E. D. Cobb
   TWRI, Book 3, Chapter A16, 1985

Particular attention should be given to the last report, because an understanding of the superposition principle and of the various factors involved in performing slug and constant rate dye injections is similar for reaeration tests and vital to their successful performance. For continuity and convenience, some of the information available in these reports will be presented again. For consistency, symbols and definitions will be the same as presented in these other reports when feasible.

Accuracy

Good engineering practice dictates that measures employed to ensure accuracy of data not exceed that necessary for an adequate analysis to meet the intended use. For example, reference (2) above suggests low and high levels of study commensurate with the objectives of the study for time-of-travel tests. Conversely, reference (3) emphasizes the need for greater accuracy and care when performing dye-dilution discharge measurements. This requirement is to be further emphasized in regard to performing tracer reaeration tests in virtually all aspects of planning, data collection, laboratory analysis, and computations.

THEORY

Behavior of Tracers in Streams

Dispersion and Mixing

Tracers used successfully in hydrologic studies are water soluble and have essentially the same physical characteristics as water (Feuerstein and Selleck, 1963; Smart and Laidlaw, 1977). Thus, when introduced into a flowing stream, they experience the same dispersion and dilution as does the element of water tagged. The use of tracers to simulate flow and transport in a water body as well as to measure the quantity of flow is widespread (Pritchard and Carpenter, 1960; Wright and Collings, 1964; Taylor, 1970; Boning, 1973; Yotsukura and Kilpatrick, 1973; Kilpatrick and Cobb, 1985; Kilpatrick and Taylor, 1986).

An understanding of how tracers behave in a stream is essential to an understanding of their application in reaeration tests. Figure 1 depicts the downstream behavior of a tracer injected as a slug in the center of flow. Note, that in figure 1 the response curves are shown as concentration versus longitudinal distance and not versus time. In figure 1, the stream has been arbitarily divided laterally into six stream tubes of equal discharge; these are defined by the seven streamlines, a through g. In practice this is done by plotting the cumulative discharge, such as measured by a current meter, versus lateral distance in the measurement cross section. The concept of stream tubes and streamlines was advanced by Chow (1964) and Yotsukura and Cobb (1972). This concept is useful in describing the behavior of a tracer and is an essential part of the technique of measuring reaeration, particularly in the application of the CRI method on wide streams.

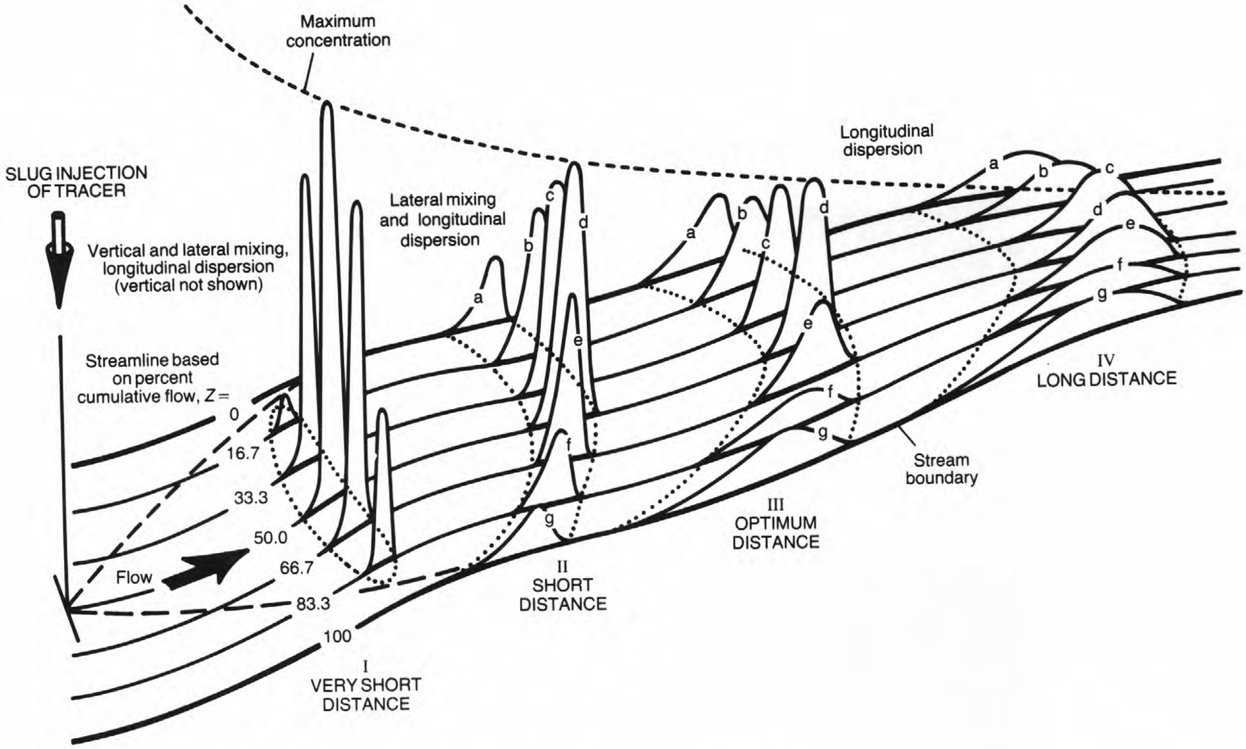

Figure 1.--Lateral mixing and longitudinal dispersion patterns and changes in distribution of concentration downstream from a single, center slug injection of tracer.

The dispersion and mixing of a tracer in a receiving stream takes place in all three dimensions of the channel (fig. 1). In this manual, vertical and lateral dispersion and diffusion will be referred to in a general way as mixing. The elongation of a tracer response cloud longitudinally will be referred to as longitudinal dispersion. Vertical mixing is normally completed first, and lateral later, depending upon the width of the stream and velocity variations. Longitudinal dispersion, having no boundaries, continues indefinitely. Thus at section I, vertical mixing may be complete, meaning that at any one streamline and time, the tracer concentration is the same near the bed of the stream as at the water surface, even though varying drastically laterally. At a short distance, lateral mixing is still taking place, as the tracer mass in transport along the different streamlines is not equal since the response curves do not have the same areas. Mixing and dispersion in two-dimensions therefore exists between sections I and II.

It should be kept in mind that measurements over relatively short distances do not necessarily yield representative results, since the entire flow is not yet tagged and simulated. The SI method of measuring reaeration using radioactive tracers is usually performed over such short distances. Similarly, the CRI two-dimensional method as employed in wide rivers is performed in a reach which is short relative to the distance required for complete lateral mixing.

An optimum mixing distance, III, is reached when the tracer response curves as observed laterally, a, b, c, ... g, have about the same areas, even though the individual response curves may vary considerably in shape and dimensions; dispersion is approaching the one-dimensional state. Nevertheless, the peak concentrations in the center of the channel may be considerably greater than peak concentrations along the banks, while the latter are longer both physically and in time of passage. Also, the tracer cloud is skewed, advancing faster in the center of the flow compared to the channel boundaries. As shown in figure 1, the tracer cloud may not necessarily be uniformily skewed. Figure 1 illustrates why sampling of the tracer cloud at several points laterally is advisable.

If the tracer response curves are next examined at a long distance, IV, the curve areas will be found to be nearly identical and peak concentrations more nearly the same laterally. Thus, a nearly one-dimensional dispersion state exists between sections III and IV with longitudinal dispersion dominating and continuing indefinitely downstream. With time and distance, peak concentrations become attenuated and the cloud lengths get longer and longer (Kilpatrick and Taylor, 1986).

When using hydrocarbon gas and dye tracers in performing the SI method of reaeration measurement, a stream reach is sought where both vertical and lateral mixing is essentially completed. A test reach normally consists of an upstream and downstream measuring section. Thus, an effort is made to select an injection site a sufficient distance upstream such that as a minimum, optimum mixing is obtained at the first measuring section (the upstream section) of the reaeration measurement reach. This is done primarily because it is essential that an accurate measurement and adjustment for dye losses be made. This can be more accurately done if lateral mixing is essentially complete in the test reach. This is not a factor when performing the SI method with radioactive tracers because the radioactive dispersion tracer is essentially conservative over the stream reaches and times employed and loss of this tracer is not a factor in the analysis and computations. The same is true for the CRI method using hydrocarbon gas and dye tracers, although results more representative of the entire stream will be obtained if a stream reach is used where optimum mixing has been obtained.

Characteristics of Response Curve

The conventional manner of illustrating the <u>response</u> of a stream to a slug injection of tracer is to plot concentration variation with elapsed time as observed at one or more points laterally at a stream cross section. To illustrate this, the tracer response curves for a single center point slug injection (see fig. 1) for streamlines b, d, and f are shown as solid lines in figure 2 for the short, optimum, and long distances. If the complete tracer cloud is to be observed, samples must be taken for the entire duration of the time of passage, T_D, if just sampled at b, d, and f. If samples are taken very close to the banks, a and g in figure 1, T_D will be much longer. Similarly, as shown, T_D will increase with distance downstream.

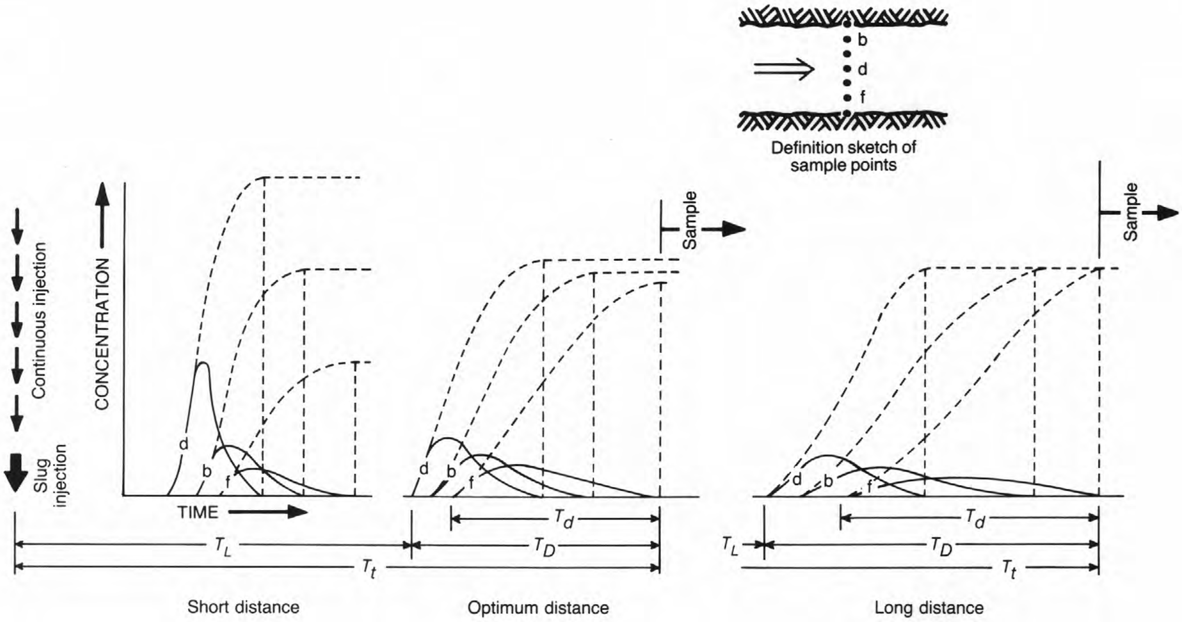

Figure 2.--Time-concentration curves for slug and simulated constant injection observed at three points laterally across channel, three different distances below the injection point.

As will be seen subsequently, it is this period of time, T_D at the most downstream cross section, that determines the minimum duration of gas injection in the CRI method of reaeration measurement. An understanding of this unique characteristic of the time-concentration response curve is essential to the performance of the CRI method and can be best understood by using the superposition principle.

Superposition Principle

A continuous, constant-rate injection of tracer may be simulated from the response curve of a slug injection using the superposition principle (Yotsukura and Kilpatrick, 1973). This can be understood best by using any one of the slug-response curves in figure 2 to simulate the response of a continuous injection at the same location. In figure 3, the solid response curve is due to the slug injection, M_1, and T_L and T_t are the elapsed times to the arrival of the leading edge and trailing edges, respectively, of this response curve. Assuming the streamflow is steady, continuing to inject a

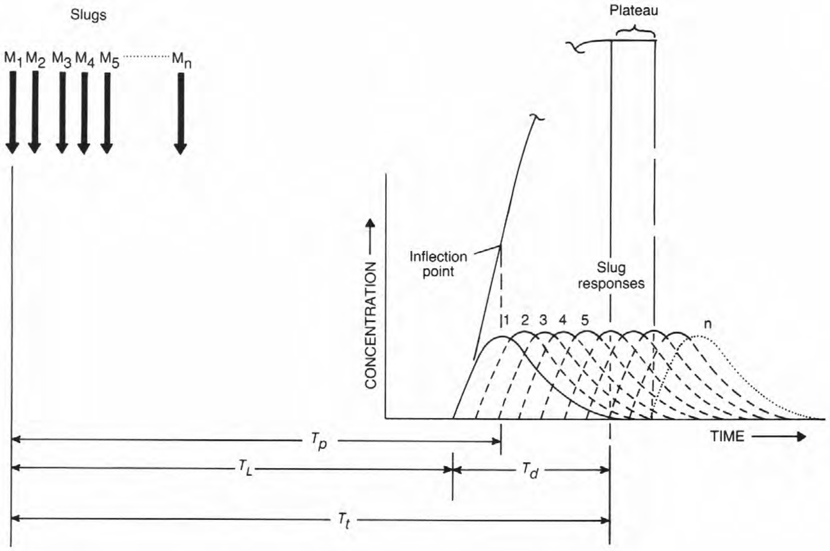

Figure 3.--Superposition of slug-response curves to simulate constant-injection buildup to a plateau at one location in stream section.

series of tracer slugs of equal amounts M_2, M_3, ... M_n, at short uniform time intervals (a constant-rate injection) would yield a series of identical response curves offset by the interval between injections. Of course, if the same soluble tracer is continuously injected, the individual response curves could not be distinguished and there is an ever-increasing buildup of concentration with time until T_t is reached. In effect, the superimposed slug-response curves are being added as they overlap. The initial buildup is ever increasing until an inflection point is reached at a time corresponding to the time of the peak, T_p, of the first slug-response curve. Buildup continues at a decreasing rate past this inflection point until a plateau is reached at the time, T_t, corresponding to when the trailing edge of the first slug response has passed the point of observation. This plateau of constant concentration is first reached at time T_t for that point in the channel. At this time, for a constant injection, an equilibrium condition is reached. Continued injection after T_t would result in a plateau of constant concentration at that point as long as the stream discharge and rate of tracer injection did not vary.

The same results illustrated in figure 3 are shown in figure 2 for the same three distances and the three lateral locations b, d, and f. The slug-response curves are used to simulate (dashed lines) the responses to a continuous injection of tracer and are obtained by superimposing the uniformly repeated slug-response curves.

It may be seen in figure 2 that for the short distance, plateaus of different concentrations are obtained laterally. This shows that mixing is poor and is identical for continuous and slug injections.

At the optimum distance[1], the plateaus laterally tend to converge to about the same concentration indicating that mixing is adequate. Note that tracer would need to be injected continuously for at least a time T_D to first reach a completely stabilized plateau across the channel between points b and f at that distance (see fig. 2). The minimum period corresponds to the difference in time for the earliest arriving tracer (center or point d) and the latest departing tracer (point f). Of course, it would be necessary to inject tracer for a time slightly greater than T_D to allow for sampling the fully developed plateau. It is important to remember that to develop a plateau close to the immediate streambanks, points a and g, injection would have to be longer and would be determined by a T_D based on the slowest moving tracer along one bank or the other. In the illustration in figure 1, the longest T_D would be the difference in times for the leading edge, T_L of response d (center) and the trailing edge, T_t of response g (right side bank).

At a long distance, the resulting plateau concentrations are virtually identical if the constant injection is made over sufficient time and if sufficient time is allowed for the buildup to be accomplished across the entire channel. What was said for the optimum distance superposition applies equally to that for the long distance. Most important, it is the duration of passage, T_D, for the most downstream sampling site which determines the minimum gas injection period for the CRI method. This is because the duration of the plateau at that site will be shorter than at any site further upstream.

In summary, the time-concentration curves resulting from a slug injection of tracer can be used to determine the minimum length of continuous gas injection necessary to perform the CRI method of reaeration measurement. Furthermore, the time of departure of the dye tracer at the sampling section, which is the response to a slug injection, corresponds to the time at which a gas plateau will have just been reached due to a continuous constant-rate injection of gas upstream. A CRI reaeration test should be designed such as to avoid sampling along the immediate streambanks so that extremely long gas injection periods are not needed.

Dye Tracer Losses and Recovery Ratios

All of the methods of directly measuring stream reaeration involve the injection of a tracer gas into the streamflow and the subsequent measurement of its desorption as it is transported downstream (Rathbun and others, 1975; Rathbun and Grant, 1978). The amount of desorption is evaluated by measuring the loss of the gas tracer between two or more sections downstream from the injection. This desorption is measured against a totally conservative tracer which is injected at exactly the same location and undergoes the same dispersion and dilution as the gas tracer.

The radioactive tracer and the hydrocarbon gas-dye tracer SI method of reaeration measurement are the same in principle but different in application,

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[1] The optimum distance is usually where mixing is about 95 percent complete. The concept of degree of mixing and how it is computed is discussed in Appendix A of the third background reference.

primarily because the dye tracer used in the latter is not totally conservative in contrast to the tritiated water used in the first. It is therefore essential that an accurate measurement of dye recoveries be made, as this enters directly into the computation of the reaeration coefficient when using the peak method; in effect, the dye concentration data are made conservative by use of recovery information.

Thus, as discussed previously, the performance of the SI method using hydrocarbon gas is best performed in a stream reach where mixing is essentially complete. It is suggested that at least three sampling points be located in each measuring section in equal or known portions of the stream discharge such as at b, d, and f of figures 1 and 2. The dye concentration-time curves should be well defined and extended to background at each sampling point. This may require sampling until concentrations are about 2 percent of the peak or 0.1 μg/L, whichever is largest. The remainder of the curve should be extrapolated to zero. Under no circumstances should the concentration-time curves be truncated at 10 percent of the peak concentration as is suggested for time-of-travel studies. The total mass of dye passing the measuring section is desired, hence the best measurement of the total areas of the concentration time curves is necessary. The dye recovery ratio R_r at any measuring section is expressed by the equation

$$R_r = \frac{W_r}{W_d} \tag{1}$$

where W_d is the weight of dye injected and W_r is the weight recovered. Since $W_d = V_I C S_G$ and $W_r = QA_c$

$$R_r = 1699 \frac{QA_c}{V_I C S_G} \tag{2}$$

where Q is the stream discharge in cubic feet per second;

A_c is the representative total area under the observed dye concentration-time curve in μg/L times minutes. If three or more concentration-time curves are observed at a section, A_c is the average, weighted on the basis of discharge. If the sample points are chosen to represent equal increments of discharge, weighting has already been accomplished. Observed dye concentrations must be based on a fluorometric calibration which also considers the specific gravity, S_G, of the dye solution (see reference 1);

C is the concentration of the injected solution, in micrograms per liter (20 percent = 20×10^7 μg/L);

V_I is the volume of dye injected, in liters having a concentration C; and

S_G is the specific gravity of the injected dye solution; 1.19 for rhodamine WT, 20 percent solution as received from the manufacturer. It should be noted that if S_G is actually other than 1.19, no error will occur if the same value is used in the preparation of standards for calibrating the fluorometer and hence is reflected in A_c.

As indicated above, $W_r = QA_c$; where good mixing exists and multiple sampling points have been selected to represent equal increments of stream discharge, A_c may be a simple average of the area of the individual dye-response curves. If mixing is not good, that is, a two-dimensional dispersion state exists and/or if sampling points were not selected to represent equal increments of discharge, QA_c in equation 2 must be the summation of the dye mass in transport along each streamline z. Thus equation 2 for the two-dimensional case may be written

$$R_r = 1699 \frac{\Sigma(\Delta Q_z A_z)}{V_I C S_G} \qquad (3)$$

A dye correction factor, J, is frequently used in the computation of the gas desorption coefficient when using the SI method (Rathbun and others, 1975). The factor J may also be expressed as

$$J = \frac{(R_r)\text{ upstream}}{(R_r)\text{ downstream}} \qquad (4)$$

using the recovery ratio for the upstream and downstream measuring sections which comprise the reaeration measurement test reach. Rather than using J outright, it is suggested that recovery ratios be computed for each measuring section so that their validity may be examined. In practice, the recovery of a dye tracer must always be less than 100 percent; R_r will usually be 0.80 to 0.95 in short stream reaches typically used for reaeration tests. If computations produce other results, usually Q or A_c are in error; commonly, A_c has not been adequately or accurately defined. In short stream reaches, A_c measured just in the center of the stream will typically yield recoveries in excess of 100 percent. Measuring the dye concentration-time curve at less than three points in a section is discouraged.

It is important that the fluorometer used be calibrated using a sample of the injected dye. Poor fluorometry techniques may yield erroneous recovery values. Errors can often be detected by computing recoveries and comparing them over the stream reach. Comprehensive field data collection and accurate laboratory analyses will avoid most problems.

Gas Desorption and Oxygen Absorption

The principle involved in measuring stream reaeration coefficients using gas tracers is that the desorption of the gas tracer is related to the absorption of oxygen under similar flow conditions; namely, the ratio of the reaeration rate coefficient to the desorption rate coefficient of the tracer gas is constant, independent of temperature or turbulence intensity.

Tank Tests

Tank stirring tests which have involved the careful concurrent measurement of oxygen absorption and gas desorption have been performed by both Rathbun (Rathbun and others, 1978) and Rainwater and Holley (1983, 1984) for the hydrocarbon gases ethylene and propane. Tsivoglou (1967) performed essentially the same tests for krypton-85 gas which is used in the radioactive method.

Rathbun and others (1978) determined that the ratios for ethylene and propane are

$$R_e = \frac{K_2}{K_e} = 1.15 \tag{5}$$

and

$$R_p = \frac{K_2}{K_p} = 1.39 \tag{6}$$

where K_e and K_p are the desorption rate coefficients for ethylene and propane, respectively, and K_2 is the reaeration rate coefficient for oxygen. The tests by Rainwater and Holley confirmed these ratios.

The use of any gas tracer to simulate oxygen is predicated on the assumption that the removal of the gas is by desorption only and that no other physical or chemical processes interfere. Experience (Holley and Yotsukura, 1984) indicates that in some instances ethylene gas may be subject to biodegradation. Ethylene, which is an unsaturated hydrocarbon, is more chemically reactive than saturated hydrocarbons such as propane. Also, hydrocarbons are known to be chemically reactive with halogens such as fluorine and chlorine, which may be found downstream of industrial or domestic sewage-treatment plants (Stedfast and Draper, 1986). Therefore, propane has become the more commonly used hydrocarbon gas for performing reaeration tests.

Temperature Corrections

The reaeration coefficient is usually expressed as being at 20 °C (Elmore and West, 1961). Stream water will seldom be at 20 °C and field determined desorption coefficients may be adjusted to 20 °C using the equation

$$K_{T_{20}} = K_{T_{\mathrm{T}}} \; (1.0241)^{(20-\mathrm{T})} \tag{7}$$

where K_T is the desorption coefficient as measured by a tracer gas at stream temperature T. Similarly, the reaeration coefficient at 20 °C when propane is the tracer gas may be expressed as

$$K_{2_{20}} = 1.39 \; K_{p_{\mathrm{T}}} \; (1.0241)^{(20-\mathrm{T})} \tag{8}$$

Gas Desorption

All methods of measuring stream reaeration involve the injection of a tracer gas into the streamflow and the subsequent measurement of its desorption as it is transported downstream. In effect, a nonconservative gas tracer is being purposely used to assess the ability of the stream to <u>desorb</u> the gas which can then be related to the capacity of the same stream reach to <u>absorb</u> oxygen. It may be assumed that the desorption of the tracer gas through the stream surface is a first order process of the form

$$\frac{dC_g}{dt} = -K_T C_g \tag{9}$$

where C_g is the gas concentration, t is time, K_T is the tracer gas desorption rate coefficient, and dC_g/dt is the rate of change of the gas concentration as a result of desorption. The amount of desorption is usually evaluated by measuring the loss of the gas tracer between two or more sections downstream from the injection. Equation 9 may be integrated and applied to a stream reach delineated by upstream and downstream measuring sections to give

$$\ln \frac{(C_g)_u}{(C_g)_d} = K_T(t_d - t_u) \text{ or } K_T = \frac{1}{(t_d - t_u)} \ln \frac{(C_g)_u}{(C_g)_d} \qquad (10)$$

where the subscripts u and d refer to upstream and downstream.

Slug-injection method

The SI method actually involves a short-term continuous injection of the tracer gas into the flow. This "quasi-slug" injection of gas is in contrast to an instantaneous slug injection and is necessary to accomplish sufficient absorption of gas into the water for measurement purposes.

As seen in figures 1 and 2, the downstream concentrations resulting from a slug injection of a gas tracer will be reduced by longitudinal dispersion, independent of the gas lost by desorption; they will be further reduced if there is flow accrual serving to further dilute the tracer cloud. To measure the actual gas desorption, it is necessary to inject a conservative tracer and the gas tracer concurrently so that both undergo identical dispersion and dilution. Therefore, the dye tracer must also be slug injected in an identical manner as the gas, that is, a short-term, continuous, "quasi-slug" injection. Thus the loss of the gas tracer relative to the conservative tracer is independent of dispersion and dilution effects. If the dye tracer is used as the conservative dispersion-dilution tracer, equation 10, with rearranging, can be expressed as

$$K_T = \frac{1}{t_d - t_u} \ln \frac{\left[\frac{C_g}{C_d}\right]_u}{\left[\frac{C_g}{C_d}\right]_d} \qquad (11)$$

in which both the gas and the dye tracer concentrations, C_d, are measured at a characteristic time of the upstream and downstream response curves. As shown in figure 4, the most commonly used characteristic time is that for the peak concentrations; hence this procedure is often called the Peak Method.

