



Techniques of Water-Resources Investigations of the United States Geological Survey

Chapter A18

DETERMINATION OF STREAM REAERATION COEFFICIENTS BY USE OF TRACERS

By F.A. Kilpatrick, R.E. Rathbun, N. Yotsukura,
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PREFACE

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The unit of publication, the chapter, is limited to a narrow field of subject matter. This format permits flexibility in revision and publication as the need arises. Chapter A18 deals with the application of dye and gas tracers for the measurement of stream reaeration coefficients.

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- TWI 5-A2. Determination of minor elements in water by emission spectroscopy, by P.R. Barnett and E.C. Mallory, Jr. 1971. 31 pages.
- TWI 5-A3. Methods for the determination of organic substances in water and fluvial sediments, edited by R.L. Wershaw, M.J. Fishman, R.R. Grabbe, and L.E. Lowe. 1987. 80 pages. This manual is a revision of "Methods for Analysis of Organic Substances in Water" by Donald F. Goerlitz and Eugene Brown, Book 5, Chapter A3, published in 1972.
- TWI 5-A4. Methods for collection and analysis of aquatic biological and microbiological samples, edited by P.E. Greeson, T.A. Ehlke, G.A. Irwin, B.W. Lium, and K.V. Slack. 1977. 332 pages.
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- TWI 7-C1. Finite difference model for aquifer simulation in two dimensions with results of numerical experiments, by P.C. Trescott, G.F. Pinder, and S.P. Larson. 1976. 116 pages.
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- TWI 8-A1. Methods of measuring water levels in deep wells, by M.S. Garber and F.C. Koopman. 1968. 23 pages.
- TWI 8-A2. Installation and service manual for U.S. Geological Survey monometers, by J.D. Craig. 1983. 57 pages.
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METRIC CONVERSION FACTORS

<i>Multiply inch-pound unit</i>	<i>By</i>	<i>To obtain metric unit</i>
inch (in)	25.40	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
pound (lb)	453.6	gram (g)
gallon (gal)	3.785	liter (L)
gallon (gal)	3,785	milliliter (mL)
foot per second (ft/s)	0.3048	meter per second (m/s)
square inch (in ²)	0.000645	square meter (m ²)
square foot per second (ft ² /s)	0.09294	square meter per second (m ² /s)
cubic foot (ft ³)	0.02832	cubic meter (m ³)
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)
parts per billion (lb/10 ⁹ lb)	≈1.0	microgram per liter (μg/L)

SYMBOLS AND UNITS

<i>Symbol</i>	<i>Explanation</i>	<i>Unit</i>	<i>Symbol</i>	<i>Explanation</i>	<i>Unit</i>
A_c	Area of the observed dye concentration-time response curve	($\mu\text{g/L}$)(min) or ($\mu\text{g/L}$)(h)	Q	Total stream discharge	ft^3/s
A_z	Area of the observed dye concentration-time response curve measured on a streamline, z	($\mu\text{g/L}$)(min) or ($\mu\text{g/L}$)(h)	ΔQ_z	Portion of total stream discharge applicable to a streamline	ft^3/s
A_g	Area of the gas concentration-time response curve	($\mu\text{g/L}$)(min) or ($\mu\text{g/L}$)(h)	Q_z	Cumulative stream discharge laterally in the cross section at streamline z	ft^3/s
B	Average width of stream	ft	Q_m	Maximum discharge in test reach	ft^3/s
\bar{c}	Weighted or average plateau dye concentration	$\mu\text{g/L}$	R_e	Ratio of oxygen reaeration rate coefficient to ethylene gas desorption rate coefficient	---
\bar{c}_g	Weighted or average plateau gas concentration	$\mu\text{g/L}$	R_p	Ratio of oxygen reaeration rate coefficient to propane gas desorption rate coefficient	---
C	Concentration of injected dye solution	$\mu\text{g/L}$	RP	Reference point	---
C_d	Observed dye concentration	$\mu\text{g/L}$	R_r	Dye recovery ratio	---
C_g	Observed gas concentration	$\mu\text{g/L}$	s	Water-surface slope	ft/ft
C_p	Observed peak dye concentration	$\mu\text{g/L}$	S_G	Specific gravity	---
d	Mean depth of stream; also a subscript denoting downstream	ft	Δt	Numerical intergration interval	min or h
e	A constant, 2.72	---	t	Elapsed time from start of injection	h
E_z	Lateral or transverse mixing coefficient	ft^2/s	t_b	Interval of time for dye concentrations to build up from the leading edge to the peak	h
ΔH	Change in elevation in test reach	ft	$t_{c,L,t,p}$	Travelttime of centroid, leading edge, trailing edge, and peak, respectively, of dye-response curve	h
i	Integration interval	---	t_i	Elapsed time to point i on response curve	h
J	Dye-loss correction factor	---	$T_{c,L,t,p}$	Elapsed time to centroid, leading edge, trailing edge, and peak, respectively, of dye-response curve	h or min
K_2	Oxygen absorption or reaeration rate coefficient	h^{-1}	T_d	Duration in time for dye cloud to pass any one point in a section	h or min
K_{20}	Oxygen absorption or reaeration rate coefficient at 20 °C	h^{-1}	T_D	Duration in time for entire tracer cloud to pass section	h or min
K_e	Ethylene gas desorption rate coefficient	h^{-1}	u	Subscript denoting upstream	---
K_p	Propane gas desorption rate coefficient	h^{-1}	V_d	Volume of dye solution	mL
K_{PY}	Propane gas desorption rate coefficient at stream temperature Y	h^{-1}	V_I	Volume of dye solution injected into stream	L or mL
K_{P20}	Propane gas desorption rate coefficient at 20 °C	h^{-1}	V_s	Volume of stock dye solution	L or mL
K_T	Tracer gas desorption rate coefficient	h^{-1}	V_w	Volume of diluent, usually distilled water	mL
K_{T20}	Tracer gas desorption rate coefficient at 20 °C	h^{-1}	v	Mean stream velocity	ft/s
K_{TY}	Tracer gas desorption rate coefficient at temperature Y	h^{-1}	v_p	Velocity of peak	ft/s
K_{Tz}	Tracer gas desorption rate coefficient along a streamline, z	h^{-1}	W_d	Weight of dye injected	g
L	Length of measurement reach	ft	W_r	Weight of dye recovered	g
L_o	Channel length required for optimum mixing; usually corresponds to about 95-percent mixing	ft	z	Streamline index, expressed as a percentage of total river discharge: $z=100 Q_z/Q$; also used as a subscript to denote a streamline	percent
M	Mass of tracer injected	g	ϵ	Absorption efficiency, expressed as a decimal	---
$M_{1,2,3,\dots,n}$	Series of slug injections of equal mass	g	ϕ	Mass distribution	---
P_g	Pressure at which the gas is metered	lb/in^2	Y	Stream temperature	°C
q	Rate of constant dye tracer injection	mL/min	Y_g	Temperature at which gas is metered	°F
q_a	Air injection rate	ft^3/h			
q_g	Rate of constant gas tracer injection	ft^3/h			
q_p	Constant-rate gas injection at standard conditions of 70 °F and 14.7 psia	ft^3/h , L/min, or lb/h			

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

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 whereby a radioactive tracer gas was injected into a stream—the principle being that the tracer gas would be *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 measuring gas-tracer desorption. 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, on methods