As has been discussed, rhodamine WT dye, which is about the most conservative dye tracer available, still experiences small losses. This may be resolved by adjusting the measured dye concentrations using the dye recovery ratios measured at each section such that for the Peak Method

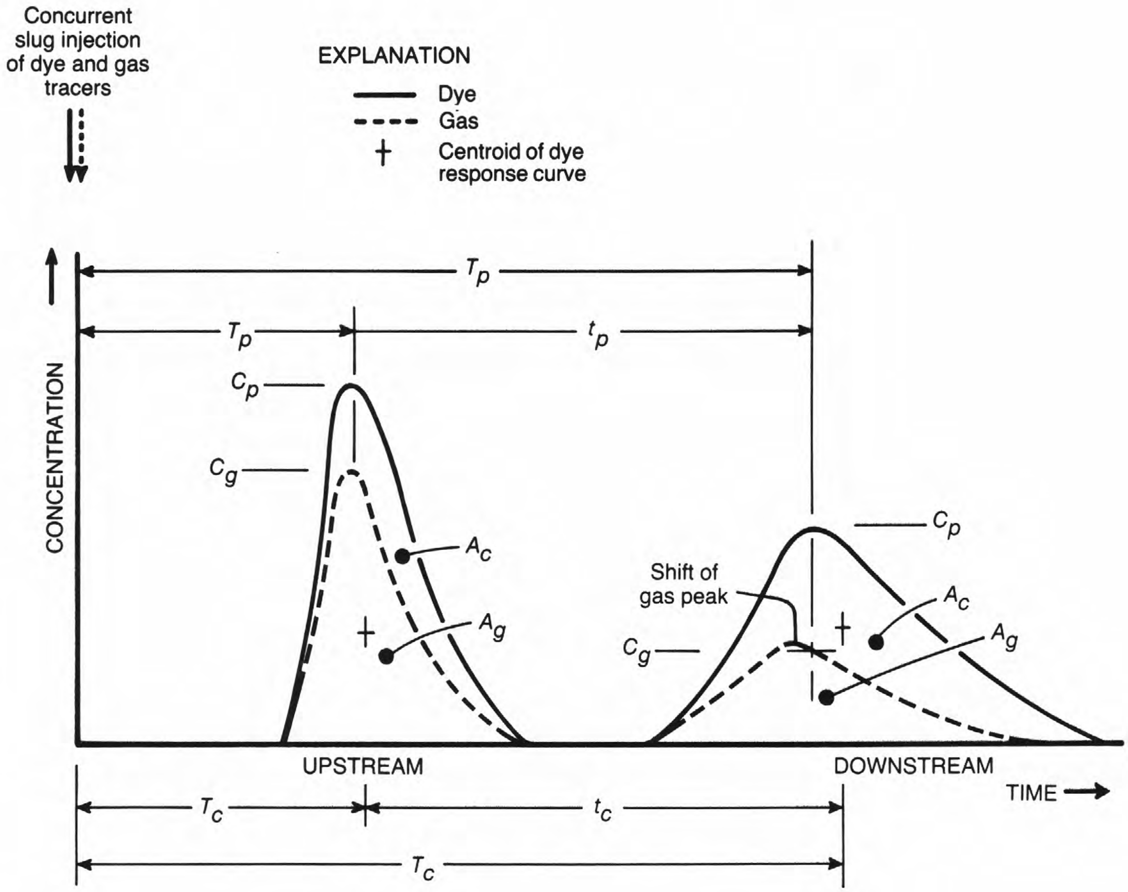

Figure 4.--Definition sketch of slug-injection type reaeration measurement.

$$K_T = \frac{1}{t_p} \ln \frac{\left[\frac{C_g}{C_p/R_r}\right]_u}{\left[\frac{C_g}{C_p/R_r}\right]_d} . \qquad (12)$$

Note that at both the upstream and downstream the measured dye concentration is made conservative by dividing by the respective recovery ratios.

If the dye correction factor, J, is used

$$K_T = \frac{1}{t_p} \ln \frac{\left[\frac{C_g}{C_p}\right]_u}{\left[\frac{C_g}{C_p}\right]_d} J \qquad (13)$$

where t_p is the traveltime from the upstream to the downstream peaks of the dye response curves, C_p are the observed peak dye concentrations and C_g are the gas concentrations observed at the same time as the dye peaks. It will be noted in figure 4 that the peak concentration of the downstream gas response curve has shifted slightly with respect to the dye response curve. This may occur where t_p is long and/or K_T is large, the gas tracer being desorbed with increasing time such as to "erode" the gas peak. Hence, the gas concentrations to be used are those existing at the time corresponding to the dye tracer peak and may not necessarily be the maximum gas concentrations. In most instances though, the gas peaks will occur at the same time as the dye peaks.

An alternative to using peak dye concentrations and the corresponding gas concentrations is to determine the reduction in mass of the gas tracer over a selected test reach, frequently referred to as the Area Method. Referring to figure 4, the gas desorption coefficient can be determined as

$$K_T = \frac{1}{t_c} \ln \frac{(A_g\ Q)_u}{(A_g\ Q)_d} \tag{14}$$

where t_c is the time of travel of the centroid of the dye response curve between the upstream and downstream measuring sections, and A_g and Q are the area of the gas response curve and stream discharge at the upstream and downstream sections, respectively. Dye tracer data are available since dye is injected to aid in sampling of the gas cloud. Dye recovery computations are not needed since the entire gas mass is being measured at the two sections rather than just selected concentrations as in the Peak Method. While the Area Method avoids the requirement to evaluate accurately dye tracer recoveries, it requires much more extensive gas sampling and hence is less often used. Note, that even though the total mass of the gas tracer is being used, the time-of-travel measurement is from centroid to centroid of the dye tracer response curves. The elapsed time to the centroid of each dye response curve is needed and best calculated by taking moments about the dye response curves with respect to t = 0. The first moment to obtain T_c for any one curve may be expressed as

$$T_c = \frac{\int_{t=0}^{t=\infty} C_d t\,dt}{\int_{t=0}^{t=\infty} C_d\,dt} \tag{15}$$

where C_d is the observed dye concentration at any time, t. The dye response curve is defined completely through its recession to the trailing edge, t_t. The computation may be performed by numerical integration. For a given test reach, t_c is equal to the difference between T_c for the upstream and downstream sections.

The areas of the gas response curves, A_g, may be evaluated either by planimetering or by numerical integration as was performed with the dye concentration data. Information on a computer program that will perform area and centroid computations for either dye or gas concentration response curves is available from the Office of Surface Water in Reston, Virginia.

For clarity, the response curves in figure 4 are as observed along a common streamline at upstream and downstream sampling sections. Preferably, the response curves for the dye are measured at three or more points (streamlines) laterally at each section and gas samples taken as necessary. The equations just presented deal with the entire flow; nevertheless, they could be just as easily applied along streamlines.

Constant-rate injection method--one-dimensional dispersion state

As seen in figures 2 and 3, if a tracer is injected at a constant rate for a sufficient length of time, a plateau concentration will be established laterally if far enough downstream for adequate mixing. If stream discharge, Q, is constant, the resulting plateau concentration when a conservative tracer is used is expressed by the dilution discharge equation (Kilpatrick and Cobb, 1985) as

$$Q = q \frac{C}{\overline{c}} \quad (1) \qquad (16)$$

where q is the rate of tracer injection and is assumed to be very small relative to Q;

C is the concentration of the tracer being injected; and

$\overline{c}$ is the resulting plateau concentration after dilution by Q.

If there is an increase in stream discharge, the plateau concentration is reduced to reflect the added dilution. Unlike the SI method, if tracer injection is continuous and at a constant rate, and mixing complete, longitudinal dispersion will not affect the magnitude of the plateau concentration; in theory, a single sample for measurement of the plateau concentration is sufficient.

If a nonconservative gas tracer is injected continuously and at a constant rate, then desorption of the gas will be reflected in an ever decreasing plateau concentration, $\overline{c}_g$, with distance downstream as depicted in figure 5. If the gas injection is long enough, longitudinal dispersion ceases to be a factor in determining the concentration levels; only dilution by flow accrual, if any, will reduce the plateau levels beyond that caused by the desorption of the gas. Thus, an approximate solution for the gas desorption coefficient is

$$K_T = \frac{1}{t_c} \ln \frac{(\overline{c}_g Q)_u}{(\overline{c}_g Q)_d} . \qquad (17)$$

This equation is approximate as it is based (Yotsukura and others, 1983) on the assumption the stream channel is straight and prismatic. The product, $\overline{c}_g Q$, may be thought of as the gas mass in transport at a section. In this

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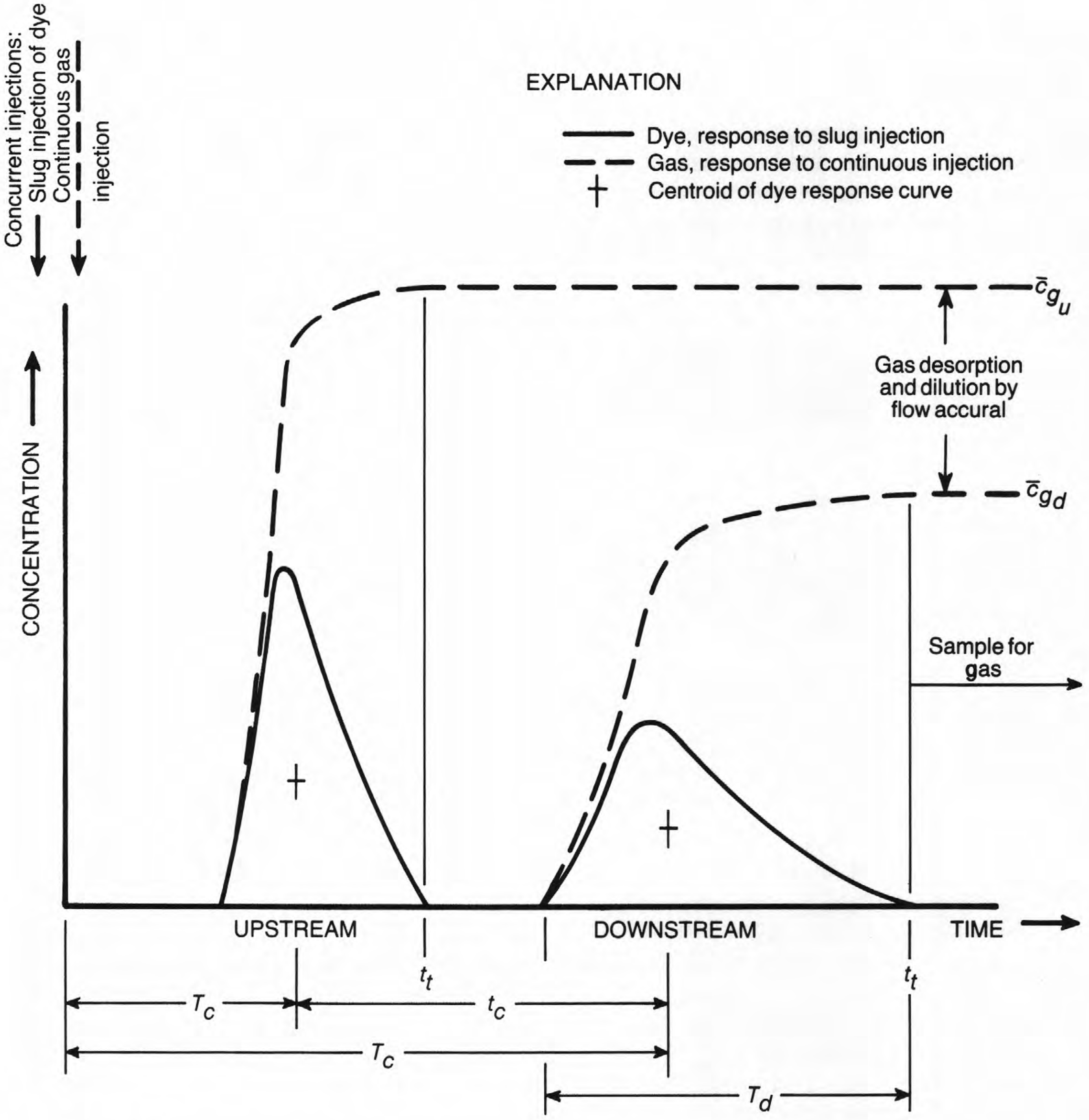
(1) For clarity, units are ignored here.



NOTE: T_d is minimum duration of continuous gas injection to just produce a plateau at the downstream sampling section at the point of observation of the dye response curve.

t_t is earliest time at which gas sampling should begin.

Figure 5.--Definition sketch of constant-rate-injection type reaeration measurement.

instance, $\overline{c}g_u$ and $\overline{c}g_d$ are the weighted average plateau concentration of the gas at the upstream and downstream measuring sections, respectively. In contrast to equation 14 in the SI technique using the Area Method, t_c is the time of travel of the centroid between upstream and downstream measuring sections of a <u>dye</u> tracer response cloud. These data are normally acquired by the instantaneous <u>slug</u> injection of the dye tracer into the streamflow at the same location and time as the continuous gas injection is initiated.

The centroid time for any one curve, T_c, may be calculated by taking moments of the dye response curve with respect to t = 0 as defined by equation 15.

A more exact solution for the desorption coefficient is obtained by the trial solution of the equation:

$$\frac{(\bar{c}_g Q)_u}{(\bar{c}_g Q)_d} = \frac{\left[\int_{t=0}^{t=\infty} f(C_d, t)\exp(-K_T t)dt\right]_u}{\left[\int_{t=0}^{t=\infty} f(C_d, t)\exp(-K_T t)dt\right]_d} \tag{18}$$

in which the left term is the ratio of the upstream gas mass in transport to that downstream. The bracketed expressions on the right are the integration of the normalized dye response curve, $f(C_d, t)$, and the first order decay function with time for both upstream and downstream measuring sections. Normalizing a given set of dye concentration-time data consists of dividing by the area of that response curve such that

$$f(C_d, t) = C_d(t)/\int C_d dt \tag{19}$$

The solution of equation 18 involves numerical integration calculations employing a number of trial K_T values estimated from the one determined by equation 17. When the ratio on the right hand side of equation 18 agrees with the left hand ratio of observed data, the trial K_T is considered as the correct desorption coefficient.

It is important to note that in the CRI method, dye losses are not a factor because normalized concentrations are used and that only a limited number of gas tracer samples need be collected on the plateaus at the measuring sections. Furthermore, the dye tracer injection, while being made exactly at the same location as the gas injection, need be only a simple instantaneous slug injection in contrast to the SI method, an apparent contradiction. In fact, an instantaneous slug injection is the most desirable. It simplifies the measurement of traveltimes and, as previously described in the section on the superposition principle, the duration in passage of the dye response curve provides exact information on how long a gas injection must be and its time of final departure, t_t, provides the exact time to sample the gas-concentration plateau.

It should be noted that thus far the approach has been taken to evaluate dye and gas concentrations, response curve areas, and properties at each measuring section in total. This may be a satisfactory approach if the tracers are sampled a sufficient distance downstream such that mixing is good and average or discharge weighted values can be used with confidence. Referring to figure 1, in some instances, especially on wide streams, it may be necessary to perform computations along given streamlines. Thus, if sampling points b, d, and f are established to represent one third of the total discharge in each section, say sections II and III in figure 1, then traveltimes and moments might best be computed for a given streamline and then averaged for any final computation. For example, even between sections III and IV in figure 1, the time of travel along streamline f may be significantly different than along streamline d because of the skewed nature of the tracer response curves.

Constant-rate-injection method--two-dimensional dispersion state

Most gas-tracer reaeration tests are performed in relatively short test reaches and small streams, the first because the nonconservative gas tracer must be desorbed to accomplish the measurement. From a practical standpoint, only a small amount of the gases such as propane and ethylene initially injected into the flow are actually absorbed by it. This, coupled with the desired desorption, limits the reach length which can be measured and still accurately measure the levels of gas concentration.

Furthermore, most field tests have been on small streams, as it was desirable to perform the measurement in a reach where the vertical and lateral mixing of the tracers were essentially complete and only longitudinal dispersion continued such as between sections III and IV in figure 1. With increased stream size, particularly width, adequate lateral mixing cannot be obtained without increasing the reach length, and this may result in gas concentrations too small to measure. In effect, for wide rivers, the distance required for achieving transverse uniformity may be longer than the study reach possible for gas-desorption measurements.

Nevertheless, there is a need for reaeration information on larger, wider streams. Yotsukura and others (1984) have expanded the application of the gas-tracer reaeration measurement technique by developing the theory and techniques of measuring gas desorption in the nonuniform plume region such as between sections I and II in figure 1. While this technique is new, and field performance demanding, it is presented in this manual to encourage its use and further development.

The CRI method applied to wide rivers uses an instantaneous slug injection of conservative dye tracer at the beginning of a continuous injection of gas tracer at some fixed source location in a cross section. As with the other methods, an upstream and a downstream measuring section comprise the test reach. At several transverse locations in the measurement cross sections, measurements are made for only dye concentration while the dye cloud is passing and then are switched to gas concentration, as was described previously when applying the CRI method to narrow streams. The primary change is that now measurements must be made between cross sections along streamlines (see fig. 1). For example, injection of the tracers might be at the 50 percent streamline, d (the source streamline), and sampling at the 33.3, 50, and 66.7 percent streamlines, at sections I and II; or preferably sections II and III as depicted in figure 1.

The logistics of performing a continuous injection in the center of a wide channel may dictate that the tracer injection take place closer to one streambank or the other; say streamline c or e in figure 1. Tracer sampling would then be performed downstream on the injection streamline and if desired at one or more paralleling streamlines. Obviously, using the CRI method in a wide stream, the desorption characteristics of the stream are being measured in only a portion of the flow.

In figure 5, the reduction in plateau gas concentrations from an upstream to a downstream measuring section could be attributed entirely to gas desorption and flow accrual if the measurement reach was far enough downstream of the source of injection for adequate mixing, for example, section III to IV in figure 1. At short distances, it can be readily visualized from figure 1 that the reduction of both gas concentrations and dye tracer concentrations would be further reduced by lateral mixing and tracer transport.

An equation similar to 17 and 18 which applies the CRI method to the two-dimensional nonuniform plume situation and to measurement along a given streamline, z, is

$$\left[\frac{(\overline{c}_g Q)_u \phi_d}{(\overline{c}_g Q)_d \phi_u}\right]_z = \left[\frac{\left[\int_{t=0}^{t=\infty} f(C_d, t)\exp(-K_T t)dt\right]_u}{\left[\int_{t=0}^{t=\infty} f(C_d, t)\exp(-K_T t)dt\right]_d}\right]_z \qquad (20)$$

All terms apply along the streamline, z, chosen for the measurement. Hence, it becomes vital that preliminary discharge measurements be made at both upstream and downstream measuring sections. From plots of cumulative discharge versus lateral distance, common streamlines are chosen for the measurements. Plateau gas concentrations, $\overline{c}_{g_u}$ and $\overline{c}_{g_d}$, are those applicable to the upstream and downstream sections along the same streamline.

In equation 20, ϕ_z is a mass distribution factor to account for the change in the nonuniform, cross-sectional distribution of tracer masses passing each measuring section. For a given location on a streamline, it is defined as

$$\phi_z = \frac{A_{c_z}}{\sum A_{c_z}\frac{\Delta Q_z}{Q}} \qquad (21)$$

The computation is made for a given streamline for each dye tracer response curve for both upstream and downstream sections. The area of each response curve, A_{c_z}, should be for the slug response curve carried to background concentration; ΔQ_z is the portion of the total discharge applicable to the chosen streamline. The more uniform in area the tracer response curves are laterally, the more nearly ϕ approaches 1.00.

The data requirements to compute ϕ_z by equation 21 for a wide stream may be extensive. On a wide stream, the complete dye response curves at 7 to 10 points laterally at both upstream and downstream sections would be required. An alternative to collecting such extensive dye data is to determine ϕ based on the steady-state gas plateau concentrations, $\bar{c}g_z$, measured laterally at each streamline; replacing $\hat{c}_z$ in equation 21 by the plateau gas concentrations gives

$$\phi_z = \frac{\bar{c}g_z}{\sum \bar{c}g_z \frac{\Delta Q_z}{Q}} . \tag{22}$$

If possible, the gas injection should be sufficient to yield measurable concentrations near the streambanks where they might be expected to be the lowest. Thus, maximum gas injection rates should be employed and measuring sections chosen carefully to minimize zero gas concentrations along the streambanks.

A second alternative for evaluating ϕ is to perform a continuous dye injection sufficient to establish steady-state plateau concentrations and use these data in place of $\bar{c}g_z$ data in equation 22. This is the least preferred alternative as it is difficult to sustain an accurate constant rate dye injection because as much day or more as may be required. This approach would, however, be the preferred method on very wide streams where zero or very low gas tracer concentrations might be expected along one or both banks.

Regardless, complete dye slug response curves must still be measured along the streamline(s) chosen for the measurement. Of the choices and for most cases, the following is recommended: (1) a slug injection of dye tracer at a point on a source streamline with complete sampling of the response curves on the same streamline and two adjacent streamlines at the two downstream sections; (2) concurrent or within a short time, continuous gas injection at the same point on the same source streamline followed by gas sampling on all streamlines once steady-state gas concentrations have been reached.

As with equation 18, equation 20 is solved by trial after estimating K_T from equation 17.

General case

It should be borne in mind that equation 20 is the general equation applicable to the two-dimensional situation, whether on a narrow or wide stream. Thus, if circumstances prohibit selection of a test reach on a narrow stream in which mixing is complete throughout the test reach, equation 20 may be used as long as the necessary data are acquired to evaluate ϕ. This may in some instances permit a lengthening of the test reach (by moving the upstream section closer to the injection point) such that $K_T t_c$ is equal to or greater than 1.00. The reason for this will be discussed later. If in fact there is any doubt about the adequacy of mixing, data should be collected to compute ϕ such that equation 20 may be used.

PLANNING THE REAERATION STUDY

The most important consideration in planning a reaeration test is to select a test period when flow conditions are close to those ultimately to be modeled. This will probably be a period of light wind and steady discharge. If regionalization is an objective, a certain flow duration will probably be desirable; maybe two or more flow durations.

In contrast, a cooperator may wish to evaluate the change in reaeration capacity with stream stage on a select reach of a stream. Hence, several reaeration measurements at different flows may be necessary.

As can be deduced from the previous sections, the successful performance of tracer type reaeration measurements requires considerable planning and careful execution if good results are to be obtained. Certain key activities must be emphasized:

1. Complete and accurate current-meter measurements of discharge must be made at all sampling sections and tracer sampling points located and identified with respect to lateral cumulative discharge. The principle of measuring along common streamlines is suggested for general use and is mandatory for reaeration measurements in relatively wide rivers.

2. Complete and accurate dye-tracer time concentration response curves must be measured at three or more lateral points in each measuring section defined to (or extrapolated to) essentially background concentration levels; preferably, these will be on streamlines common to upstream and downstream sections which comprise a test reach.

3. Stream test reaches and the corresponding measuring sections should be chosen such that tracer mixing and residence times between sections are adequate. The exception is for the case of two-dimensional nonuniform mixing where sufficient data must be collected to account for the nonuniformity.

Reach Selection

The selection of the test reach may be based on the need to evaluate permissible waste loading below a discharge point. More commonly, it is part of an overall regional study to develop predictive equations for estimating reaeration coefficients for general use by State or Federal licensing and for waste-management purposes. If so, it is important that the test reach be representative of the streams of concern. If possible, the reach should be uniform in longitudinal slope and hydraulic properties such as roughness and cross section. A reach having little or no inflow is desirable. Excessive islands and wide shallow sections should be avoided unless representative of the streams to be tested; the narrower, deeper the stream reach, the better the lateral mixing.

Accessibility to the test reach for the purposes of dye and gas injections, current-meter measurements, and sampling must be borne in mind. Accessibility to the injection site is probably the most important as pressurized gas cylinders must be placed close to the bank and diffuser lines and plates placed in the stream.

Mixing Length Requirements

Except for the case of wide rivers where it is accepted that it will not be feasible to obtain complete lateral mixing in the test reach, the selection of the injection site relative to the downstream test reach must consider the mixing length distance to the upstream measuring section such that an adequately mixed condition exists.

Repeating from background reference 3, the optimum distance, L_o, in feet, required for adequate lateral mixing of a tracer injected in the middle of the streamflow may be estimated by the equation

$$L_o = 0.1 \frac{vB^2}{E_z} , \qquad (23)$$

where E_z is the lateral mixing coefficient in feet squared per second,
v is the mean stream velocity, in feet per second, and
B is the average stream width, in feet.

Table 1 provides values of E_z for selected depths and slopes to aid in estimating the optimum mixing length from equation 23. The distance, L_o, should be considered the preferred <u>minimum</u> distance between the point of tracer injection and the first measuring section; greater distances will be to advantage if they fit into other criteria. Furthermore, from the stand-point of gas injection, it is important that the distance to the first section where gas is to be sampled preferably be at least 1 hour traveltime from the point of gas injection to ensure that all the gas is truly in solution (R. E. Rathbun, written commun., 1987).

Table 1.--Values of the lateral mixing coefficient, E_z, for selected average flow depths and slopes

(Note: $E_z = 1.13d^{3/2}s^{1/2}$)

Depth, d (ft)	Slope, s (ft/ft)					
	0.001	0.002	0.004	0.006	0.008	0.010
1.0	0.04	0.05	0.07	0.09	0.10	0.11
2.0	.10	.14	.20	.25	.29	.32
3.0	.19	.26	.37	.46	.52	.59
4.0	.29	.40	.57	.70	.81	.90
5.0	.40	.56	.80	.98	1.13	1.26
6.0	.52	.74	1.05	1.29	1.48	1.66

Note: s is the water-surface slope, and
d is the mean depth of the stream.

Adequacy of Residence Time

As can be seen by equations 10, 13, 14, 17, 18, and 20, a logarithmic relation exists between the tracer concentrations and the desorption coefficient. Thus, the computation of K_T may be subject to increasing error as the ratio of upstream and downstream gas concentrations drops significantly below 2.72, or conversely the product of K_T and t_c below 1.0. Thus, there must be sufficient gas residence time between sampling sections such that the ensuing computation will be accurate. This is probably the most important criteria in planning and selecting the test reach. Thus, K_T and t_c should be estimated for a proposed test reach and the distance between upstream and downstream sections increased to make $K_T t_c$ equal to or greater than 1.0, if possible. For planning purposes the time of travel between the peaks may be used.

The estimation of traveltimes is straight forward and involves examination of any current-meter and time-of-travel measurements made in the proposed reach, as well as field reconnaissance of the reach if possible. It should always be borne in mind that average velocities determined from current-meter measurements will normally be faster than the true reach average; steep mountain streams may be an exception.

As part of a regionalization study, Boning (1973) reported two equations to estimate the velocity of a dye cloud's peak concentration, v_p. For pool-and-riffle type reaches with slopes, s, ranging from 0.00012 to 0.0057 feet per foot, the equation is:

$$v_p = 0.38\ Q^{0.40}\ s^{0.20} \tag{24}$$

where v_p is in feet per second and Q is discharge in cubic feet per second. For channel-control type reaches with slopes ranging from 0.00016 to 0.0023 feet per foot, the equation is:

$$v_p = 2.69\ Q^{0.26}\ s^{0.28} \tag{25}$$

The difference in estimated elapsed times to the peaks or centroids is the traveltime between the upstream and downstream response curves or the estimated residence time for the gas in transit in the test reach.

An estimate of K_T may be based on an estimate of K_2, the reaeration coefficient. Numerous empirical equations exist for this purpose. The Tsivoglou-Neal (1976) equation

$$K_2 = 0.054\ \Delta H/t_c \tag{26}$$

seems best for stream reaches having a slope greater than 0.003 feet/foot. In this equation, ΔH is the change in elevation in the reach in feet and t_c is in hours. The equation by Owens, Edwards, and Gibbs (1964)

$$K_2 = 0.906 v^{0.67}/d^{1.85} \tag{27}$$

appears to give good results when the reach slope is less than 0.003 feet/foot. In this case, v is the mean velocity in feet per second and d the mean depth in feet in the reach being studied.

For propane, $K_p = 0.719K_2$ and equations 26 and 27 may be written as

$$K_p = 0.039\,\Delta H/t_c \tag{28}$$

$$\text{and } K_p = 0.651v^{0.67}/d^{1.85} \tag{29}$$

for K_p at 20 °C. In the above equations, K_2 and K_p are in log to the base e units of per hour. If water temperatures are significantly different than 20 °C, it may be desirable to adjust K_p using the equation

$$K_{p_T} = K_{p_{20}}\,(1.0241)^{T-20} \tag{30}$$

where T is the actual stream temperature (Rathbun, 1979).

Equations 24, 25, 26, and 28 require estimation of reach slope or elevation drop in the proposed test reach. These may be estimated from topographic maps and in some instances determined from actual instrument surveys. A plot of elevation versus stream centerline distance from a topographic map is helpful in estimating slopes and changes in elevation.

Caution must be used in estimating the mean depth to use in equations 27 and 29. Too much weight should not be given to current-meter measurements as their depths will not normally be representative of pool sections which usually make up a greater portion of many stream reaches. If estimates or measurements of B and v are available, the mean depth may be estimated from the equation

$$d = \frac{Q}{Bv} \tag{31}$$

which is the application of the continuity equation for a given stream discharge, Q.

Having estimates of t_p and K_p, calculate their product; the units used should yield a dimensionless number. If the product is less than 1.00, it is desirable to move the measuring sections further apart. In this regard, it may be necessary if only certain locations are accessible to move the first measuring section upstream, closer to the injection point to increase the length of the test reach and use the CRI method for the reaeration test. This means that data collection for all methods should be sufficient to apply equation 20 even if ϕ is proven to be 1.00.

Discharge Measurements

Current-meter type discharge measurements should be made at the injection site and at the two downstream measuring sections which comprise the test reach. If there are changes in stage during the reaeration measurement or since the current-meter measurements were made at the two downstream sections, additional discharge measurements should be made. Accurate discharge measurements are very important and should represent the flow during the reaeration test as nearly as possible. Discharge should be referenced to stage and reference points or staff gages should be used to carefully observe changes in flow conditions. When using the CRI method, the current-meter measurements at the two downstream sections often may be made just prior to sampling; the sampling locations in the section are then flagged on the taglines, based on selective cumulative discharge points. If possible, these points should be on common streamlines between the two measuring sections which comprise the test reach. If boat traffic exists, lightweight string may be left suspended safely across the channel with suitable bright tape marking the sampling locations.

For tests on wide rivers where planning is more acute, current-meter discharge measurements may best be made in advance of the actual reaeration measurement so that injection source and sampling streamlines and sections may be resolved and suitably identified. In such cases, bouys may be located at the injection and sampling points.

Gas Injection

Most hydrocarbon gases such as propane and ethylene are not readily absorbed into water. The adaptation of these gases as nonconservative tracers required devising means of forcing a sufficient quantity of gas into the flowing stream to tag it sufficiently for measurement of the resulting desorption as it is dispersed and transported through a test reach.

Diffusers

The low solubility of the hydrocarbon gases requires that they be injected into the flow via one or more submerged diffusers. The Marox brand flat-plate ceramic diffuser (see fig. 6) having a 2-micron diameter pore size has proven successful. Crawford (1985) used a series of Zimpro passive diffusers having a 1.5- to 2.0-micron pore size mounted in a series of racks and used as shown in figure 7. The number of diffusers used in a test depends primarily on the stream discharge being tagged. Several diffusers may be fed from one gas tank using manifolds such as shown in figure 8.

The individual Marox and Zimpro diffuser racks shown in figures 6 and 7 have surface areas of about 75 and 125 in^2. Table 2 provides a rule of thumb for the number of diffusers to use for ranges of stream discharge. If the diffusers are placed in water significantly deeper than 1 foot, fewer diffusers may be required and conversely, more may be needed if the gas injection is in a shallower depth of water.

Regardless of the type or brand of gas diffusers used, they must be placed to duplicate the dye injection as nearly as possible. This becomes of particular importance in the CRI method applied in a wide stream where any differences in tracer source configurations between gas and dye could be reflected in the concentration response curves resulting at relatively short distances downstream. In most instances, the dye will be slug injected as a point source in the center of the flow. Therefore, if several diffusers are used such as shown in figure 7, they should be aligned longitudinally in the channel, parallel to the flow.

Figure 6.--Ceramic diffuser plates stored and transported in custom-made box.

Table 2.--Criteria for selecting the number of diffusers for injecting gas into different stream discharges; diffuser plates are assumed to be 2 microns in pore size, 75 square inches in surface area, and placed in 1 foot of flowing water

Range in stream discharge in ft^3/s	Number of diffusers
0 - 10	1
11 - 50	2
51 - 100	3
101 - 400	4-6

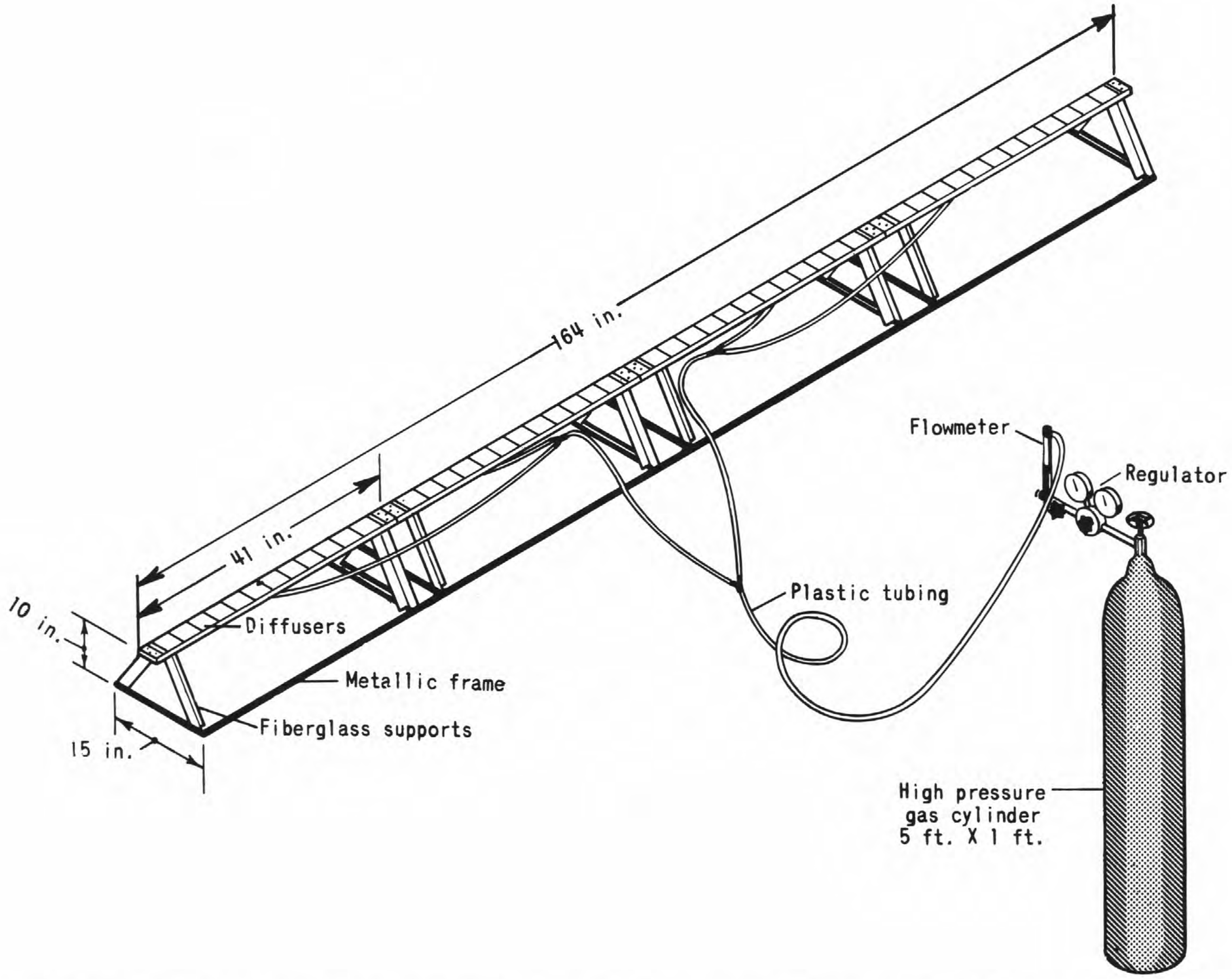


Figure 7.--Gas-injection apparatus using flat plate porous ceramic diffusers epoxied into channels to form four racks (from Crawford, 1985).

The diffusers should be placed in as deep of water as available, compatible with the 50-percent discharge point or other point selected for injection. The cumulative discharge graph based on a current-meter measurement at the injection site should be used as a guide in locating the gas and dye injection point. The actual location relative to percent cumulative discharge from the left bank should be noted.

Tests by various investigators indicate that only 5 to 20 percent of the gas injected is actually absorbed into the water, the balance escaping at or a short distance downstream of injection. As a rule, the most upstream sampling section should be at least 1 hour time-of-travel downstream of the gas injection point to ensure the gas is truely in solution. The efficiency of the gas injection is largely a function of the depth of flow over the

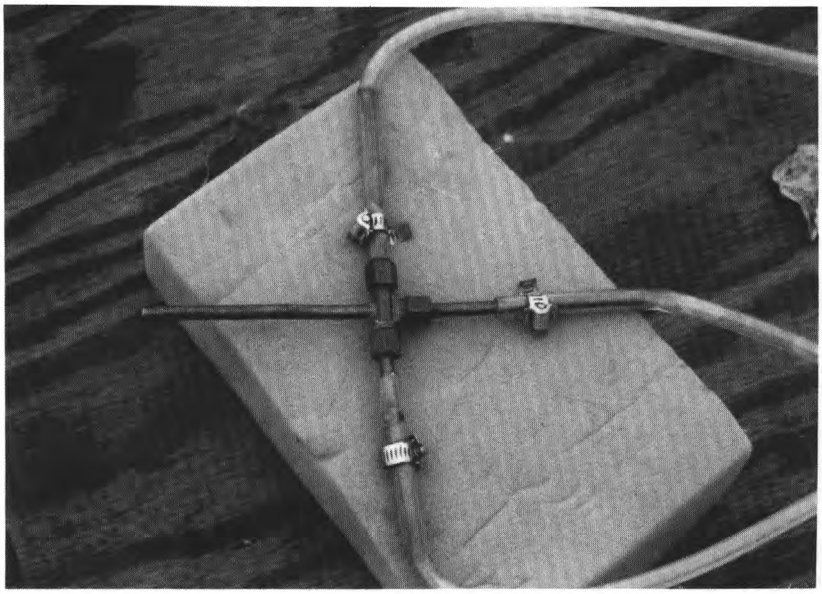


Figure 8.--Three-way manifold used to supply gas to diffusers from one gas cylinder.

diffusers, the bubble size produced by the diffusers, and the water temperature which affects the gas solubility and hence the driving force for absorption. Knowledge of the actual efficiency of the gas-injection system is not necessary as long as a stable, measurable gas concentration is established in the measurement test reach downstream.

Proper care and cleaning of the diffusers to avoid algae growth has been found necessary. Stedfast (written commun., 1987) has obtained good results by exposing the diffusers to river water the minimum length of time and upon removal immediately flushing them with clean water and an algicide. This approach would seem to have considerable merit as it minimizes the opportunity for algae to build up in the diffusers. Parker (written commun., 1985) found that the gas injection rate might not be stable for a short initial period after prolonged nonuse of the diffusers and recommended a preliminary period of gas injection and observation to make certain injection rates are stablized.

Tanks

Propane, the more widely used hydrocarbon gas tracer, can be of the ordinary commercial grade obtainable from camping trailer or regular commercial suppliers. There are restrictions on the size of pressurized gas tanks that may be transported on the highways, varying from State to State. Tank sizes range from the small cooking grill type 20-lb tanks (see fig. 9) up to 100-lb commerical cylinders. A 100-lb tank inside a protective circular steel housing is shown in figure 10; vandalism may be a problem where gas injection must continue for a day or more. Freezing of the regulator units seems to be less of a problem with the larger tanks and if rates are kept below 40 ft^3/h. Large tanks also are preferred when performing the CRI type of test which may

Figure 9.--Single gas diffuser plate being supplied from a 20-pound propane tank.

Figure 10.--100-pound propane gas cylinder inside protective circular steel housing; dual stage regulator and flowmeter may be seen through access door on top of tank.

require as long as 48 hours or more of continuous injection. Table 3 lists the most common pressurized tank sizes, and purchase and filling costs for propane as of 1986. The 100-lb size tank may also be rented.

Table 3.--Typical costs for purchasing and filling propane gas tanks (1986)

Tank size in pounds	Purchase cost in dollars	Cost to fill with commercial grade propane in dollars
20	30	7.50
30	50	11.50
40	65	13.00
100	100	37.00

Rates

To ensure and measure a constant rate of gas injection, a flow regulator and flowmeter (see figs. 7 and 10) must be used with each tank. One- or two-stage regulators and flowmeters such as produced by Airco and Linde have proven reliable. When propane is being used, a CO_2 (carbon dioxide) type flowmeter (rotameter) should be used, as the two gases have essentially the same specific gravity allowing the propane gas rate to be read directly.

As indicated earlier, hydrocarbon gases are not readily absorbed into water. In addition to the use of diffusers, it is necessary to continuously inject the hydrocarbon gas tracer for 1/2 to 2 hours when using the SI method and up to 48 hours when using the CRI method. In the first, the short-duration injection may be considered a "quasi-slug" injection. In the SI method, no attempt is made to produce plateau concentrations downstream, although a brief concentration plateau may be observed at the first measuring section downstream, but seldom at the second section.

Conversely, fundamental to the CRI method is a long-term injection of gas such that plateau-concentration levels will result at both sections; see figure 5.

The stability of the continuous gas injection is vital to the performance of a CRI-type reaeration measurement. As a check on the flow rate, and more important its constancy, a small portable platform scale may be placed beneath the gas cylinder and weight change with time noted during the progress of the test. These are available from most laboratory supply houses for approxmately $50 and will handle up to 250 lbs accurately. Such a backup procedure is highly recommended as it verifies the constancy of the gas-injection rate, in some instances a problem when tank and regulator freezeup occur. This procedure is desirable because propane is present in the cylinder as a liquified gas. The tank pressure gage of a two-stage regulating valve will indicate only the vapor pressure of the propane at the prevailing temperature. This pressure will remain constant as long as any propane remains in the cylinder, and thus, is no indication of the amount of propane remaining. Problems most frequently occur if the temperature is near freezing and/or the tank is 20 percent or less full.

Knowing the weight of gas remaining in a tank is also helpful in determining if refilling is necessary for another test. It is highly advisable to precheck and test gas injection and diffusers in advance of actual field tests. It should be remembered that propane is highly explosive and its use in confined spaces or near flame is to be avoided. Concentrations of propane as it escapes from the water surface during a field test are normally insufficient to explode or ignite but excessive injection rates should be avoided.

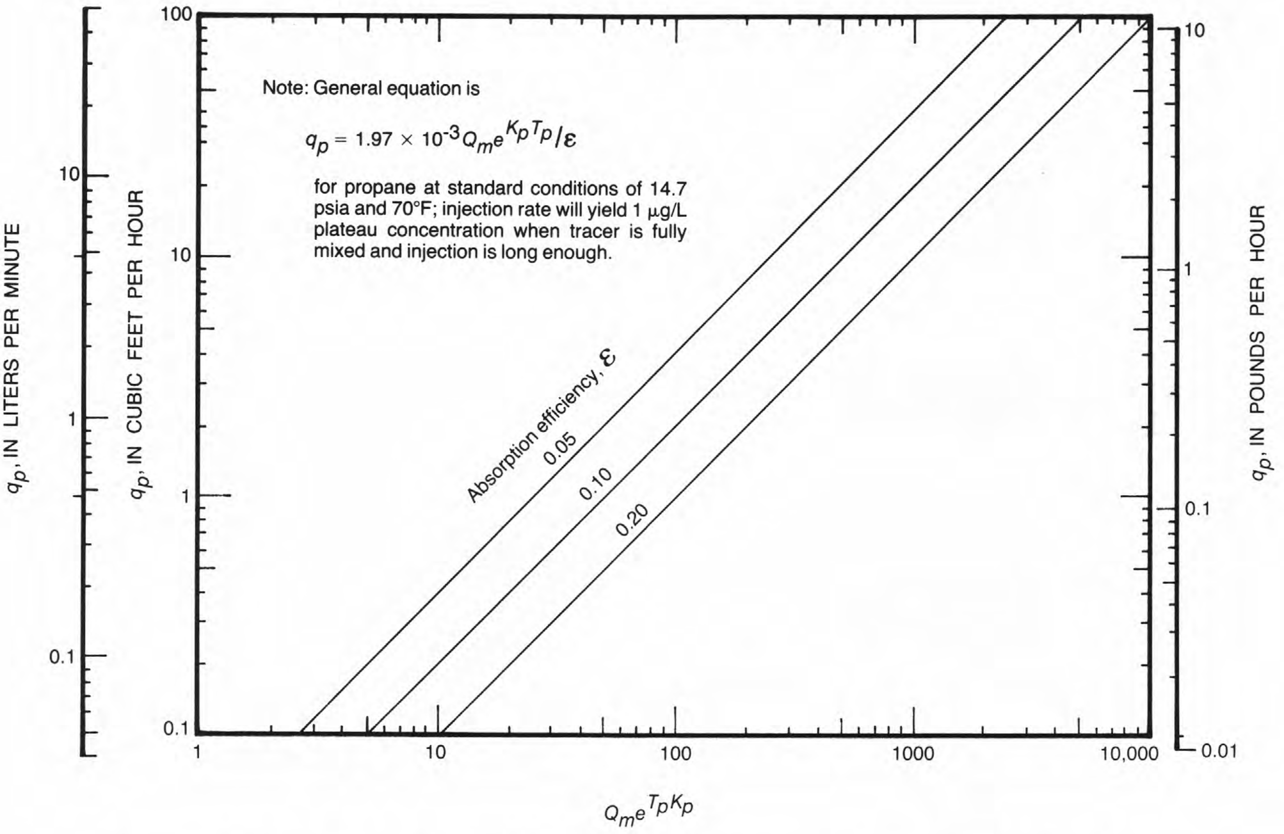
For planning purposes, it is necessary to estimate the gas-injection rate needed for a given test and how long it must be sustained to develop a steady-state gas concentration plateau at the most downstream measuring section. If a gas plateau is established at the most downstream measuring section, it will be established at all locations upstream, as long as constant-rate gas injection is continuing. It was shown by Rathbun (written commun., 1987) that the propane gas injection rate necessary to produce a 1 µg/L plateau concentration could be related to the diffuser efficiency, stream discharge, and the first order desorption of the propane by a general equation of the form:

$$q_p = 1.97 \times 10^{-3} \; Q_m e^{T_p K_p} / \varepsilon \qquad (32)$$

where q_p is the constant-rate gas injection in ft^3/h at standard conditions of 70 °F and 14.7 psia;
Q_m is the maximum stream discharge, usually at the most downstream section in ft^3/s;
T_p is the elapsed time to the peak concentration at the most downstream section, in hours;
K_p is the desorption coefficient for propane in $hours^{-1}$ at 20 °C;
e is the constant, 2.72; and
ε is the absorption efficiency expressed as a decimal.

Figure 11 is a graph of this equation for three different absorption efficiencies for standard conditions. Note that the overall efficiency of the injection can be very significant in determining the injection rate or conversely the resulting gas plateau concentrations downstream.

Figure 11 is for a resulting downstream concentration of 1 µg/L; thus, in use injection rates should be increased accordingly. It is advisable to plan for concentrations of 2 µg/L or larger considering the uncertainties in the various estimates. Larger concentrations should be sought when tests on wide rivers are being performed and gas concentrations may be zero along the streambanks. Furthermore, the injection rate should be based on how efficient the injection system may be expected to be. Referring to figure 11, if the efficiency is expected to be high, the lower curve is used, as the lower rate will ensure adequate gas concentrations in the water. If a low efficiency injection is likely, the higher curve and hence a higher rate should be employed to ensure adequate gas concentrations in the water.



Note: General equation is

$$q_p = 1.97 \times 10^{-3} Q_m e^{K_p T_p} / \varepsilon$$

for propane at standard conditions of 14.7 psia and 70°F; injection rate will yield 1 µg/L plateau concentration when tracer is fully mixed and injection is long enough.

Figure 11.--Graph to aid in selecting propane gas injection rates.

The gas-injection rate, q_p, has been shown in three different units, as various commercial flowmeters use these units. The scale on the right is in pounds per hour as a convenience in measuring and confirming the constancy of the flow rate from pressurized gas tanks by timing the weight change during the test. This rate scale in conjunction with knowledge of how long to inject is also an aid in determining what size of gas tank is required.

Figure 11 is intended primarily for use in selecting the rate of gas injection and size of tank needed for performing the CRI type of reaeration measurement. It may also be used to estimate a rate for the quasi-slug injection used in the SI method. Since no concentration plateau will be attained at the most downstream section with short injection durations, it is suggested that any rate chosen from figure 11 be increased about five-fold for the SI method, perhaps more if an unusually long reach is involved. This may also require increasing the number of diffuser plates to avoid excessive gas loss at the injection point. Observation that excessive gas is escaping the water surface at the injection site will indicate reduced efficiency; therefore, for the SI method the duration may have to be increased without disturbing the rate that was set. The last is suggested because manipulating the gas injection rate at the start of a test may result in the observation of erratic gas concentrations at the downstream sections. Once chosen and set, the gas rate should be left unaltered. Constancy is more important than an exact rate.

The rate of propane injection calculated from equation 32 or obtained from figure 11 must be adjusted to an air rate, q_a, using the equation

$$q_a = q_p \sqrt{\frac{14.7}{14.7 + p_g}} \sqrt{\frac{460 + T_g}{530}} \sqrt{\frac{44}{29}} \tag{33}$$

where p_g and T_g are the pressure in psig and temperature in degree Fahrenheit, respectively, at which the propane is metered. The last term is the ratio of the molecular weights of propane and air which can be dropped if a carbon dioxide rotameter is used as the molecular weight of the latter is 44. The pressure p_g is the delivery pressure on the propane regulating valve and normally varies from 50 to 60 psig for the Marox diffusers. The metering temperature, T_g is usually close to 32 °F. Equation 33 gives the air rate which is used with the rotameter calibration (assuming it is calibrated for air) to determine the rotameter setting to give the desired propane injection rate. The same equation also applies if the rotameter is calibrated in liters per minute.

For typical operating pressures and temperatures (p_g = 55 psig and T_g = 32 °F), equation 33 simplifies to

$$q_a = 0.44\ q_p \tag{34}$$

If equation 32 and 34 are combined and an absorption efficiency of 8.7 percent is assumed, equation 33 simplifies to

$$q_a \approx 10^{-2}\ Q_m e^{K_p T_p} \tag{35}$$

Note that this is the rate to yield a gas plateau of 1 μg/L; the rate must be increased proportionally to obtain larger plateau concentrations. Equation 35 is for p_g = 55 psig, T_g = 32 °F, and ε = 0.087 and should not be used if conditions are considerably different, especially metering pressure and diffuser efficiency. It is assumed that a carbon dioxide rotameter is being used when applying both equations 34 and 35.

Duration

As mentioned previously, a continuous, constant-rate gas injection of from 1/2 to 2 hours is usually necessary in the SI method. The longer times should be used where diffuser efficiency is expected to be low; the test reach or estimated traveltime is long, or the water discharge is large.

A more exact method is available for determining the duration of gas injection needed for the CRI method. Referring to the section under Theory, it is shown that the duration of passage, T_D, of the entire dye response curve at a given section due to a slug injection of dye upstream is also the minimum duration of constant-rate gas injection required to just establish a gas concentration plateau at the same section (see figs. 2 and 3). Kilpatrick (written commun., 1987) analyzed a large amount of the time of travel and reaeration type data collected nationwide and showed (fig. 12) that the duration of passage of slug-produced response curves could be related to the traveltime of their peaks. Three curves are shown, two for when the response curve is terminated at 10 and 2 percent of its peak and one for when the trailing edge of the curve has fully returned to background. The last corresponds to a duration of injection which will ensure that a steady-state gas plateau has been reached. Some additional time should be added to allow for sampling. Knowledge of the approximate duration of gas injection in conjunction with the rate in pounds per hour from figure 11 will indicate the minimum size of gas tank needed. The use of the last 20 percent of tank volumes should be avoided.

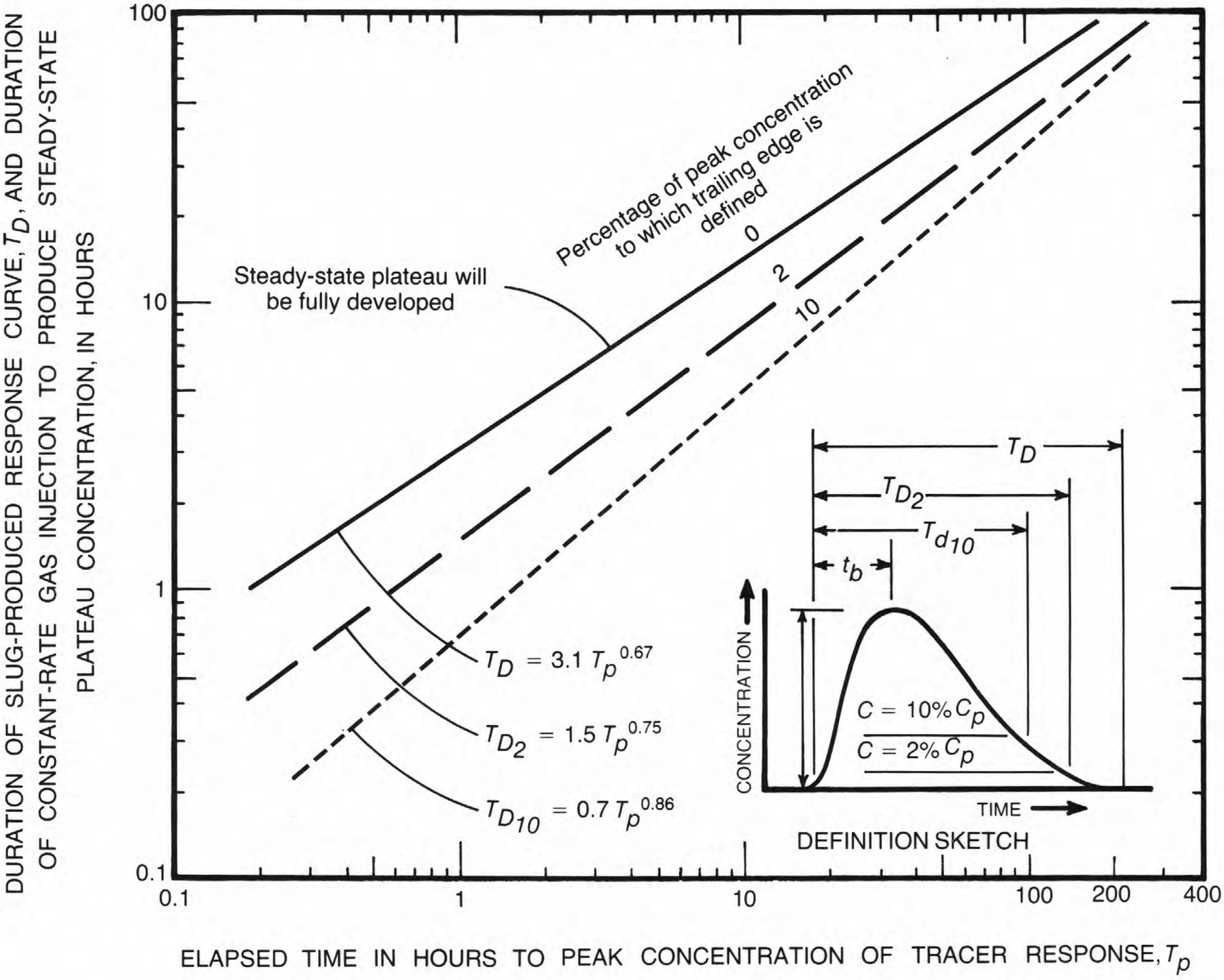


Figure 12.--Graph to estimate duration of slug-produced response curve as defined to different trailing edge concentrations and to estimate duration of constant-rate gas injection required to develop steady-state plateau concentration for different peak traveltimes.

Examination of the upper curve of figure 12 reveals that when the elapsed time to the peak, T_p, is 3 hours, it could take as long as 6.5 hours for the response curve to pass; when T_p is 10 hours, T_D could be as long as 14 hours and at T_p equal 31 hours, T_D is also 31 hours. The duration becomes less than T_p for larger values of T_p. If the estimated T_p exceeds 31 hours, the gas injection may be made equal to T_p.

The curves of figure 12 are approximate and should be used for planning purposes only. In practice, when performing the CRI method, a slug of dye is injected simultaneous with the start of continuous gas injection or shortly afterwards when the gas rate is observed to be constant. Observation of the slug produced dye concentration response curves at the two downstream measuring sections is not only data needed for the computation of K_T, but should be used to guide the gas sampling and actual length of injection.

Dye Injection

The dye tracer is referred to as the dispersion-dilution tracer as its simultaneous injection with the gas tracer provides an independent measure of the reduction in the gas-tracer concentrations caused by flow accrual and dispersion over and above the reduction due to gas desorption which it is desired to measure.

Slug-Injection Method

In the SI method of reaeration measurement, the short-term continuous gas-tracer injection must be exactly matched in location and time with a constant rate of dye injection. The methodology for continuous injection of the dye tracer is identical to that described in background reference 3 and will be treated only briefly here.

Injection equipment

The most satisfactory dye-injection device is a battery driven positive displacement or peristaltic pump. The pump shown in figure 13 is a small fluid-metering pump operating on a 12-volt dc battery withdrawing a dye solution from a graduated cylinder. This pump is a valveless, positive-displacement pump in which the flow rate can be varied from 0 to 48 milliliters per minute. Different models producing accuracies on the order of 1 percent are available in a range of capacities. The valveless feature is desirable from the standpoint of cleanliness and its capability to handle dirt and foreign material in the dye solution. While the rate settings have been found to be reproducible with a fair degree of accuracy, the actual injection rate should be independently measured such as is being done volumetrically in figures 13 and 14. As with the gas injection, rate constancy is more important than setting some exact rate.

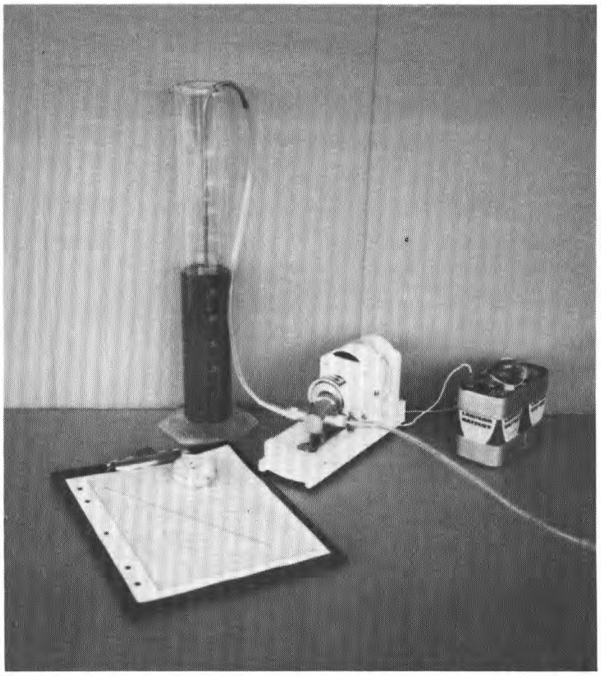


Figure 13.--Pump and graduated cylinder used for constant-rate dye injection.

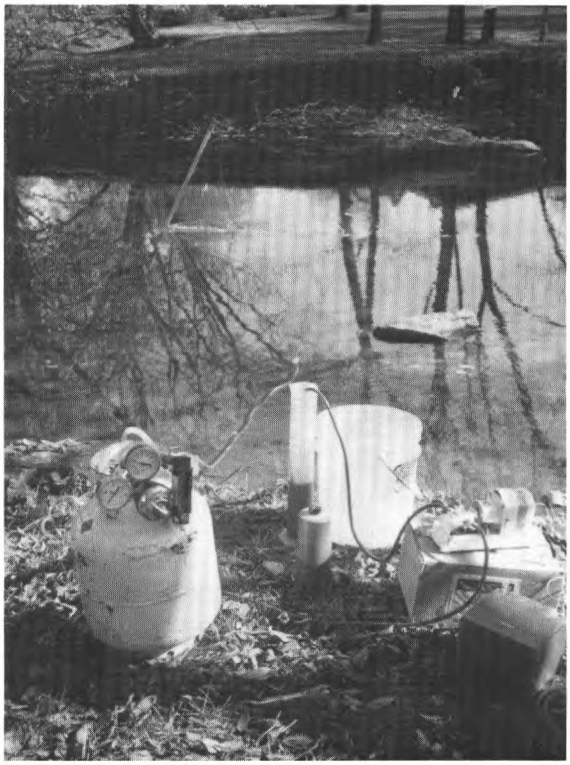


Figure 14.--Reaeration test using 20-pound propane tank and dye injection. Dye solution is being injected from graduated cylinder using battery-driven injection pump; the cylinder is refilled as needed with the same dye solution with injection rate being determined by timing change in volume in graduated cylinder.

Injection rates

The dye dilution discharge equation (continuity equation)

$$Q = 5.89 \times 10^{-7} q \frac{C}{\bar{c}} \qquad (36)$$

was used to develop the family of curves shown in figure 15 for selecting dye-injection rates and concentrations to yield approximately a 10 microgram per liter plateau concentration at the most upstream section for a range of stream discharges. In equation 36 and figure 15

Q is the discharge of the stream, in cubic feet per second;
q is the rate of injection of the tracer, in milliliters per minute;
C is the concentration of the dye solution injected into the stream, in micrograms per liter; and
$\bar{c}$ is the equilibrium, or plateau concentration, in micrograms per liter, averaged or weighted across the sampling section.

In figure 15, $\bar{c}$ has arbitarily been chosen as 10 µg/L as this is readily measurable and will also ensure adequate concentrations at the downstream section.

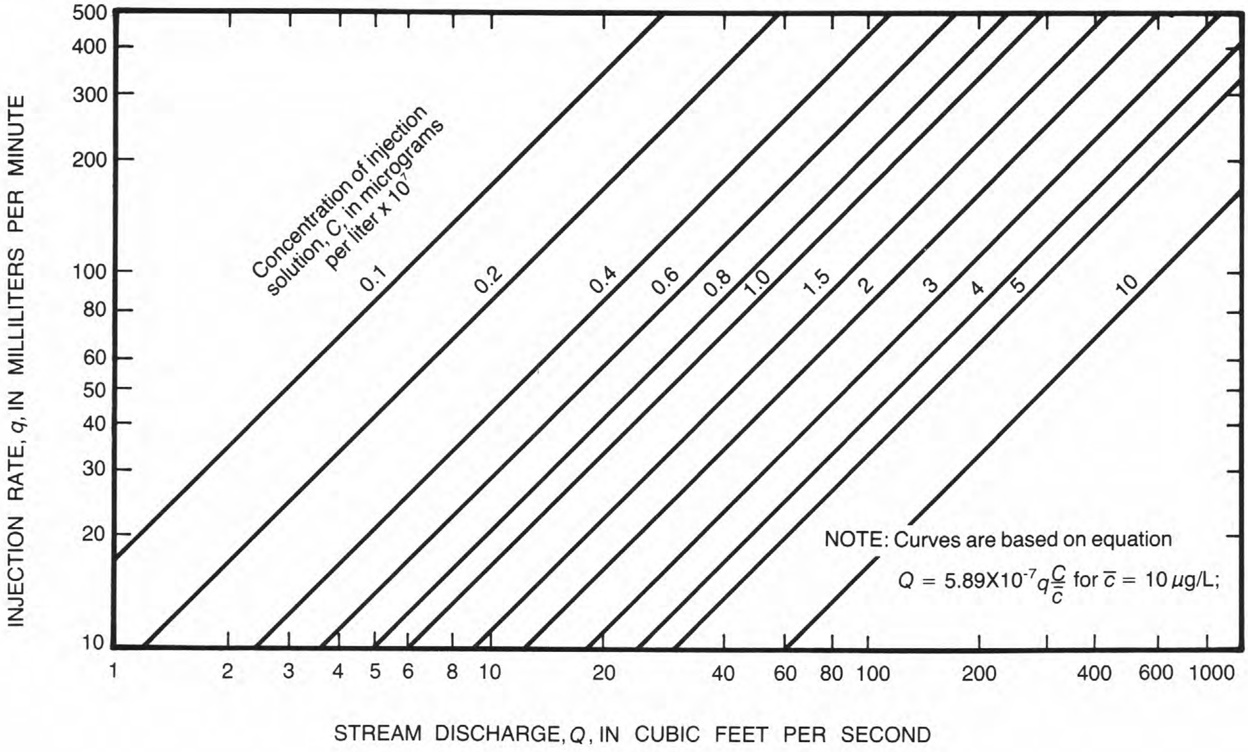


Figure 15.--Graph used for estimating rates of dye injections for different stream discharges and concentrations of injection solutions.

Concentrations

Table 4 provides convenient combinations of volumes of rhodamine WT 20-percent dye and water to yield approximately 5 gallons of bulk solution for the concentrations shown in figure 15. These data assume the specific gravity of 20-percent rhodamine WT dye to be 1.19. Five gallons will normally be sufficient for a number of measurements and can be prepared in advance. Subsequent laboratory analysis and fluorometer calibrations are simplified if several tests can be performed with one dye solution.

Table 4.--Convenient volumes of water and dye to mix for preparing bulk solutions of selected dye concentrations

Desired concentration C in µg/L x 10^7	Volumes to mix together		Volume of mixture in gallons
	V_w Water, in milliliters	V_d 20% rhodamine WT dye, milliliters	
10	10,700	7,750	4.87
10	11,000	8,000	5.02*
5	14,100	3,750	4.72
5	15,000	4,000	5.02*
4	14,850	3,000	4.72
3	15,600	2,250	4.72
2	16,350	1,500	4.72
1.5	16,350	1,100	4.61
1.5	17,850	1,200	5.03*
1.0	17,100	750	4.72
0.8	17,250	600	4.72
0.6	17,400	450	4.72
0.4	17,550	300	4.72
0.2	17,700	150	4.72
0.1	17,770	75	4.72

*In many instances, commercial 5-gallon containers are slightly greater in actual volume; the smaller volumes allow for easier mixing.

Constant-Rate-Injection Method

Seemingly contradictory, the CRI method of reaeration measurement uses an instantaneous slug injection of dye tracer at the start of continuous gas injection. As previously discussed, the resulting response downstream is used to guide gas injection and sampling and also is needed directly for the computation of the desorption coefficient. Figure 16 provides a convenient means of estimating the volume of 20-percent rhodamine WT dye to inject to produce a peak concentration of 1 µg/L at the most downstream measuring section. The distance L and the discharge Q should therefore be for the most downstream section. In figure 16

C_p is the peak concentration at the downstream sampling site, in micrograms per liter;
L is the distance to the downstream section, in feet;
Q is the stream discharge at the downstream section, in cubic feet per second;
V_s is the volume of rhodamine WT 20-percent dye, in milliliters; and
v is the mean stream velocity, in feet per second.

The estimate of the volume of dye to be injected obtained from figure 16 will produce a peak concentration of about 1 μg/L. A peak concentration of 5 to 10 μg/L is suggested; therefore, the dye volume should be increased proportionally as desired.

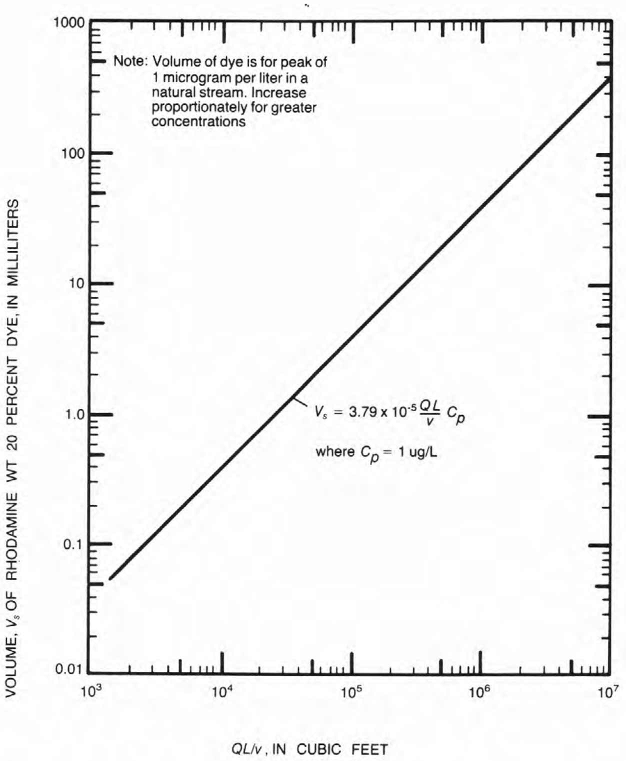


Figure 16.--Quantity of rhodamine WT, 20-percent dye required for slug injection to produce a peak concentration of 1 microgram per liter (μg/L) at a distance downstream, L, at a mean velocity, v, and with a discharge, Q, in the reach.

Care should be taken to mix the contents of the container thoroughly before withdrawing the desired amount. For very small quantities, graduated "To Contain" pipets should be used. Special pipets of tough borosilicate glass, with white graduations, are available for use in the field. Rhodamine WT 20-percent dye is rather viscous and tends to cling to the sides of graduated cylinders and other laboratory glassware; mixing with a larger quantity of water before injection will help to obtain an accurate injection of the amount measured.

Just before withdrawing the concentrated dye, about 10 L of river water should be measured accurately into a container (most buckets will readily contain 10 to 12 L). The exact amount of dye withdrawn should be measured and delivered to the large container. The exact volume of rhodamine WT 20-percent dye and water mixture to be injected into the stream must be recorded.

A sample of the mixed tracer solution must be retained, in the event standards are to be prepared from it; 100 mL is a desirable sample amount.

Sampling

General

Regardless of method, the field measurement of the dye-response curves guides the gas sampling and the data are also needed for the computation of the desorption coefficient. For this reason, a fluorometer must be used in the field for immediate sample analysis but samples must be reanalyzed in the laboratory to ensure accuracy.

Regardless of method, a minimum of three points laterally across each stream measuring section should be selected for both dye and gas sampling. The points should be located based on cumulative discharge and flagged or otherwise identified for repeat sampling. The same cumulative discharge points (streamlines) should be used for both upstream and downstream sections. Table 5 is provided to assist in selecting the sampling point locations for a given test to represent various discharge increments. More sampling points are recommended on the wider and shallower streams.

Dye

Scheduling sampling

One of the most difficult aspects of planning any kind of dye tracer study is scheduling sampling such that data are not lost; particularly the leading edge of dye clouds which are advancing faster than the peaks. The difficulty is that scheduling is usually done on the basis of an estimate of the mean velocity which, if accurate, applies more to the peak or the mass center than the leading edge. Taylor and others (1984) analyzed several hundred sets of time-of-travel type data and found that the normal slug-produced response time-concentration curve could be represented as a scalene triangle. In this triangular depiction, one-third of its total duration, T_D, was the time, t_b, from the leading edge to the peak; the remaining two-thirds being the time to recede to a concentration equal to 10 percent of the peak concentration. Referring to figure 12, if T_D is determined for the 10

Table 5.--Locations of sampling points based on cumulative discharge

Number of sampling points	Percent of total discharge sampled at each point	Locations of sampling points									
		1	2	3	4	5	6	7	8	9	10
		Cumulative discharge in percent									
3	33.3	16.7	50	83.3							
5	20.0	10.0	30.0	50.0	70.0	90.0					
7	14.3	7.1	21.4	35.7	50	64.3	78.6	92.9			
10	10.0	5.0	15.0	25.0	35.0	45.0	55.0	65.0	75.0	85.0	95.0

percent level based on an estimate of T_p, reducing T_p by one-third of T_D will provide an approximation of when the leading edge of the dye will arrive.

As an alternative, Kilpatrick (written commun., 1987) found that if the time to the peak, T_p, could be estimated for the sampling location in question, t_b, in hours, could be approximated by the equation

$$t_b = 0.23\ T_p^{0.86} + 0.2 \qquad (37)$$

which may be simplified to

$$t_b \cong \frac{T_p^{0.86}}{4} \qquad (38)$$

Thus for initial planning, dye sampling should precede T_p by t_b, with considerable allowance for error.

Once the dye has been detected in the field at the first sampling section, the results can be extrapolated to the downstream section with greater confidence.

The number and frequency of dye samples may also be estimated from the estimate of T_D. The dye slug-response curve can normally be well defined by 30 well-placed data points. Therefore, division of T_D by 30 will give approximately the frequency of sampling needed. More frequent sampling from the leading edge to and <u>through</u> the peak and less toward the trailing edge are common practice because of the skewed shape characteristic of most response curves. Complete definition of the response curves is essential to accurate reaeration measurements, so samples should be taken until the concentration has dropped to background levels or can be estimated to zero concentration with minimum error.

Techniques

When possible, persons involved in the dye injection should not be used for dye sampling because of the potential for contamination of samples.

In most cases, sampling can be performed by wading and the bottle lowered slowly toward the bottom as it fills. Sampling from boats may be necessary on larger streams. The floating syringe type boat sampler (Kilpatrick, 1972) is very useful for sampling the long duration dye slug response curves, especially at night. The sampler boat may be anchored at the 50 percent discharge point. Dye samples should still be manually collected, less frequently if necessary, in at least two other locations in the section such as at the 16.7 and 83.3 percent (see fig. 1 and table 5) discharge points. Occasionally samples should be taken at the boat to confirm the automatic sampler data. The more frequent automatic sampler data may be used to shape the other response curves which may be more poorly defined, especially during night-time hours. The best practice is to visit the one or more floating samplers, collecting check samples and if possible noting the time when the sampler is collecting a given sample. The latter helps confirm the timing of the automatic sampler.

Flowthrough fluorometer sampling is not normally recommended as it ties up the equipment and is subject to many equipment problems. The fluorometer is best located in the field to analyze individual bottle samples being obtained at the different measuring points and sections.

All dye samples should be returned to the laboratory for more accurate fluorometer analysis under temperature controlled conditions.

Gas

One of the most critical areas in performing reaeration measurements is in the gas sampling procedure. The objective is to deliver a sample to the laboratory which contains the same gas concentration as existed in the river; further desorption or loss of gas in the sample bottle must be avoided. This is accomplished by the following means: (1) the injection of a small quantity of formalin to prevent biological degradation during storage, (2) the use of tightly sealed borosilicate glass vials sealed with Teflon septa screw caps, (3) immediate protection of the samples from excessive heating or cooling, (4) prompt shipment in insulated containers, and (5) prompt laboratory analysis.

Scheduling sampling

In the SI method, the gas and dye are both injected simultaneously and continuously from the exact same location and for the same duration, 1/2 to 2 hours. Sampling the gas-response curve is guided entirely by the field observed dye-response curve. If the peak method is used, gas samples should be taken just prior to, during, and just after the dye peak. An excess number should be collected and only selected ones best defining the gas peak submitted for laboratory analysis. If the area method is to be used, gas samples must replicate the dye-response curve from start to finish. Only selected gas samples which are believed to be adequate for defining the gas-concentration-time curve are shipped to the laboratory for analysis.

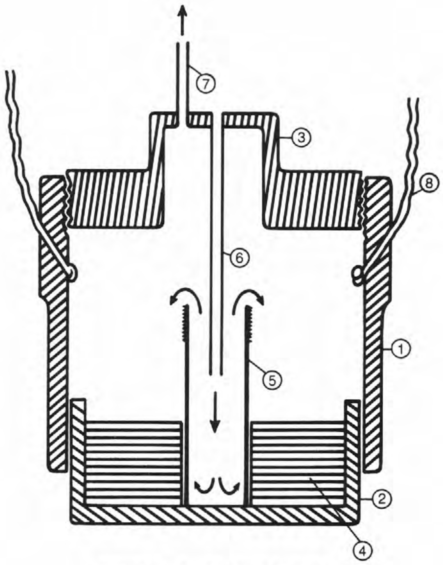
When using the CRI method, gas samples need be collected only after the plateau level is reached; in fact, it serves no purpose to sample for gas concentrations prior to this time which can be determined very accurately from the dye-response curve data. The dye-response curve should be defined completely down to background levels at which time a steady-state gas plateau will be fully established and can be sampled.

Techniques

Figure 17 is a sketch of a gas sampler designed specifically (Parker, written commun., 1985) to hold the 40 mL bottle. The 40 mL glass vial may be obtained from the Geological Survey Central Laboratory. Important features are:

1. The sample bottle is flushed many times in the process of filling.
2. The sample bottle is kept submerged while injecting the formalin and placing the Teflon sealed cap.
3. The container is large enough to permit capping with the fingers and for easy removal.

Sample holders similar to those shown in figure 17 are suggested, as they are inexpensive and effective in obtaining representative gas samples.



DESCRIPTION OF COMPONENTS

1. 4-inch PVC couple
2. Unthreaded end cap
3. Threaded end cap
4. Layers of lead
5. 40-mL sample bottle
6. 1/4-inch I.D. plastic intake pipe
7. 1/4-inch I.D. plastic air discharge tube
8. Rope sling

Figure 17.--Design of gas sampler; requires approximately 40 seconds to fill.

Figure 18 shows the 40-mL glass vial in place; the intake tube must project into the vial when the pipe cap is threaded in place. Figure 19 shows the sampler being lowered into the flow. In figure 20, 1 ml of a 37-percent formalin stock solution is being injected into the submerged sample bottle with a syringe just prior to capping. The sample bottle is then capped, figure 21, while still covered with water, making certain to place the Teflon surface facing the inside of the sample vial. Gas sample bottles are then placed in an insulated cooler, checking their caps for tightness at that time. The samples should be neither excessively cooled nor warmed, the objective being to keep them at about the same temperature as collected. As soon as possible, the gas samples are inspected for the presence of bubbles and if found, discarded. For this reason, extra samples should be collected and only selected ones shipped to the laboratory. The laboratory should be notified by phone when and how many samples are being shipped.

PERFORMANCE OF SLUG-INJECTION REAERATION MEASUREMENTS

This section will illustrate by example the techniques and analysis procedures suggested for performing an SI-type reaeration measurement. The State Environmental Control Board is concerned with the waste loading entering Rath Creek just upstream of Highway 1 and needs to know the reaeration capabilities of the downstream reach (see fig. 22). Of particular concern is the extent of natural purification and the level of DO at a water supply withdrawal point 4 miles downstream. Data will be obtained to allow computation of reaeration coefficients using both the peak and area methods.

Planning

Careful planning of the field test is as important as its execution. Planning begins with examination of maps, reports, and any existing hydrologic data already existent on the stream to be tested.

Selection of Test Reach

Figure 22 shows a sketch of Rath Creek and provides data on its properties useful in planning and selecting a test reach. Initial planning was to inject dye and gas tracers at an access area just below the Highway 1 bridge in an area where depths were in excess of 2 feet. The initial mixing of the tracers would be accomplished in the 12,000 feet down to the Highway 2 bridge crossing. The measurement reach would be the 8,000 feet of channel down to the State park. The downstream section is to be located just upstream of a significant inflow from Bun Creek, as it was recognized that poor mixing conditions would exist downstream of this inflow. The motel and covered pavilion would serve as sites for the fluorometer when sampling at the upstream and downstream sections, respectively.

Reach slope

A plot of contour elevations versus stream centerline distance through as well as upstream and downstream of the proposed test reach as picked from a topographic map yielded an average slope of 0.001 ft/ft.

Figure 18.--Placement of 40-milliliter sample vial in holder.

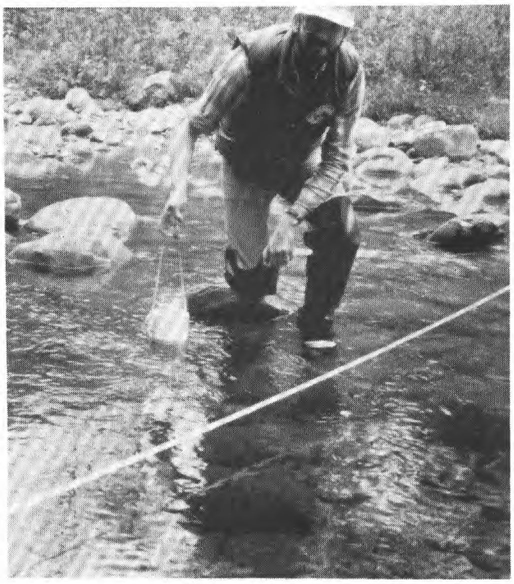


Figure 19.--Collecting gas sample at selected point in measuring section.

Figure 20.--Injection of 1 milliliter of formalin solution into submerged sample just prior to capping.

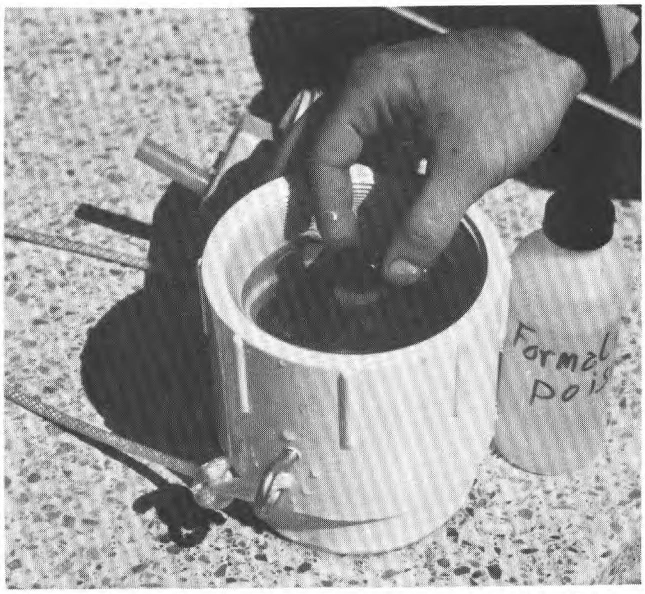


Figure 21.--Sealing sample with Teflon-lined cap just prior to removal and storage in ice chest.

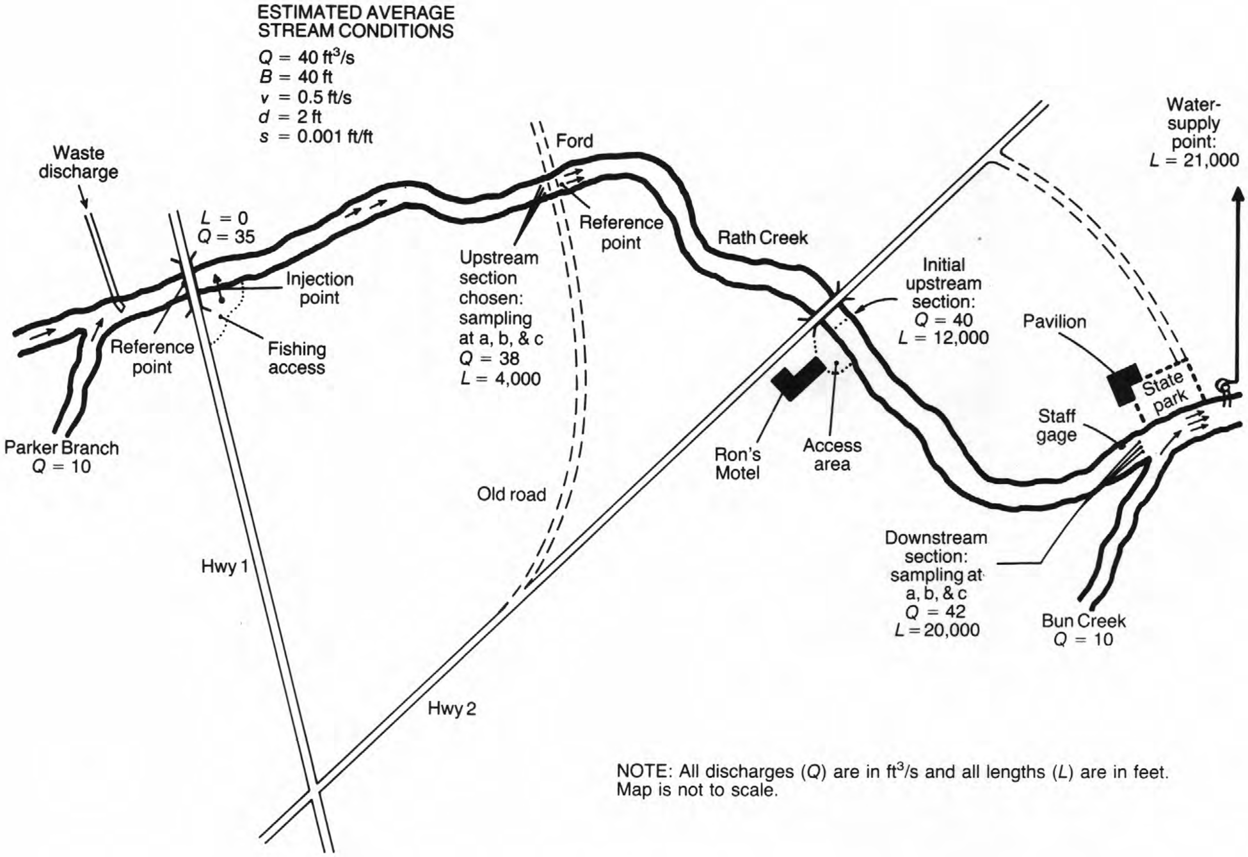


Figure 22.--Sketch of stream reach used in examples of reaeration measurements.

Traveltimes

This is a pool- and riffle-type stream so using equation 24 compute a peak velocity of

$$V_p = 0.38\ (40)^{0.4}\ (0.001)^{0.2} = 0.42 \text{ ft/s}$$

This is consistent with a mean velocity of 0.5 ft/s estimated from current-meter measurements made at Highway 1 and 2 bridges several years previous as part of a low-flow study. The slower velocity is probably the most realistic since current-meter measurements are usually made in sections having greater than average velocities.

Using 0.4 ft/s, the peak traveltimes to the upstream and downstream sections may be estimated as

$$\text{Upstream: } \frac{12{,}000 \text{ ft}}{0.4 \text{ ft/s}} \times \frac{1}{3{,}600 \text{ s/h}} = 8.33 \text{ hours}$$

$$\text{Downstream: } \frac{20{,}000 \text{ ft}}{0.4 \text{ ft/s}} \times \frac{1}{3{,}600 \text{ s/h}} = 13.89 \text{ hours}$$

Therefore, the traveltime of a peak, t_p, through the test reach is 13.89 - 8.33 = 5.56 hours.

Mixing length

Using equation 23 and table 1, an optimum mixing length from the point of injection is computed as

$$L_o = 0.1 \frac{(0.4)(40)^2}{0.1} = 640 \text{ ft.}$$

While this is just an estimate, 12,000 feet is available from Highway 1 to Highway 2 and, hence, mixing should be more than adequate.

Residence time

The decision is to use propane as the gas tracer in the test. It is desirable that the product of its desorption coefficient, K_p, and the peak time of travel, t_p, be 1.00 or greater. Equation 29 is used to estimate the desorption coefficient for propane as

$$K_p = 0.651(0.4)^{0.67}/(2)^{1.85} = 0.098/\text{h}$$

thus $K_p t_p$ = 0.098/hour x 5.56 hours = 0.54 which is significantly less than 1.00. A longer test reach is needed.

Inspection of figure 22 reveals that mixing should be more than adequate at an old road crossing upstream at a distance of 4,000 feet downstream of the injection point. The traveltime to this section is computed as before and is approximately 2.78 hours such that the time of travel of a peak in this longer test reach is 13.89 - 2.78 = 11.1 hours and $K_p t_p$ = 0.098/hour x 11.1 hours = 1.09. While this evaluation is based on numerous estimates, there should result with the actual field test a product close to 1.00 to ensure accuracy in the computation.

Injection Rates

Gas injection

Gas injection should be reasonably efficient if depths at the injection site are in excess of 2 feet. Based on a downstream discharge of 42 ft^3/s and table 2, use two diffusers to be supplied by one gas tank. Gas injection for 1 hour should be sufficient.

To use the curves in figure 11 (or equations 32 and 35), compute $Q_m e^{T_p K_p}$ for the stream conditions described in figure 22 and previously estimated, applicable to the most downstream section as

$$Q_m e^{T_p K_p} = (42 \text{ ft}^3/\text{s}) e^{(13.89 \text{ h})(0.098/\text{h})} = 164.$$

From figure 11, determine that a constant gas injection rate of 3.23 ft^3/h is needed for a plateau of 1 µg/L assuming an absorption efficiency of 10 percent. Since this is to be a 1 hour long "slug injection," plan for a plateau of 5 µg/L or more, knowing that lesser concentrations will actually result at the most downstream section. Thus $5 \times 3.23 = 16.15$ ft^3/h; plan for approximately a 16 ft^3/h injection rate which from figure 11 is equivalent to less than 2 lb of propane for the 1-hour test. A 20-lb propane tank is more than sufficient for the test.

Previous tests have shown that metering temperatures and pressures have typically been about 32 °F and 55 psig, respectively. Thus, based on equation 34, the air injection rate to set will be

$$q_a = (0.44)(16\ ft^3/h) \approx 7\ ft^3/h.$$

Dye injection

The dye injection will be for 1 hour duration at the same location as the gas injection. Examination of figure 15 indicates that for a stream discharge of 42 ft^3/s, a dye solution having a concentration, C, of 2×10^7 µg/L will yield a 10 µg/L plateau concentration if injected at a rate of 34 mL/min. While a 10 µg/L concentration might not exist at the downstream section, dye concentrations as low as 1 µg/L would be acceptable, thus a considerable margin exists for the dye plateau to be reduced by longitudinal dispersion and still be adequate for accurate fluorometric measurement. It is important, too, that dye concentrations be less than 10 µg/L at the water supply intake (Hubbard and others, 1982).

An injection rate of 34 mL/min for 1 hour would require a total dye solution volume of approximately 2 liters or 1/2 gallon. Table 4 provides the volumes of dye and water to mix together for preparing approximately 5 gallons of solution. Additional tests on other streams are planned in which stream discharges range from 20 to 50 ft^3/s, hence a large volume of 2×10^7 µg/L solution would be useful. Using table 4, prepare approximately 2.5 gallons of 2×10^7 µg/L solution by adding 750 mL of 20 percent rhodamine WT dye to 8,175 mL of tap water. Note that it is satisfactory to use chlorinated tap water for preparing concentrated solutions of dye, but not for preparing standards. This is preferable to using cold river water which may release air bubbles and cause problems with the dye injection equipment.

After thoroughly mixing the solution, retain and store a 100 mL bottle of this dye solution for preparing fluorometer standards later.

Preliminary test schedule

The elapsed times to the peaks of the dye cloud were estimated previously as approximately 2.8 hours and 13.9 hours for the upstream and downstream sections, respectively. Figure 12 may be used to estimate other properties of the dye response curves at the upstream and downstream sections to provide a means of scheduling the tracer injection and sampling. These estimates are tabulated in table 6 and depicted in figure 23 to aid planning. As may be seen, the first arrival of the dye is estimated to be at 2.2 and 11.8 hours at upstream and downstream sections, respectively, from the time injection is started.

The last dye is estimated to depart the upstream and downstream sections at 9.4 and 29.8 hours elapsed time, allowing for the 1 hour of injection.

Table 6.--Estimated properties of slug response curves for scheduling sampling for slug-injection type reaeration test; all times in hours

(Note: duration of dye injection = 1 hour)

Description	Upstream section	Downstream section
1. Elapsed time to peak, T_p	2.8	13.9
2. *Duration for truncation at 10 percent C_p: $T_{D_{10}}$	1.7	6.2
3. Buildup from leading edge to peak, t_b: $t_b = \frac{T_{D_{10}}}{3}$	0.6	2.1
4. Elapsed time to start sampling leading edge: $T_p - t_b$	2.2	11.8
5. Elapsed time to trailing edge at 10 percent C_p: (2) + (4) + 1 hour	4.9	19.0
6. *Duration, T_D, for truncation at 0 percent C_p	6.2	17.0
7. Elapsed time to trailing edge, T_f, at 0 percent C_p: (4) + (6) + 1 hour	9.4	29.8

*From figure 12

A sketch such as figure 23 also aids in deciding when to make the tracer injections to best acquire the necessary samples during daylight hours. As can be seen, if tracer injection is started at dawn, the peak of the downstream tracer response curve may hopefully be sampled late in the same day. The remainder or receding portion of the downstream tracer response will have to be sampled through the night and morning hours of the second day. If only the SI-peak method is to be used, only dye samples would have to be acquired the second day. The floating automatic syringe sampler, supplemented occasionally with manually collected samples, would suffice for defining the downstream dye response curve. Unfortunately, no automatic gas sampler is available for use under such circumstances. A sketch such as that in figure 23 also aids as shown in deciding on the sampling interval to ensure adequate definition.

It is very important to realize that the above estimates may be in considerable error and that ultimate sampling must always be guided by real time field results.

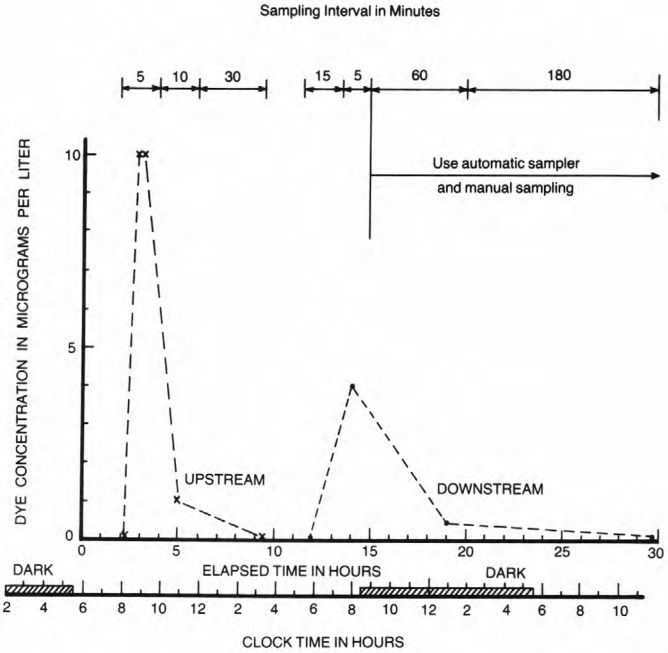


Figure 23.--Sketch of estimated response curves for guidance in scheduling slug-injection type field reaeration test

Field Test-Peak Method

Preliminary preparation made the afternoon previous to the actual test included:

1. Establishment of reference points at the injection and upstream sections and a temporary staff gage at the downstream section to measure gage heights and hence any change in discharge during the test.

2. A current-meter measurement was made at the upstream section and the 50 percent discharge point located distance wise from the left bank. Staff readings were made at all three sections at the same time the current-meter measurement was made.

3. The gas diffuser and dye injection lines were located and secured in the center of flow and made ready to hook up to the diffusers in the morning.

The actual test started early the next day and consisted of the following:

4. Initiation of gas and dye injection was at 6 a.m. and corresponds to $t = 0$ for all data collection and analysis; the setup was as shown in figure 14.

5. While one hydrologist measured both the gas and dye injection rates[1], the other measured stage both before and after making a current-meter measurement at the upstream section of the test reach.

6. At t = 1 hour, background samples are collected at the upstream section and gas and dye injection is terminated at the injection site. The injection apparatus is removed immediately and the dye pump and line and gas line and diffuser flushed with tap water.

7. Upon completion of the current-meter measurement, the tagline is left in place and the locations corresponding to the 16.7, 50, and 83.3 percent cumulative discharge points flagged (see table 5).

At this time, a minimum of two men should be available in preparation for sampling both gas and dye.

8. The fluorometer is setup in the vehicle and dye sampling begun at the center point at t = 2 hours. Samples are analyzed immediately and plotted on a graph similar to figure 23; stream water temperatures are measured and recorded.

9. With the first appearance of dye at the upstream section, dye sampling proceeds at approximately 5-minute intervals at all three sampling points.

10. The immediate analysis and plotting of the dye concentrations continues until values approach about 7 µg/L (knowing that a brief plateau of about 10 µg/L is likely) at which time gas samples are collected at 5- to 10-minute intervals through the dye peak. Judgment should be exercised to sample for gas several times at each point just prior to and as the dye peak is seen to occur.

11. Stage measurements are made periodically at the upstream section. No additional discharge measurements are made, unless a 10 percent or greater change in discharge has occurred. A change in stage of a few hundredths of a foot can mean a significant change in discharge.

12. Dye sampling continues at a less frequent rate, the fluorometer being used to immediately analyze samples and the data plotted concurrently.

13. The dye samples are retained and stored out of direct light.

14. The gas samples are checked, caps tightened if necessary, and any containing gas bubbles discarded; the remainder are stored in ice chests with little or no chilling as required to maintain them at approximately stream temperature. Large bottles of stream water are placed in an ice chest to help maintain them at the original stream temperature.

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[1] See figure 17 in background reference 3.

15. Except for checking injection rates, steps 5 through 14 are repeated at the downstream section with the sampling schedule being altered as necessary based on the results of the dye-concentration time plots at the upstream section.

16. Dye samples are taken manually at 1/2-hour intervals up until 9 p.m. (t = 15 hours), after which the automatic sampler anchored in the center is used. The motel being close by, manual dye samples are also collected at all three points at 9 and 10 p.m. and again at 6 and 10 a.m. of the second day. The center sample collected manually at the floating sampler was noted to coincide with the twelfth sample taken by the floating sampler which had been geared to sample every 45 minutes starting at 9 p.m.

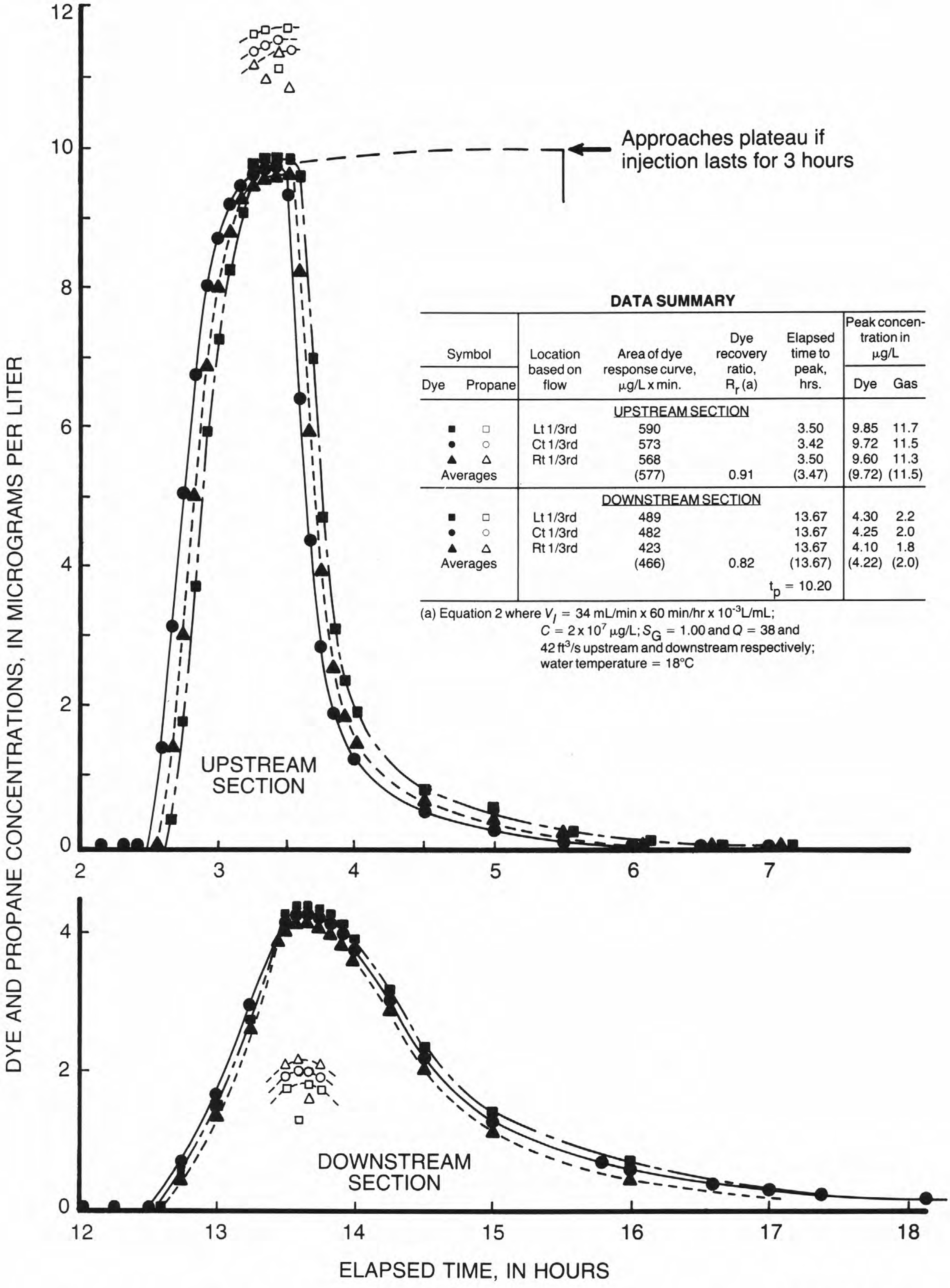
17. All samples are returned to the office. Fluorometer dye standards are prepared from a sample of the 2 x 10^7 μg/L dye mixture that was injected. All dye samples, standards, background samples, and stream samples are analyzed at one temperature. These dye-concentration time data are plotted and 12 gas samples, 4 from each point, are selected, based on their proximity to the dye peak. Twelve gas samples are also selected for downstream; all 24 are shipped to the laboratory. The laboratory is informed by phone to expect the 24 samples and as to the kind of analysis desired.

Data Analysis and Computations-Peak Method

The dye concentration data obtained from reanalysis of samples in the laboratory and the propane gas concentration data are all plotted as in figure 24 for both upstream and downstream sections.

Dye Data

As can be seen in figure 24, the dye concentration-time data plot smoothly and the response curves at the three sampling points are essentially the same, being slightly faster in the center than along the sides. Normally, it is advisable to plot each point response curve separately and draw a smooth fitting curve through each set of data. It will be noted that at the upstream section the dye first arrived in the center at t = 2.5 hours elapsed time and was essentially gone at t = 6.5 hours such that its duration was 4.0 hours. Had the dye injection been an instantaneous slug injection instead of one lasting 1 hour, the duration would have been 3 hours. Thus, at this specific section and point, dye and/or gas tracer would have to be injected for a minimum of 3 hours for a steady-state plateau to develop. As the data show, the dye curve is climbing toward the plateau level of 10 μg/L as intended which was the basis for picking a dye injection rate of 34 mL/min from figure 15. The plateau is never fully reached as dye injection was for 1 hour instead of 3 hours. The point is that no attempt should be made to fit a horizontal line to the peak data (unless the injection is longer than the duration of the response), but instead it should be realized that this last 2 hours in which the dye would be climbing toward a plateau is a mirror image in shape to the recession. This knowledge can be used to fit the curve to the peak data as has been shown in figure 24 for the upstream section. Conversely, the data for the downstream section indicates a response duration of about 8 hours (if



DATA SUMMARY

Symbol		Location based on flow	Area of dye response curve, µg/L x min.	Dye recovery ratio, R_r (a)	Elapsed time to peak, hrs.	Peak concentration in µg/L	
Dye	Propane					Dye	Gas
			UPSTREAM SECTION				
■	□	Lt 1/3rd	590		3.50	9.85	11.7
●	○	Ct 1/3rd	573		3.42	9.72	11.5
▲	△	Rt 1/3rd	568		3.50	9.60	11.3
Averages			(577)	0.91	(3.47)	(9.72)	(11.5)
			DOWNSTREAM SECTION				
■	□	Lt 1/3rd	489		13.67	4.30	2.2
●	○	Ct 1/3rd	482		13.67	4.25	2.0
▲	△	Rt 1/3rd	423		13.67	4.10	1.8
Averages			(466)	0.82	(13.67)	(4.22)	(2.0)
					t_p = 10.20		

(a) Equation 2 where V_l = 34 mL/min x 60 min/hr x 10^{-3}L/mL; $C = 2 \times 10^7$ µg/L; S_G = 1.00 and Q = 38 and 42 ft^3/s upstream and downstream respectively; water temperature = 18°C

Figure 24.--Tracer data acquired for slug injection, peak method of reaeration measurement.

extended to essentially background) and hence there is no indication that a plateau is forming as continuous injection would have had to take place for at least 7 more hours.

As seen, the areas of the three dye response curves at each of the two sections are very nearly the same, indicating good mixing. The areas of the individual time-concentration curves should be determined by planimetering or mathematically using a numerical integration scheme such as employed in computing a current-meter discharge measurement. A program available from the Office of Surface Water is available to numerically integrate such data to obtain areas. Accurate results will be obtained if a sufficiently small time interval is used to define adequately the shape and hence the area of the response curve. Normally, it is best to draw a smooth curve through the data and pick the values from the plot rather than attempting to use actual data. Frequently, the placement of a smooth curve through the bulk of the data will require ignoring some data points, hence only data conforming to the best fit curve should be used.

Furthermore, it should be borne in mind that the response curves and area computations must include all of the tracer mass, thus computations should include dye data extended to essentially background levels.

In figure 24, the average areas of the upstream and downstream sections are 579 and 481 μg/L x minutes, respectively. The reduction in the areas of the downstream dye response curves is due to dilution by a 4 ft^3/s gain in stream discharge and by actual dye loss. Equation 2 allows for the increase in discharge, since the actual discharge at each section during cloud passage is that used in the computations. Recovery ratios of 0.91 and 0.82 are computed for the upstream and downstream sections, respectively.

The traveltime between the peaks may be obtained by picking the average elapsed time to the upstream and downstream sections, respectively, and subtracting to get the difference. These data and results are shown in the Data Summary on figure 24.

Gas Data

The propane gas concentrations corresponding to times around the peak are also plotted in figure 24 for both upstream and downstream cross sections. The data scatter more than the dye data, but more or less conform to the shape of the dye curves. The exceptionally low gas concentrations are ignored as these are attributed to propane losses prior to laboratory analysis. The peak gas concentrations chosen from the plots are picked to coincide in time with the peak dye concentrations chosen from the response curve for each point. Note that the gas concentrations at the upstream section are greater than the dye concentrations, but because of desorption, are less than the dye concentrations at the downstream section.

Computations

The data shown in the Data Summary of figure 24 may be used with equation 12 to compute the desorption coefficient for propane as

$$K_p = \frac{1}{10.20\ h} \ln \frac{0.91\ \frac{11.5}{9.72}}{0.82\ \frac{2.0}{4.22}}$$

$$K_p = \frac{1}{10.20\ h} \ln (2.77)$$

$$K_p = 0.10\ h^{-1}$$

This is very close to the estimated value of 0.098/h used initially. Using equation 8, K_2 at 20 °C may be computed, adjusting K_p as measured at 18 °C.

$$K_{2_{20}} = 1.39\ K_{p_T}\ (1.0241)^{(20-T)}$$

$$K_{2_{20}} = (1.39)(0.10/h)(1.0241)^2 = 0.15\ h^{-1}$$

Field Test-Area Method

The reaeration coefficient may also be measured using the Area Method with essentially the same procedures as just described for the Peak Method, except that gas and dye samples must be collected to define the entire tracer response curves for both. Since gas tracer concentrations cannot be readily measured in the field, the dye response curve as measured onsite must be used to guide gas sampling. Extra gas samples should be collected and only selected ones forwarded to the laboratory for analysis. Because the gas analyses are relatively expensive, maximum use should be made of the dye response curves to guide gas sampling and to limit the number submitted for laboratory analysis.

For example, in the previous example, mixing of the dye tracer is good at the upstream section and excellent at the downstream section, as may be seen from the dye concentration data. Thus, even though gas samples would be collected throughout the duration of the response curves at all three points in each section, subsequent plot of the dye-concentration data would indicate that definition of the gas response curve just in the center of the flow at the downstream section was all that was necessary.

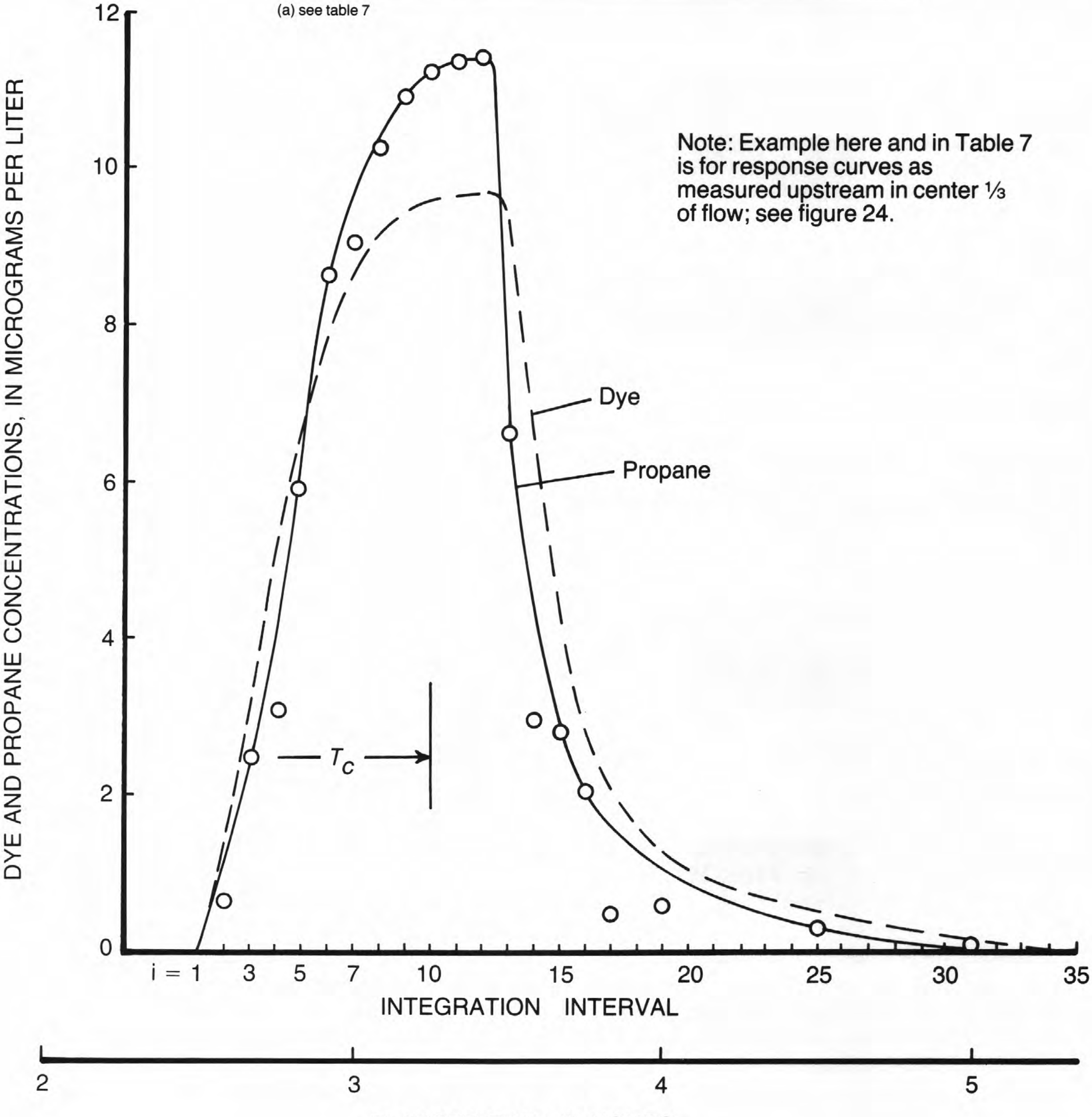
Figure 25 shows a plot of concentrations of selected gas samples collected in the center of the flow at the upstream section along with the companion dye response curve. This dye response curve as measured in the center at this section and presented previously in figure 24 is shown again in figure 25 on an expanded time scale. It can be seen again that some of the gas concentration data plot low and should be ignored. Note too, that the gas peak seems to drop quicker than the dye peak. This reflects the desorption of the propane gas which tends to erode the trailing edge of the gas response curve. Similar plots of both gas and dye response curves for the left and right third of the section were made but for the sake of clarity are not shown.

At the downstream section, only the gas samples collected in the center were analyzed and plotted.

DATA SUMMARY AND COMPUTATIONS

Location based on flow	Area of Gas Response Curve, µg/L x min		Elapsed time to centroid of dye response curve, T_c, hours		Travel time t_c, hours	Propane desorption coefficient, K_p at 18°C in h^{-1}
	Upstream	Downstream	Upstream	Downstream		
Lt 1/3rd	588	---	3.49	14.41	10.92	0.097
Ct 1/3rd	561(a)	185	3.23(a)	14.35	11.12	0.091
Rt 1/3rd	562	---	3.40	14.24	10.84	0.093
Averages	(571)	(185)	(3.37)	(14.33)	(10.97)	(0.094)

(a) see table 7



Note: Example here and in Table 7 is for response curves as measured upstream in center ⅓ of flow; see figure 24.

Figure 25.--Preparation of gas response curve using dye response curve as a guide and selection of numerical integration interval for computation of curve area and centroid.

Unlike the Peak Method, the Area Method uses in the computation of the desorption coefficient the traveltime of the centroid of the dye cloud. This requires that the centroid of each dye response curve be computed relative to t = 0; see equation 15. The numerical integration to accomplish this is shown in table 7 using data picked from the dye response curve shown in figure 25 for just the center curve. The computation should be performed independently on each dye response curve and averaged for upstream and downstream sections. Note that Δt_i, the numerical integration interval, has been chosen as 5 minutes which results in 35 increments and defines the response curve with minimum error. The computer program available from the Office of Surface Water will accomplish this same calculation as well as the entire computation of the desorption coefficient. The elapsed centroid times for the upstream and downstream dye response curves are shown in the Data Summary and Computations Table of figure 25 along with other pertinent data for computing the desorption coefficient.

The desorption coefficient may be computed using equation 14 as

$$K_p = \frac{1}{10.96} \ln \frac{(570 \times 38)}{(187 \times 42)}$$

$$K_p = \frac{1}{10.97} \ln (2.71) = 0.094 \text{ h}^{-1}$$

And K_2 at 20 °C may be computed using equation 8 as

$$K_{2_{20}} = (1.39)(0.091/\text{h})(1.0241)^2 = 0.14 \text{ h}^{-1}$$

Note that in the Data Summary and Computations Table that the desorption coefficient can also be computed for each third of the flow with very similar results. This assumes that the area of the gas response curve is the same at all three points in the downstream section. Each third of the flow is treated as a separate stream tube.

PERFORMANCE OF CONSTANT-RATE-INJECTION REAERATION MEASUREMENT

General

The planning aspects prior to performing a CRI type reaeration measurement are essentially the same as discussed previously for the SI method. Differences relate to the fact that the dye injection is an instantaneous slug injection and the gas injection is constant rate and continuous for a duration somewhat longer than the duration of passage of the most downstream dye response curve. This may influence overall scheduling of the test, in particular the timing of gas sampling.

Narrow Streams--One-Dimensional Dispersion

Rath Creek, previously used in the SI type measurement, will also be used as an example to illustrate the CRI method applied to a narrow stream for the case when one-dimensional dispersion exists. The same channel and flow conditions will be assumed and the same test reach will be used (see fig. 22).

Table 7.--Numerical integration of dye response curve to obtain elapsed time to centroid; data are for upstream section at center of channel

i	Elapsed time, t, from t = 0 in hours (1)	Dye concentration C_d, in µg/L (2)	Area increment, Δt x C_d (a) (µg/L x h) (3)	Incremental moment t x Δt x C_d (4)
1	2.50	0	0	0
2	2.58	1.40	0.117	0.302
3	2.67	3.00	.250	.668
4	2.75	5.10	.425	1.169
5	2.83	6.40	.533	1.508
6	2.92	8.00	.667	1.948
7	3.00	8.70	.725	2.175
8	3.08	9.23	.769	2.368
9	3.17	9.52	.793	2.514
10	3.25	9.62	.802	2.606
11	3.33	9.65	.804	2.677
12	3.42	9.72	.810	2.770
13	3.50	9.20	.767	2.059
14	3.58	6.40	.533	1.908
15	3.67	5.20	.433	1.589
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.
28	4.75	.32	.027	.128
29	4.83	.28	.023	.111
30	4.92	.23	.019	.093
31	5.00	.20	.017	.085
32	5.08	.15	.012	.061
33	5.17	.10	.008	.041
34	5.25	.05	.004	.021
35	5.33	0	0	0

(a) $\Delta t = 5$ min = 0.0833 h

$\Sigma = 9.55$ µg/L x h $\qquad \Sigma = 30.889$

$A_c = 573$ µg/L x min

$$T_c = \frac{30.889}{9.55} = 3.23 \text{ h}$$

Dye Injection

To use figure 16 in estimating the quantity of 20 percent rhodamine WT dye to slug inject, compute QL/v for the downstream section as

$$\frac{QL}{v} = \frac{(42\ ft^3/s)(20{,}000\ ft)}{(0.4\ ft/s)} = 2.1 \times 10^6$$

Entering figure 16 indicates that 80 mL of 20 percent rhodamine WT dye should produce a peak of about 1 µg/L. A peak of about 5 µg/L would be acceptable and well below the 10 µg/L maximum allowed. Thus, $V_s = 5 \times 80$ or 400 mL of dye should be injected.

Gas Injection and Tank Size

To use figure 11, compute $Q_m e^{T_p K_p}$ for the most downstream section as before and determine that a gas injection rate of 3.23 ft^3/h is needed for a plateau of 1 µg/L (assuming an absorption efficiency of 10 percent). A plateau concentration of 5 µg/L is desired at the most downstream section, thus $5 \times 3.23\ ft^3/h = 16.15\ ft^3/h$ is necessary. Use a rate of about 16 ft^3/h; this is equivalent to about 1.8 lb of propane per hour (scale on right side of fig. 11).

The traveltime to the downstream dye peak was originally estimated to be 13.9 hours. From figure 12, determine that a constant rate gas injection of approximately 17 hours will be necessary to produce a steady-state gas plateau; assume a 20-hour continuous injection to allow time for sampling. Thus, a tank containing in access of 36 lbs of propane (1.8 lbs/h x 20 h) is required. A 50-lb tank would be sufficient and not involve using the last 20 percent of the tank.

Preliminary Test Schedule

To plan the test, estimate the arrival and duration of passage of the dye response as was previously done for the SI test. Table 8 is similar to table 6, but for a slug injection of dye and a 20-hour continuous injection of propane gas. Figure 26 is prepared from this data to aid in selecting injection and sampling schedules to best utilize daylight hours and provide for comprehensive data collection. It is important to note that a gas plateau will exist at the upstream section well in advance and for many hours before it is established downstream. The elapsed time to the trailing edge of the dye response curve corresponds to the time at which a steady-state plateau is reached at upstream and downstream sections, respectively, assuming the gas and dye injection start at the same time and location.

The dye response curves at the upstream and downstream sections would be scheduled for sampling exactly as was done previously for the SI test. Since the dye sampling is far more extensive than the gas sampling, scheduling should favor this effort. A 6 a.m. slug injection of dye would still seem the best, as it allows most of the sampling of the downstream dye response curve to take place in daylight hours; automatic sampling is sufficient from about 9 p.m. on.

Table 8.--Estimated properties of slug response curves for scheduling sampling for constant-rate-injection type reaeration test; all times in hours

(Note: Dye injection is instantaneous and gas injection is continuous for 20 hours)

Description	Upstream section	Downstream section
DYE RESPONSE CURVE		
1. Elapsed time to peak, T_p	2.8	13.9
2. *Duration for truncation at 10 percent C_p: $T_{D_{10}}$	1.7	6.2
3. Buildup from leading edge to peak, t_b: $t_b = \frac{T_{D_{10}}}{3}$	0.6	2.1
4. Elapsed time to start sampling leading edge: $T_p - t_b$	2.2	11.8
5. Elapsed time to trailing edge at 10 percent C_p: (2) + (4)	3.9	18.0
6. *Duration, T_D, for truncation at 0 percent C_p	6.2	17.0
7. Elapsed time to trailing edge, T_f, at 0 percent C_p: (4) + (6)	8.4	28.8
GAS PLATEAU		
8. Elapsed time to termination of steady-state plateau (4) + 20 hours continuous gas injection	22.2	31.8
9. Elapsed time between peaks, t_p from line 1 above		11.1
10. Recommended elapsed time to sample downstream		30
11. Recommended elapsed time to sample upstream (hourly immediately following stable plateau at 8.4 hours)	9.0	
12. Samples likely to be used in concert with those collected downstream at 30 hours (30 hours - 11.8 hours, rounded to nearest hour; collect samples every 1/2 hour to bracket 18 hours)	18.0	

*From figure 12

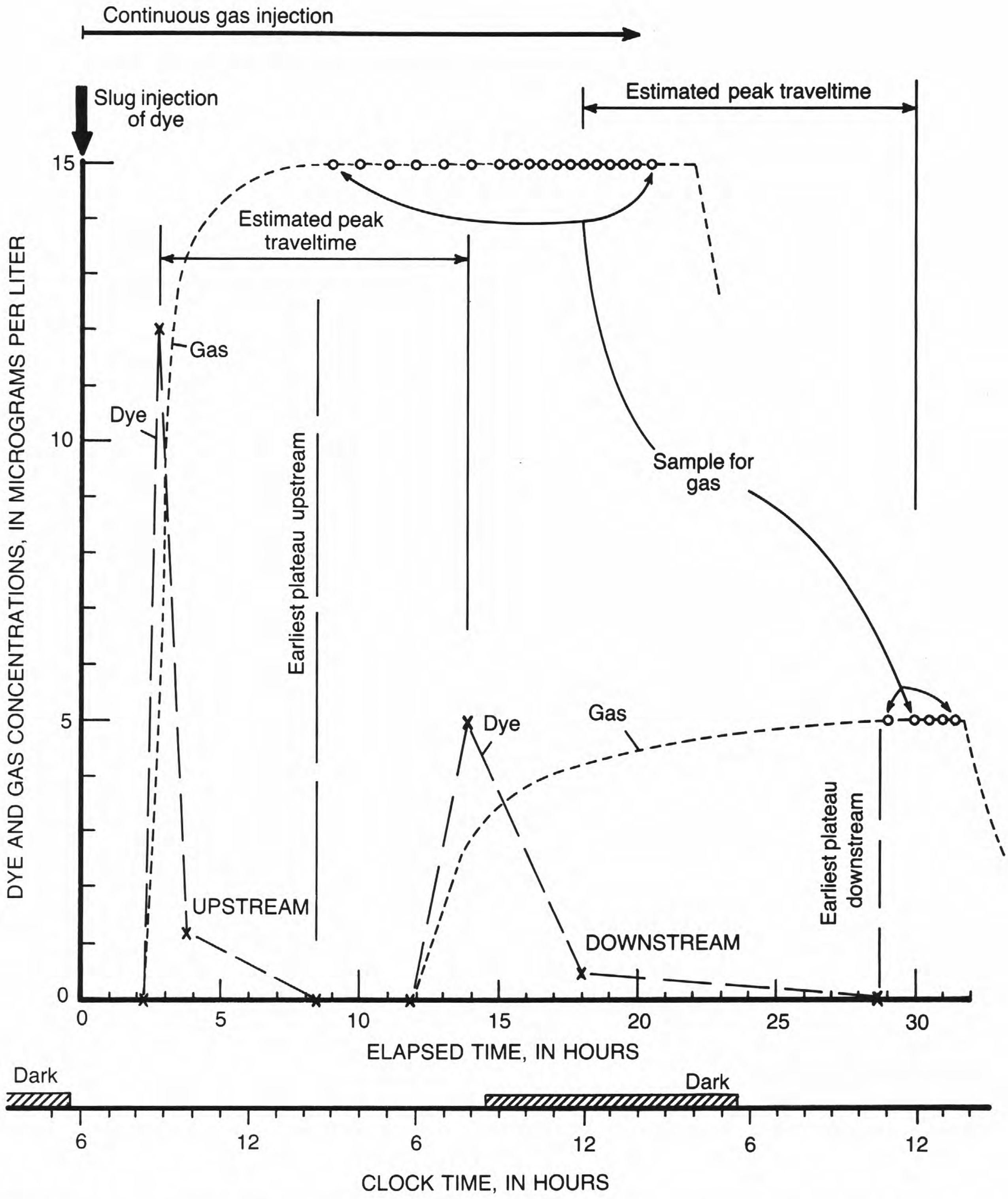


Figure 26.--Sketch of estimated response curves for guidance in scheduling constant-rate-injection type field reaeration test.

Gas injection is to start at 6 a.m. (t = 0) and could terminate 20 hours later at 2 a.m. of the second day. Note this is 10 hours *before* sampling the plateau downstream! In practice, the gas could be turned off any time the following morning; this is one reason for having a tank with extra capacity. In the example, if streamflow is steady, gas samples could then be collected upstream at any time from t = 8.4 hours to 22.2 hours. It is recommended that gas samples be taken upstream as soon as a stable plateau is known to exist; if proven excessive, they can be discarded. It is desirable to sample the same fluid mass if possible, especially if the flow is changing slightly. The estimated time of travel of the peaks is 11.8 hours. Therefore, it would appear likely that the upstream gas samples that will be used will correspond to about t = 18 hours, 12 hours before gas sampling downstream at t = 30 hours. A logical schedule for the upstream site would be to sample for gas every hour starting at t = 9 hours and every 1/2 hour at about t = 16 hours.

The time at which a steady-state plateau is reached downstream will be apparent from observing when the recession of the dye response curve has reached background levels. This could be well before the estimated 28.8 hours. Sampling upstream at t = 9 hours and later would allow *picking* the samples to *match the time of travel* of the dye response curves, data not available until completion of the test. *Preliminary planning is highly advisable but the dye response curves should be measured in the field and dictate actual gas sampling*.

Field Test-Constant-Rate-Injection Method--One-Dimensional Dispersion

Preliminary preparation made the afternoon previous to the actual test included:

1. Establishment of reference points at the injection and upstream sections and a temporary staff gage at the downstream section to measure gage heights and, hence, detect any change in discharge during the test.

2. A current-meter measurement was made at the upstream section and the 50-percent discharge point located distance wise from the left bank. Staff readings were made at all three sections at the same time the current-meter measurement was made.

3. The gas diffuser line was located and secured in the center of flow and made ready to hook up to the diffuser plates in the morning.

The actual test started early the morning of the next day and consisted of:

4. Continuous propane gas injection was started at 6 a.m. concurrent with an *instantaneous* slug injection of 400 mL of 20 percent rhodamine WT dye; 6 a.m. corresponds to t = 0 for all data collection and analysis. Based on equation 34, an air injection rate of 7 ft^3/h was set on the rotameter. A platform scale was placed under the gas

tank and weight change with time noted periodically (see fig. 27).[1] The 400 mL of 20 percent rhodamine WT was premixed with 9,600 mL of river water prior to slug injection; a 100 mL sample was retained for future preparation of standards and fluorometer calibration.[2]

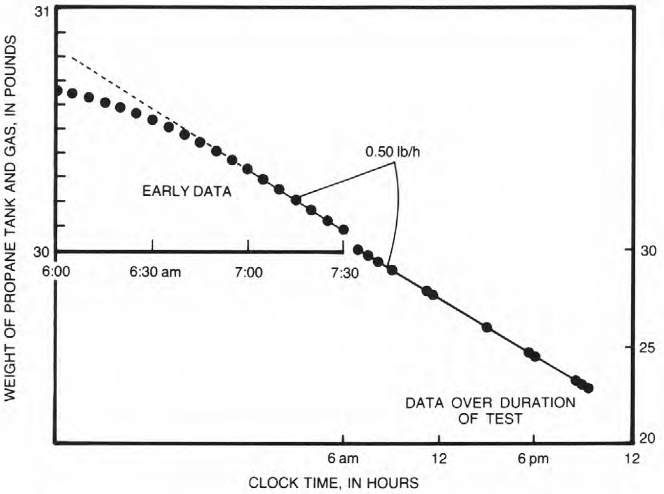


Figure 27.--Determination of rate and constancy of propane gas injection by measurement of weight change with time.

5. One hydrologist stayed at the injection site until the injection rate was observed to be constant. As noted in figure 27, a constant rate was not attained until 7 a.m. The hydrologist also collects several background samples for use in fluorometric analysis.

6. Another hydrologist proceeds to the upstream section comprising the test reach making a current-meter discharge measurement and observing stage both before and after.

7. Upon completion of the current-meter measurement, the tagline is left in place and the locations corresponding to the 16.7-, 50-, and 83.3-percent cumulative discharge points flagged (see table 5).

8. The fluorometer is set up in the vehicle and dye sampling at 5-minute intervals begun at the center point at t = 2 hours. Samples are analyzed immediately and plotted on a graph such as shown in figure 28. (Note that figure 28 is a final data plot based on careful

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[1] See figure 17 in background reference 3.

[2] See section "Alternative Method of Analysis and Computation" in background reference 3.

laboratory analyses of dye and gas samples but for brevity is discussed here as if it was the field analysis of the dye data.)

9. Stream water temperature is now observed to be 18 °C.

10. With the first appearance of dye at the upstream section, dye sampling proceeds at approximately 5-minute intervals at all three sampling points; in figure 28, for clarity, only the center dye response curve is presented.

11. As the dye peak passes, sampling is less frequent.

12. The dye samples are retained and stored out of direct light.

13. The data plot of dye concentration, figure 28 (or dial readings), versus time is examined and used to predict new times of travel to the downstream section.[1] For example, while the measured leading edge and estimated time of arrival were identical, the trailing edge is at about t = 5 hours instead of 8.4 hours as was estimated; sampling schedules at the downstream section are modified as necessary.

14. Examination of figure 28 indicates the trailing edge of the upstream dye response curve to be at t = 5 hours. Since the gas injection was an hour late in stablizing (see fig. 27), the gas plateau at the upstream section will be fully stablized at t = 6 hours. Starting at t = 6 (12 noon), sets of three gas samples were taken at 1/2-hour intervals upstream.

15. Stage measurements are made periodically at the upstream section and no additional discharge measurements made unless a 10 percent or greater change in discharge has occurred.

16. All equipment is moved to the downstream section and steps 6 through 12 repeated as newly scheduled.

17. As the downstream dye cloud starts to recede, the centroid traveltimes upstream and downstream are estimated as 3 and 14 hours, respectively; thus, gas samples taken upstream and downstream 11 hours apart represent the same fluid element undergoing gas desorption.

18. As the downstream dye response curve continues to recede (fig. 28), it is estimated that its duration will be about 6 hours (18.5 hours - 12.5 hours). Furthermore, if the gas injection had been stable initially, a stable gas plateau would be reached at t = 18.5 hours. Since it didn't stablize until an hour after the start (see fig. 27), a stable gas plateau would be reached at t = 19.5 hours. Since this corresponds to 1:30 a.m. of the second day, a decision must be made to complete the test that night or the next morning.

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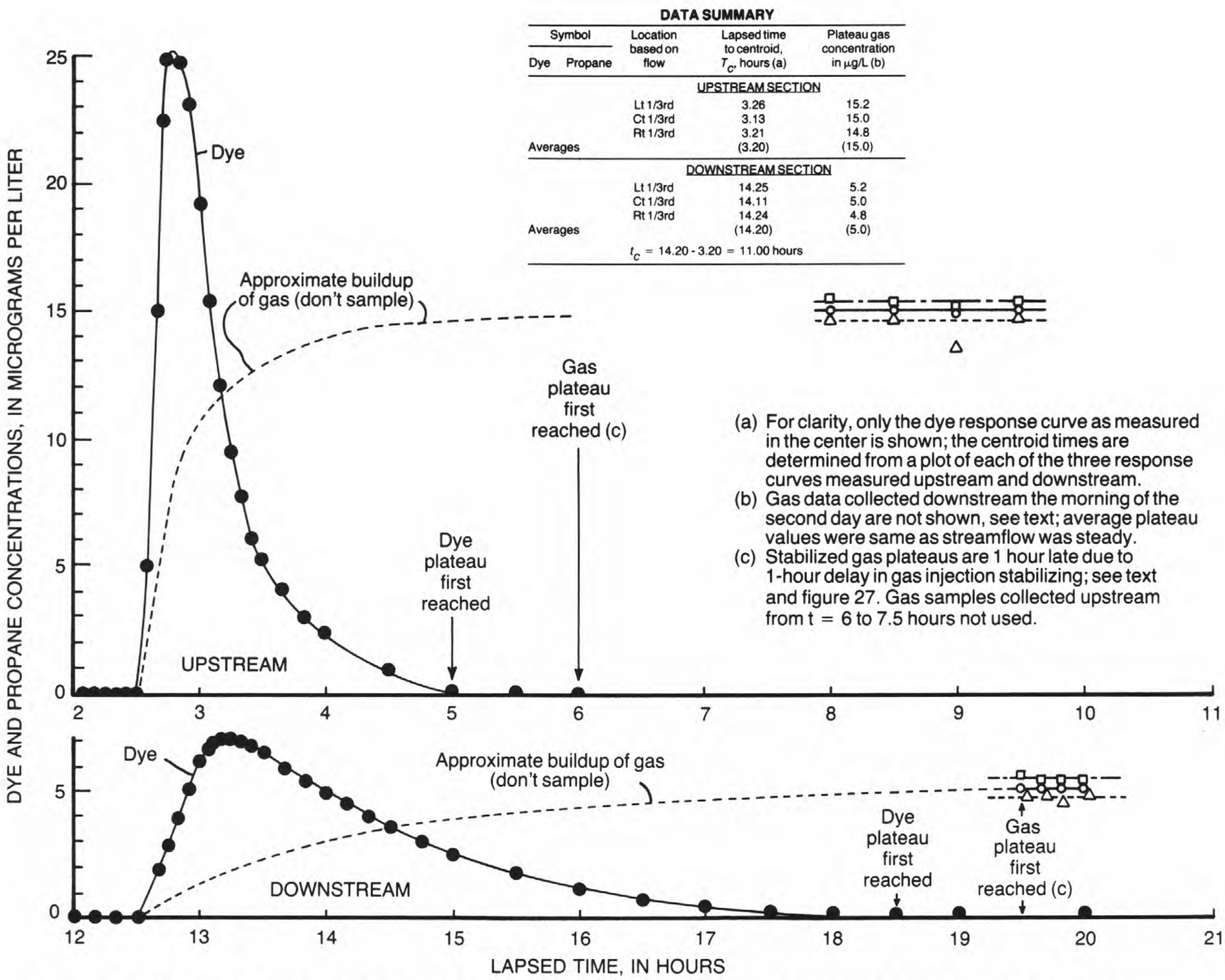
[1] See figure 15 in background reference 2.



DATA SUMMARY

Symbol Dye	 Propane	Location based on flow	Lapsed time to centroid, T_C, hours (a)	Plateau gas concentration in µg/L (b)
			UPSTREAM SECTION	
		Lt 1/3rd	3.26	15.2
		Ct 1/3rd	3.13	15.0
		Rt 1/3rd	3.21	14.8
Averages			(3.20)	(15.0)
			DOWNSTREAM SECTION	
		Lt 1/3rd	14.25	5.2
		Ct 1/3rd	14.11	5.0
		Rt 1/3rd	14.24	4.8
Averages			(14.20)	(5.0)

t_c = 14.20 - 3.20 = 11.00 hours

(a) For clarity, only the dye response curve as measured in the center is shown; the centroid times are determined from a plot of each of the three response curves measured upstream and downstream.

(b) Gas data collected downstream the morning of the second day are not shown, see text; average plateau values were same as streamflow was steady.

(c) Stabilized gas plateaus are 1 hour late due to 1-hour delay in gas injection stabilizing; see text and figure 27. Gas samples collected upstream from t = 6 to 7.5 hours not used.

Figure 28.--Tracer data acquired for constant-rate-injection method of reaeration measurement.

If the test is to be completed that night, gas sampling would be at t = 19.5 hours downstream to match samples taken upstream earlier at t = 8.5 hours (chosen so that t_c = 11 hours).

If the test is to be completed the next morning, the gas samples could be taken at t = 26 hours (8 a.m.) downstream and those collected upstream at t = 15 hours (9 p.m.) chosen as representative matching ones (t_c = 11 hours).

Note that continuous gas injection for 7 hours (19.5 - 12.5 hours) would be sufficient to _just_ establish a gas plateau at t = 19.5 hours. Thus, if the test is to be completed that night, the gas injection could have been terminated at 1 p.m. or if the next morning, at 7:30 p.m. of the first day (26.0 hours - 19.5 hours + 7 hours = 13.5 hours or 7:30 p.m.). Thus, in either case the gas injection could be safely terminated well in advance of sampling.

This example illustrates the importance of a timely field plot of the dye data for both upstream and downstream sections and knowledge of the important properties of the dye slug response in scheduling gas injection and sampling the overall test.

19. Since it was necessary to sample the downstream dye response curve through the night with the automatic sampler and recover them the next morning, it was decided to collect gas samples downstream at 1:30 a.m. and 8 p.m. every 10 minutes for 1/2 hour to be matched with gas samples upstream at about 2:30 p.m. and 9 p.m. Thus, duplicate sets of data would be available for analysis.

20. Gas injection was terminated at 10 p.m. of the first day and several rate checks made at this time (see fig. 27). This allowed time for sampling; furthermore, it was this hour ($t = 16$ hours) before sufficient dye data were available at the downstream section to permit the above decisions to be made.

21. All dye samples are stored out of direct light, gas samples are checked, caps tightened if necessary, and any containing gas bubbles discarded; the remainder are stored in ice chests with little or no chilling as required to maintain them at approximately stream temperature.

22. All samples are returned to the office. Fluorometer dye standards are prepared from a sample of the dye mixture that was injected. Note that the solution injected has a concentration of 0.952×10^7 µg/L in contrast to 20×10^7 µg/L for straight rhodamine WT.[1] This shortens the preparation of fluorometric standards as well as improves accuracy because the first serial dilution has in effect been made in the field and <u>is the same solution that was injected</u>.

23. All dye samples, standards, background samples, and stream samples are analyzed at one temperature. These dye-concentration-time data are plotted as in figure 28. Since two sets of gas data were collected, 48 gas samples are chosen for shipment to the laboratory. Each data set consists of 24 samples, 12 upstream and 12 downstream (four from each of three sampling points). The upstream and downstream samples were taken 11 hours apart such as to measure the gas desorption in essentially the same element of flow.

Data Analysis and Computations--Constant-Rate-Injection Method--One-Dimensional Dispersion

The dye concentration data obtained from reanalysis of samples in the laboratory and the propane gas concentration data are all plotted in figure 28 for both upstream and downstream sections. Just the dye data collected in the center are shown for clarity.

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[1] Using equation 7 in background reference 3.

As can be seen in figure 28, the dye concentration-time data plot smoothly, with the peak falling from 25.0 μg/L upstream to 7 μg/L downstream. A numerical integration of the six dye response curves such as is illustrated in columns 2 through 5 in table 9 for just the center response curves yields the centroid traveltimes shown in the Data Summary of figure 28. The average time of travel from upstream to downstream sections, t_c, was 11.00 hours.

Plateau gas concentrations were found to have dropped on the average from 15.0 μg/L upstream to 5.0 μg/L downstream. These data along with stream discharges may be used with equation 17 to compute an estimated propane gas desorption coefficient as

$$K_p = \frac{1}{t_c} \ln \frac{(\bar{c}_g Q)_u}{(\bar{c}_g Q)_d} = \frac{1}{11.00\ \text{h}} \ln \frac{(15.0\ \mu\text{g/L} \times 38\ \text{ft}^3/\text{s})}{(5.00\ \mu\text{g/L} \times 42\ \text{ft}^3/\text{s})} = 0.091\ \text{h}^{-1}$$

This value may be used as a basis for selecting trial values of K_p in equation 18. Equation 18 for propane may be expressed in the form

$$\left[\frac{(\bar{c}_g Q)_u}{(\bar{c}_g Q)_d}\right]_z = \left[\frac{\left[\sum_{i=1}^{N} \frac{C_d\ \Delta t}{A e^{K_p t_i}}\right]_u}{\left[\sum_{i=1}^{N} \frac{C_d\ \Delta t}{A e^{K_p t_i}}\right]_d}\right]_z \qquad (39)$$

where the individual dye response curves observed on a given streamline, z, upstream and downstream are numerically integrated. The computational process is shown in abbreviated form in columns 6 through 12 in table 9. Note that the normalizing of the dye concentration data involves dividing each by the total area of the specific response curve. The data and computations in table 9 are just for the center streamline (z = 50 percent) using dye data picked from the response curves shown in figure 28; a similiar procedure should be used for data on other streamlines such as at z = 16.7 and 83.3 percent if three points are chosen for observation. As seen in table 9, column 1, N = 32 and 34 were chosen to adequately define each response curve and resulted in Δt, the integration interval being 5 and 10 minutes upstream and downstream, respectively. The ratio $\Delta t/A_z$ becomes a constant for a given response curve; C_d values are the dye concentrations at i points, t_i being the elapsed time to each point. Since the approximate value of K_p was 0.091 h^{-1}, values of 0.090 and 0.100 h^{-1} were chosen for the first two trial computations; columns 7 through 10 in table 9.

As shown at the bottom of table 9, these two trial calculations produced ratios of 2.67 and 2.98. Interpolating for a measured value of 2.71 indicates K_p = 0.091 h^{-1}, or the same as estimated by equation 17. A third trial computation using K_p = 0.091 h^{-1} verifies this calculation.

Table 9.--Computation of areas, centroids, and desorption coefficient along center streamline (z = 50 percent), constant-rate-injection method, narrow stream

					Trial computation of K_p						
						Trial 1: K_p=0.090/h		Trial 2: K_p=0.100/h		Trial 3: K_p=0.091/h	
i	Elapsed time, t_i hours	Dye concentration C_d, (a) µg/L	Area increment C_d Δt (b) µg/L x hrs	Incremental moment t_i x Δt x C_d µg/L x $(hrs)^2$	$\frac{\Delta t}{A_z}$	$e^{K_p t_i}$	$\frac{\Delta t\ C_d}{A_z e^{K_p t_i}}$	$e^{K_p t_i}$	$\frac{\Delta t\ C_d}{A_z e^{K_p t_i}}$	$e^{K_p t_i}$	$\frac{\Delta t\ C_d}{A_z e^{K_p t_i}}$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
	UPSTREAM, CENTERLINE DYE RESPONSE CURVE										
1	2.58	5.00	0.42	1.08	0.005	1.261	0.020	1.294	0.019	1.265	0.020
2	2.67	15.00	1.25	3.34	.005	1.272	.058	1.306	.057	1.275	.058
3	2.75	25.00	2.08	5.72	.005	1.281	.096	1.317	.094	1.284	.096
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
30	5.00	0.25	0.02	0.10	.005	1.568	.001	1.649	.001	1.576	.001
31	5.08	.15	.01	.05	.005	1.580	0	1.662	0	1.588	0
32	5.17	.05	0	0	.005	1.592	0	1.677	0	1.601	0
			A_z = Σ = 16.81	Σ = 52.68		Σ = 0.755		Σ = 0.732		Σ = 0.753	
		T_{c_z} = 52.68/16.81 = 3.13 hrs									
	DOWNSTREAM, CENTERLINE DYE RESPONSE CURVE										
1	12.68	1.85	0.31	3.93	0.012	3.13	0.007	3.55	0.006	3.17	0.007
2	12.83	3.85	.64	8.21	.012	3.17	.015	3.61	.013	3.21	.014
3	13.00	6.30	1.05	13.65	.012	3.22	.023	3.67	.021	3.26	.023
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
32	17.83	0.15	0.03	0.53	.012	4.98	0	5.95	0	5.07	0
33	18.00	.10	.02	.36	.012	5.05	0	6.05	0	5.14	0
34	18.17	.05	.01	.18	.012	5.13	0	6.15	0	5.23	0
			A_z = Σ = 13.92	Σ = 196.40		Σ = 0.283		Σ = 0.246		Σ = 0.278	
		T_{c_z} = 196.40/13.92 = 14.11 hrs									
		Calculated $\left[\left(\sum_{i=1}^{N} \frac{C_d\ \Delta t}{A_z e^{K_p t_i}}\right)_u \Big/ \left(\sum_{i=1}^{N} \frac{C_d\ \Delta t}{A_z e^{K_p t_i}}\right)_d\right]_{z=50}$			=	$\frac{0.755}{0.283}$ = 2.67		$\frac{0.732}{0.246}$ = 2.98		$\frac{0.753}{0.278}$ = 2.71	

Measured $\left[[\bar{c}_g Q]_u / [\bar{c}_g Q]_d\right]_{z=50}$ = (38 ft³/s x 15.00 µg/L)/(42 ft³/s x 5.00 µg/L) = 2.71

(a) Dye concentrations are picked from response curves shown in figure 28.

(b) Δt = 5 minutes (0.083 hours) for upstream section and 10 minutes (0.167 hours) for downstream section.

Similar computations are performed with the dye and gas data collected on streamlines, z = 16.7 and z = 83.3; the results are summarized in table 10.

Table 10.--Summary of desorption and reaeration coefficient computations for constant rate injection method--one-dimensional dispersion

Streamline z, percent of flow	Measured $\frac{[\bar{c}_g Q]_u}{[c_g Q]_d}$ (a)	Final K_p as calculated by trial h^{-1}	Reach average $K_{2_{20}}$ h^{-1} (c)
16.7	$\frac{38 \times 15.20}{42 \times 5.20} = 2.64$	0.089	
50.0	$\frac{38 \times 15.00}{42 \times 5.00} = 2.71$	0.091 (b)	0.133
83.3	$\frac{38 \times 14.80}{42 \times 4.80} = 2.79$	0.094	

(a) See figure 28
(b) See table 9
(c) By equation 7

Information on a computer program to perform all the computation shown in table 9 is available form the Office of Surface Water in Reston, Virginia.

Wide Streams--Two-Dimensional Dispersion

Example

A reach on the Pat River will be used as an example in performing a CRI type reaeration test on a wide river where two-dimensional dispersion will likely exist; the reach is shown in figure 29. A reach approximately 4 miles long and 200 feet wide, averaging 1.5 feet deep, and having an average slope of 0.003 ft/ft is selected for the test. The reach is chosen for its uniformity, lack of inflow, lack of islands, and accessibility. A preliminary estimate of stream discharge is 150 ft^3/s; thus the average velocity is about 0.5 ft/s. The test reach will be comprised of four sections, an upstream section at L = 0 where the dye and gas injections will be made and three sampling sections downstream.

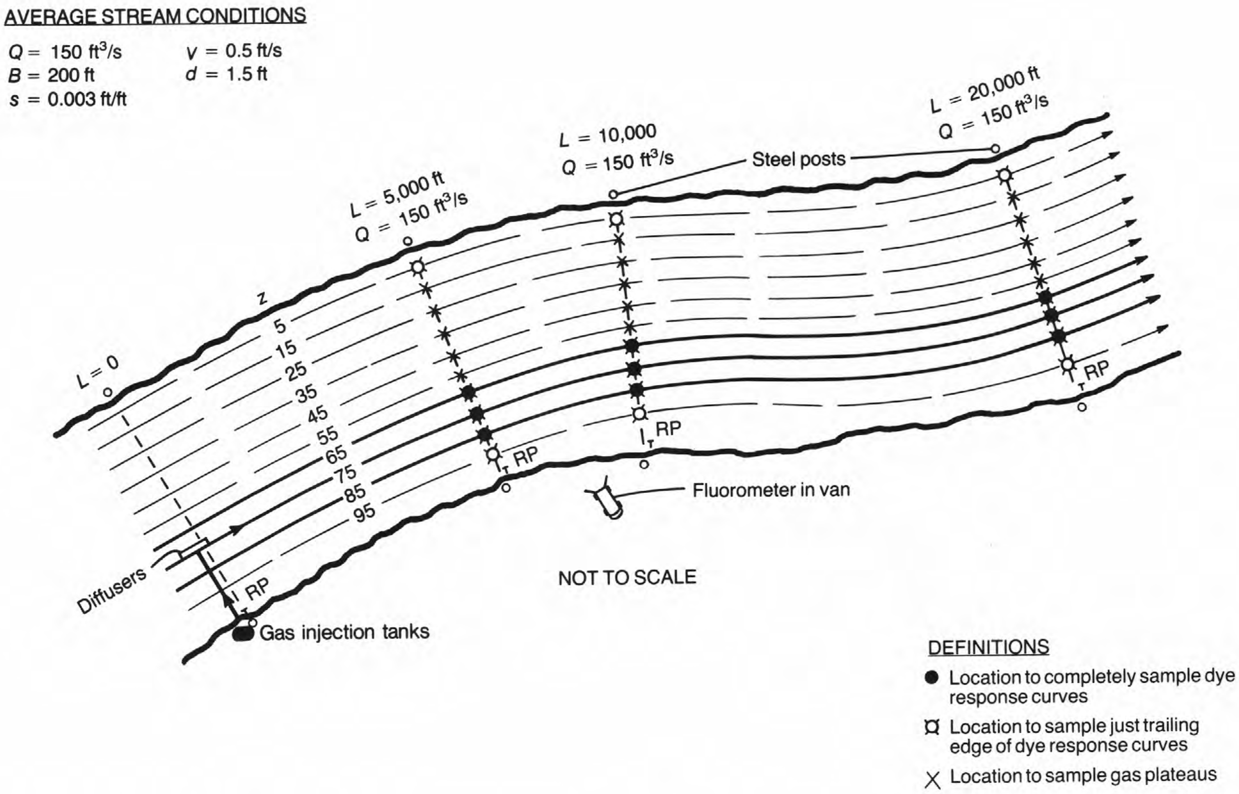

Figure 29.--Sketch of test reach on the Pat River showing layout for a constant-rate-injection type reaeration test on a wide river with two-dimensional dispersion.

Preliminary Tests, Planning, and Preparations

It is planned to perform the field test over a 3-day period. The first day would consist of site preparation and discharge and stage measurements. The second day would consist of a preliminary dye slug test with sampling at two or more sections downstream to determine the best test reach. These data would also be used in the integrations on the right side of equation 20 if stream discharge does not vary significantly during the 3 days. A constant rate gas injection would be performed the third day with or without a concurrent dye slug injection depending on whether or not there is a significant change in discharge by the third day and if the initial sections chosen prove satisfactory based on an analysis and interpretations of the preliminary dye slug test data. These data will provide true time-of-travel information and may require revision of the sections to obtain sufficient residence time or better mixing.

Selection of test reach

Equation 23 indicates that the optimum mixing length for an injection in the center would be

$$L_o = 0.1 \frac{vB^2}{E_z} = 0.1 \frac{(0.5)(200)^2}{0.11} \approx 18{,}200 \text{ ft.}$$

Thus, mixing might be expected to be good at the very end of the 4-mile reach; that is, a nearly one-dimensional (longitudinal) dispersion state will have been reached. Two-dimensional dispersion (lateral mixing and longitudinal dispersion) are expected to exist at sections closer to the injection point.

Equation 28 may be used to estimate a propane desorption coefficient for a 15,000-foot reach as

$$K_p = (0.039) \frac{\Delta H}{t_c} = (0.039 \text{ ft}^{-1}) \frac{(0.003 \text{ ft/ft})(15{,}000 \text{ ft})}{(15{,}000 \text{ ft}/0.5 \text{ ft/s})/(3{,}600 \text{ s/h})}$$

$$= (0.039) \frac{(45)}{(8.33 \text{ h})} = 0.21 \text{ h}^{-1}$$

Therefore, if the test was performed in a 15,000-foot reach, $K_p t_c \approx (8.33 \text{ h})(0.21 \text{ h}^{-1}) \approx 1.75$, which is >1.0 and would suggest a shorter reach, could be used. Since these are very approximate estimates, the decision is to initially locate measuring sections at 5,000, 10,000, and 20,000 feet downstream of the injection point.

Estimated elapsed times and durations

The elapsed times to the peaks, leading and trailing edges, and dye response curve durations at the three sections are estimated using an average velocity of 0.5 ft/s, figure 12, and equation 38 and summarized in table 11.

These are estimated average properties, and the dye cloud might be expected to arrive sooner along the center streamlines and later along the banks. Caution must therefore be used to avoid missing the early data. The decision is to begin sampling on streamlines z = 65, 75, and 85 percent at elapsed times of 1.5, 4, and 8 hours at the three sections.

Dye injection

Using the equation in figure 16, the quantity of 20 percent rhodamine WT dye to produce a peak of 5 µg/L at 20,000 feet would be 4,500 mL. An average peak of about 5 µg/L should be obtained at the 20,000-foot section with lower concentrations near the left streambanks, especially at the 5,000-foot section. For this reason, if in doubt, an amount of dye to produce an average peak of 10 µg/L or more could be used if no water-supply intakes existed in the test reach.

Table 11.--Summary of average dye response curve properties at three sections in proposed test reach on the Pat River

Property	Section at 5,000 ft	Section at 10,000 ft	Section at 20,000 ft
Elapsed time to peak, T_p, hours	2.78	5.56	11.11
Duration of entire dye response curve, T_D, hours (from figure 12 or equation $T_D = 3.1\ T_p^{0.67}$)	6.15	9.79	15.56
Elapsed time to leading edge, T_e, hours ($T_e = T_p - t_b$ where $t_b = (T_p^{0.86}/4)$)	2.18	4.47	9.13
Elapsed time to trailing edge, T_f, hours ($T_e + T_D$)	8.33	14.26	24.69

Gas injection

Water depths at the point of injection are known to be over 5 feet. This, and the availability of new diffusers, suggests the efficiency of the gas injection system might be as high as 20 percent. An average plateau concentration of 5 µg/L at the downstream section will be sought and this value used in computing the gas injection rate. Using figure 11, with a peak traveltime of 11.11 hours (for 20,000 feet), an estimated K_p of 0.21 h^{-1}, an average gas plateau of 5 µg/L, and ε equal to 0.2 yields a propane injection rate of 75 ft^3/h. This exceeds the upper limit of the gas rate controller. The scale on the right of figure 11 indicates this rate is equivalent to about 8.5 lbs/h. Table 11 indicates a maximum cloud duration of 15.56 hours which is the length of gas injection needed if preliminary estimates are correct. This amounts to a total of about 132 lbs of propane, thus two 100-lb tanks will be required and allow the injection rate for each tank to be about 38 ft^3/h of propane. Using equation 34, the air rate to be set on each rotameter will be about 17 lbs/ft^3.

Performance of Test

Preparations

The first day, the four sections comprising the test reach are monumented with steel posts on both banks. Stage reference points are established on the right bank of all four sections. Taglines are stretched across at the four sections and conventional boat-type current-meter discharge measurements made; stage is measured concurrent with each discharge measurement. The measurements are computed immediately with discharge recorded accumulatively. Ten points are then located on each taglined section at the 5,000-, 10,000-, and 20,000-foot distances. As shown in table 5, the 10 points are located at the 5-, 15-, 25-, ... 75-, 85-, and 95-percent cumulative discharge points at each section. To avoid collisions with passing boats, the taglines were removed after the sampling points had been marked by bouys.

The decision was to locate the point of injection or source streamline on the 75-percent streamline as this allowed the propane tanks to be located on the right bank and feed the diffusers via 100-foot plastic lines. Furthermore, at this point water depths were found to be about 6 feet, thus the efficiency of the gas injection might be expected to be high.

Dye test

At 6 a.m. ($t = 0$) of the second day, a slug of 4,500 mL of 20-percent rhodamine WT premixed with 15,500 mL of river water was injected at $z = 75$ at section 1. A 100-mL sample of the mixture was retained for later fluorometric analysis.

Dye sampling was initiated at $t = 1.5$, 4, and 8 hours downstream at the 5,000-, 10,000-, and 20,000-foot sections only on streamlines 65, 75, and 85. Dye samples were rapidly analyzed using a fluorometer located on the right bank near the three sections. As seen in figure 30 along the $z = 75$ streamline, the leading edges arrived at $t = 2.58$, 6.00, and 12.68 hours which was considerably slower than estimated in table 1.[1]

At $z = 65$, 75, and 85 at the three sections, dye sampling was continued until background levels were reached or could be estimated. As soon as dye concentrations approached background levels at $z = 65$, 75, and 85, dye samples were collected at $z = 5$ and 95 until the dye cloud was found to have essentially passed in its entirety. The longer durations measured along the banks would dictate the length of gas injection the next day and also determine when gas concentrations had plateaued across each section and could be sampled to determine ϕ. Figure 30 is a plot of these data for the three sections.

Based on these field plots of the dye response curves, the decision is to use all three sections in the gas test and thus two sets of data will be available: 5,000 to 20,000 feet and 10,000 feet to 20,000 feet.

All dye samples are forwarded to the laboratory for final analysis.

Frequent stage measurements indicated stream discharge to be constant from $t = 0$ through the passage of the dye cloud. Nevertheless, a current-meter measurement was made at the 10,000-foot section at $t = 10$ hours.

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[1] The reader will note that for simplicity and comparison purposes, the dye response curves used in the previous example will be used here as applying to $z = 75$ at the 5,000- and 20,000-foot sections, respectively. Furthermore, the data plotted in figure 30 are those obtained later in the laboratory following careful fluorometric analysis but is discussed here as if it were the field data plots.

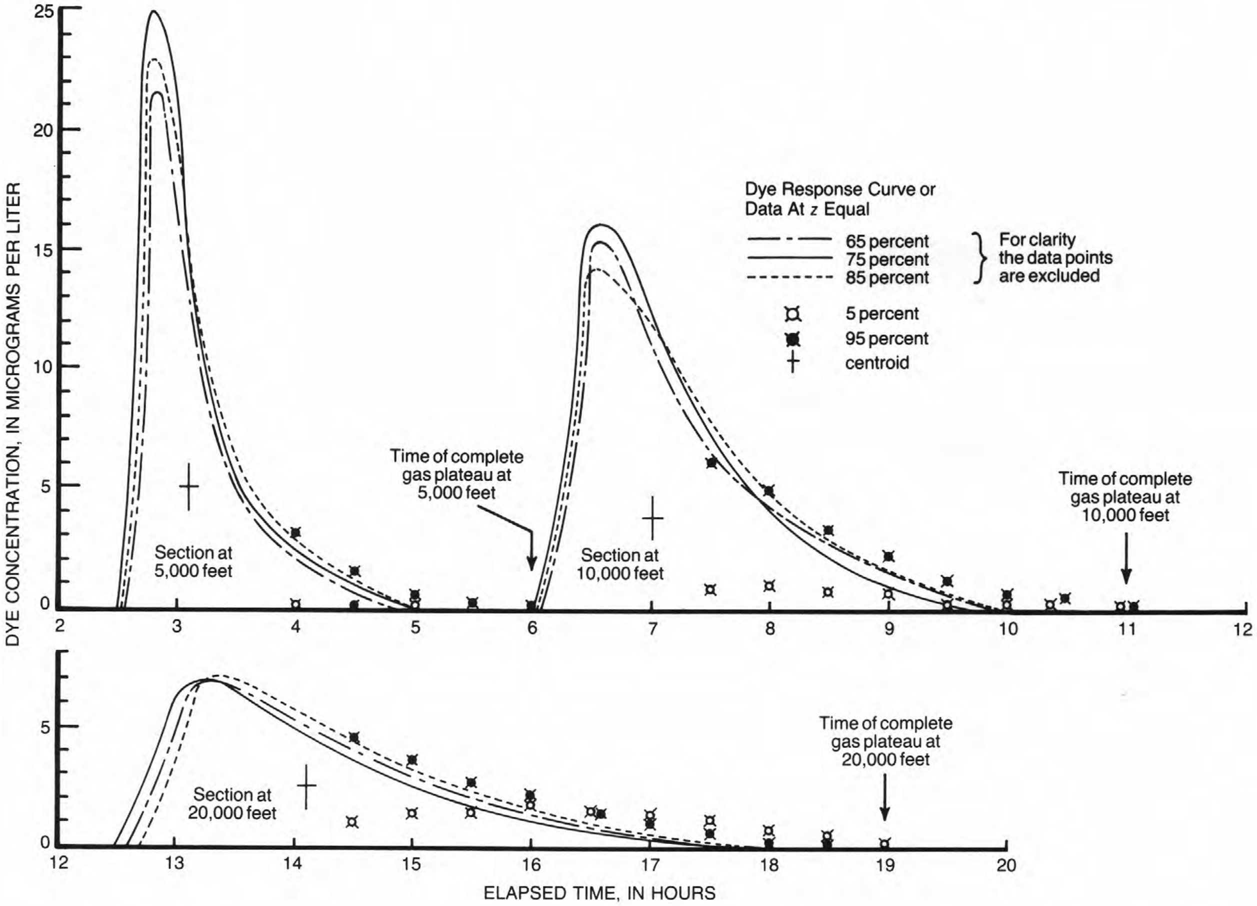

Figure 30.--Dye tracer response curves and data for constant-rate-injection method of reaeration measurement with two-dimensional dispersion.

Propane test

The dye response curves and data obtained as a result of an actual slug injection and sampling as shown in figure 30 are extremely valuable in determining exact information on the duration of gas injection required and when stable gas plateaus will exist downstream for sampling. The complete dye response curves shown in figure 30 are for the 65-, 75- (source streamline), and 85-percent streamlines and because of their uniformity suggest good mixing for the part of the channel sampled. However, had dye response curves been measured at all streamlines, particularly those left of the source streamline, ever smaller curves would have been observed, indicating incomplete mixing over the channel width. As the dye samples taken at z = 5 and 95 percent indicate, very low concentrations would exist along the banks, particularly the left bank at the 5,000-foot section. Similarly, lateral mixing would not be too good even at the 20,000-foot section as injection at the 75-percent streamline amounts to a partial side injection.

The fully defined dye response curve data are used subsequently in the computation of K_p. The selected dye samples taken at z = 5 and 95 percent were obtained to show when stable gas plateaus would exist at each section, particularly at the 20,000-foot section. In the example, if gas injection was sufficiently long, stable plateaus would exist at 6.0, 11.0, and 19.0 hours elapsed times at the 5,000-, 10,000-, and 20,000-foot sections, respectively.

Inspection of figure 30 indicates centroid traveltimes of approximately 11 hours between sections 5,000 and 20,000 feet and 7 hours between 10,000 and 20,000 feet. Thus, if gas sampling were performed at t = 19 hours at the 20,000-foot section, it should be performed at t = 8 and 12 hours at the 5,000- and 10,000-foot sections, respectively, to represent the same water mass in transport in which gas is being desorbed. Thus, inspection of figure 30 indicates stable plateaus will have existed for 2 hours (8 - 6 hours) at the 5,000-foot section and 1 hour (12 - 11 hours) at the 10,000-foot section.

The dye data at the 20,000-foot section also indicate a <u>minimum</u> gas injection of 6.5 hours (19.00 - 12.50) would be required. Obviously it would be desirable to inject longer to allow time for sampling the gas at 20,000 feet.

Two 100-lb propane tanks were positioned on a platform scale and shielded with a protective enclosure. Eight diffuser plates were placed in a longitudinal line at z = 75, four diffusers being supplied by each tank. A gas injection of approximately 38 ft^3/h was started from each tank at 10 p.m. (t = 0 for the gas data) of the second day for 10 hours, and turned off at 8 a.m. of the third day. Gas sampling would be performed at t = 9 hours (7 a.m.), 13 hours (1 p.m.), and 20 hours (6 p.m.) at 5,000, 10,000, and 20,000 feet, respectively, on the third day. At these times at each of the 10 streamlines, four gas samples were taken in quick succession.

Observations of stage throughout the third day indicated only minor changes. Discharge measurements were made at the 5,000-foot section at 9 a.m. and at the 20,000-foot section at 5 p.m. No significant changes were noted. Had there been significant change, ± 10 percent, it would have been necessary to repeat the dye test along z = 65, 75, and 85 percent.

Analysis and Computations

Dye data

All dye samples along with background samples and a sample of the dye solution injected were returned to the laboratory for careful analysis. Figure 30 shows the dye response curves as measured at z = 65, 75, and 85 at all three sections. The response curves on z = 75 are made solid as it is this data for the 5,000-foot and 20,000-foot sections that will be used subsequently in the computations.

Gas data

Of the 120 gas samples collected, selected ones were submitted for laboratory analysis. The results are shown in figure 31 plotted from left to right with cumulative discharge on streamlines. As can be seen, lateral mixing between the injection point and the 5,000-foot section was insufficient to yield any gas concentrations along the left bank and only very low concentrations at the 10,000-foot section. Similarly, lateral mixing is still not

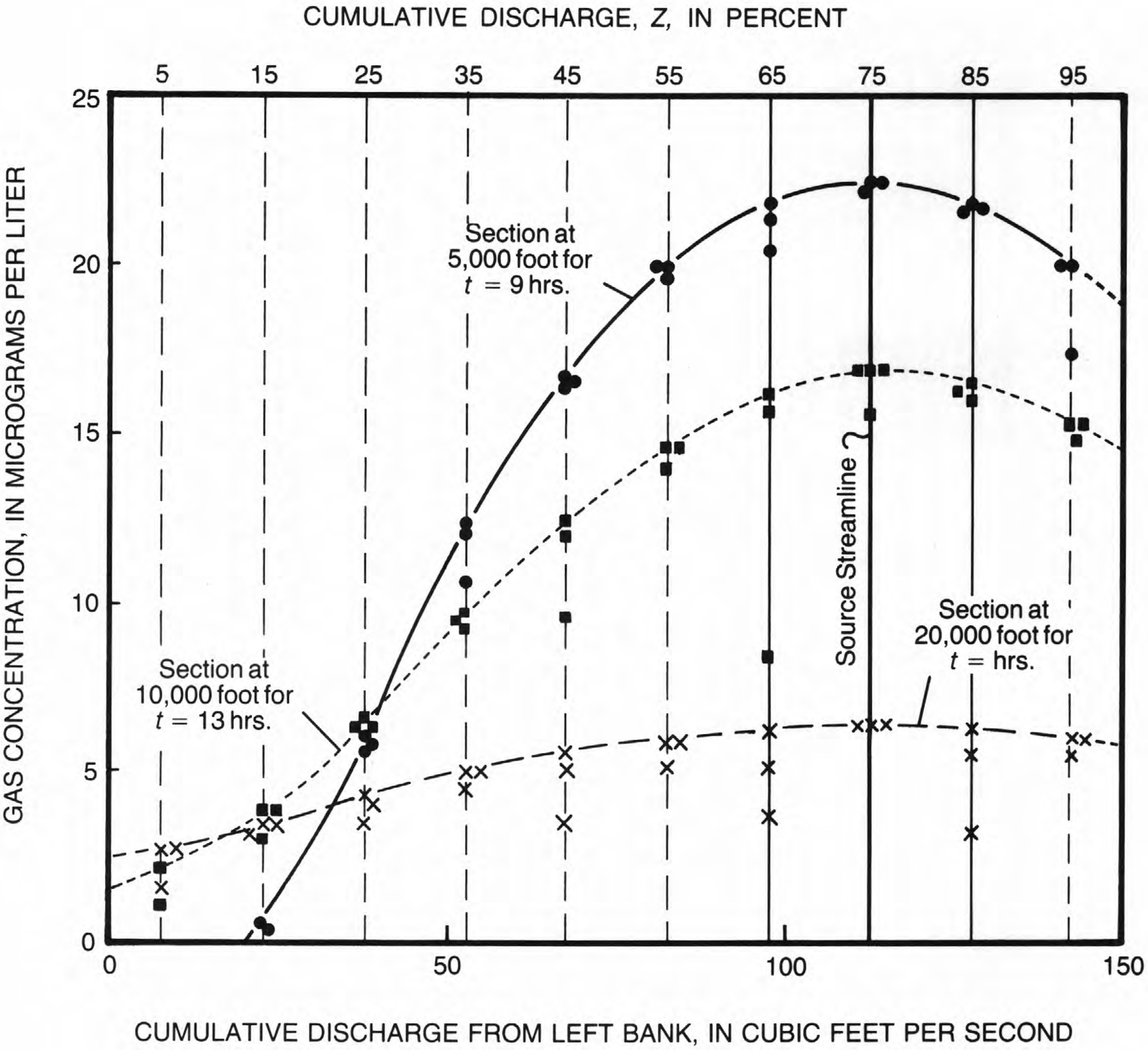

Figure 31.--Lateral distribution of plateau gas concentrations at the three measuring sections on the Pat River.

complete at the 20,000-foot section due primarily to the injection being at z = 75 percent instead of 50 percent. This amounts to a partial side injection. Theoretically (Kilpatrick and Cobb, 1985), a side injection requires four times the distance to mix as a center injection; these data would tend to confirm this.

Average gas plateau concentrations are selected for computing the distribution factor ϕ using equation 22. These computations are shown in table 12 for the 5,000-, 10,000-, and 20,000-foot sections. Note that zero concentrations were present at the 5,000-foot section but posed no problem in computing ϕ.

Table 12.--Computation of distribution factor ϕ at the 5,000-, 10,000-, and 20,000-foot sections using gas concentration plateaus for the Pat River

z in percent	$\bar{c}_g$ μg/L	$\frac{\Delta Q_z}{Q}$	$\bar{c}_g \frac{\Delta Q}{Q}$	$\phi_z = \frac{\bar{c}_g}{\sum \bar{c}_g \frac{\Delta Q}{Q}}$
		5,000-FOOT SECTION		
5	0	0.1	0	
15	0.50	.1	.05	0.035
25	6.00	.1	.60	.424
35	12.20	.1	1.22	.862
45	16.70	.1	1.67	1.179
55	20.0	.1	2.00	1.412
65	21.8*	.1	2.18	1.540*
75	22.5**	.1	2.25	1.589**
85	21.9*	.1	2.19	1.547
95	20.0	.1	2.00	1.412
		1.0	Σ = 14.16	
		10,000-FOOT SECTION		
5	2.1	0.1	0.21	0.184
15	3.7	.1	0.37	.324
25	6.6	.1	0.66	.578
35	9.7	.1	0.97	.850
45	12.3	.1	1.23	1.078
55	14.6	.1	1.46	1.280
65	16.2	.1	1.62	1.420*
75	16.9	.1	1.69	1.402**
85	16.6	.1	1.66	1.455*
95	15.4	.1	1.54	1.350
		1.0	Σ = 11.41	
		20,000-FOOT SECTION		
5	2.6	0.1	0.26	0.506
15	3.4	.1	0.34	.661
25	4.2	.1	0.42	.817
35	4.9	.1	0.49	.953
45	5.5	.1	0.55	1.070
55	5.9	.1	0.59	1.148
65	6.2*	.1	0.62	1.206*
75	6.4**	.1	0.64	1.245**
85	6.3*	.1	0.63	1.226*
95	6.0	.1	0.60	1.167
		1.0	Σ = 5.14	

*Used to compute K_p along streamlines adjacent to source streamline.

**Used to compute K_p along source streamline; see table 13.

Computation of desorption coefficient

Equation 20 may now be numerically integrated in similar fashion as was equation 18 to yield an equation which includes the ratio of the distribution factors applicable to each streamline.

$$\left[\frac{(\bar{c}_g Q)_u \phi_d}{(\bar{c}_g Q)_d \phi_u}\right]_z = \left[\frac{\left[\sum_{i=1}^{N} \frac{C_d\ \Delta t}{Ae^{K_p t_i}}\right]_u}{\left[\sum_{i=1}^{N} \frac{C_d\ \Delta t}{Ae^{K_p t_i}}\right]_d}\right]_z \qquad (40)$$

Computations must be along given streamlines; in this example streamlines z = 65, 75, and 85. The numerical integration computations are as previously demonstrated in table 9 for the one-dimensional case and will not be repeated. As before, an initial value of K_p may be estimated from equation 17 (along streamline z = 75) as

$$K_p = \frac{1}{t_c} \ln \frac{(\bar{c}_g Q)_u \phi_d}{(\bar{c}_g Q)_d \phi_u} = \frac{1}{10.98} \ln \left[22.50 \times \frac{150}{10} \Big/ 6.40 \times \frac{150}{10}\right]$$

$$K_p = \frac{1}{10.98} \ln\ [3.52]\ [0.784] = 0.092\ h^{-1}.$$

Note that the appropriate distribution factors have been applied to equation 17. This estimate is considerably less than the value of 0.21 h^{-1} originally used in planning but since it is based on actual data and is corrected for distribution it should be close to the correct value. Trial computations were made along streamlines 65, 75, and 85 for both reaches until the ratio on the right side of equation 37 was in agreement with the left. Table 13 shows a summary of K_p and K_2 as determined for z = 65, 75, and 85 for both reaches. Note that in column 2 of table 13 that the gas transport ratios are approximately 2.75 as the residence time was sufficient from 5,000 feet to 20,000 feet to produce a large desorption of gas. In contrast, from 10,000 to 20,000 feet the desorption was less and the gas transport ratios in column 4 vary from 2.22 to 2.34; thus more weight was given the data for the longer reach.

A point to be made is that because initial estimates of K_p may be considerably in error, the product $K_p t_c$ used in initial planning should probably be significantly larger than 1.00 (or $(\bar{c}_g Q)_u/(\bar{c}_g Q)_d$ significantly larger than 2.72). Furthermore, if data collection is comprehensive, sufficient residence time can be obtained by placing the upstream measuring section closer to the injection point in a region where two-dimensional dispersion exists but adjusting the data by computing distribution factors.

Table 13.--Summary of desorption and reaeration coefficient computations for constant-rate-injection method--two-dimensional dispersion

	Reach 5,000 to 20,000 feet		Reach 10,000 to 20,000 feet		
Streamline z, percent of flow	Measured $\left[\frac{[\bar{c}_gQ]_u\phi_d}{[\bar{c}_gQ]_d\phi_u}\right]_z$ (a)	Final K_p as calculated by trial h^{-1} (b)	Measured $\left[\frac{[\bar{c}_gQ]_u\phi_d}{[\bar{c}_gQ]_d\phi_u}\right]_z$ (a)	Final K_p as calculated by trial h^{-1} (b)	Average $K_{2_{20}}$ for 5,000- to 20,000-foot reach h^{-1} (c)
(1)	(2)	(3)	(4)	(5)	(6)
65	$\frac{21.8 \times 15 \times 1.206}{6.2 \times 15 \times 1.540} = 2.75$	0.092	$\frac{16.2 \times 15 \times 1.206}{6.2 \times 15 \times 1.420} = 2.22$	0.110	
75	$\frac{22.5 \times 15 \times 1.245}{6.4 \times 15 \times 1.589} = 2.76$	0.092	$\frac{16.9 \times 15 \times 1.245}{6.4 \times 15 \times 1.402} = 2.34$	0.115	0.13
85	$\frac{21.9 \times 15 \times 1.226}{6.3 \times 15 \times 1.547} = 2.75$	0.092	$\frac{16.6 \times 15 \times 1.226}{6.3 \times 15 \times 1.455} = 2.22$	0.110	

(a) See figure 31 and table 12
(b) By equation 40
(c) For stream temperature of 18 °C

REGIONALIZATION

As in most hydrologic studies, it is impractical to attempt to measure all streams for their reaeration coefficient; hence, numerous emperical equations have been developed to apply to a given region. Many of these depend on the evaluation of other parameters of pertinence to the reaeration capabilities of streams. Thus, when performing gas and dye tracer reaeration measurements, other parameters should be measured or estimated to further regionalization efforts or the development of better emperical equations and models.

Other Data Needs

In all instances, measurements of channel and hydraulic properties should be made. These normally include width, mean depth, hydraulic roughness, and longitudinal slope. The type of stream should be noted; for example, is it pool and riffle or does channel control exist in most of the test reach. All of the above change with river stage; hence, reaeration measurements at more than one stage on the same stream may be advisable.

On wide and/or exposed streams, the measurement of wind speed and direction relative to the orientation of the stream is desirable. Yotsukura and others (1984) suggest that one well placed wind speed and direction meter would be sufficient in most cases.

Since relative humidity and water and air temperatures influence desorption, their measurement is advisable.

The gas transfer process can also be affected by changes in water-quality parameters such as methylene blue active substances as an indicator of detergent concentrations, color as an indicator of the concentration of organic acids, specific conductance as an indicator of dissolved solids concentrations, and suspended solids as an indicator of suspended inorganic concentrations in the water column (Bennett and Rathbun, 1972).

When sufficient data become available, it may become possible to estimate reaeration coefficients from photographs of the stream reach. Thus, representative photographs of the stream reach <u>at the flow being tested</u> are advisable.

SUMMARY AND CONCLUSIONS

This manual describes in detail how to perform reaeration measurements on streams using dye and gas tracers injected concurrently or in tandem to simulate oxygen absorption. Two basic approaches are presented differing in the mode of injection and hence sampling; both have their advantages and disadvantages. Both, though, require greater effort and care in their performance than is the case for most other type tracer studies if accurate results are to be obtained. But both are fully within the capabilities of the average hydrologist. They should first be familiar with routine dye tracer and fluorometry techniques before attempting tracer reaeration type measurements; these are well described in the other manuals available in this series (Hubbard and others, 1982; Kilpatrick and Cobb, 1985; Wilson and others, 1986).

The equipment required for either type test is essentially the same. It is suggested that the Constant-Rate-Injection Method has certain advantages over the Slug-Injection Method because:

1. A simple slug injection of dye rather than a constant rate injection is required.

2. Sampling of the dye response curves is essentially the same for both methods but the CRI method may require less gas sampling; an exception would be for wide rivers where more extensive sampling is required.

3. The CRI method can be used in narrow as well as wide rivers where two-dimensional dispersion exists. That the test may be performed closer to the point of injection and, hence, in a region where two-dimensional dispersion may exist, allows longer test reaches to be utilized; and, hence, the accuracy that occurs with greater gas residence times is obtained.

While not emphasized during the description of the SI method, the occurrence of two-dimensional dispersion with such a test (intentionally or otherwise) can be adjusted for by use of the same lateral distribution correction factors as were used with the CRI method. To do so would require extensive definition of the dye response curves laterally at the measuring sections. The determination of ϕ by measurement of plateau gas concentrations laterally as is done in the CRI method is a much more practical approach; hence, the CRI method is particularly recommended for wide streams.

This report has provided sufficient detail and examples to allow manual computation of desorption coefficients by a variety of methods. Some of the computations are very laborious and more easily performed by computer. The Office of Surface Water has prepared a program to perform most of the computations for both the SI and CRI methods. The program is tailored to conform to the data collection and analysis procedures discussed in this report; its use is encouraged.

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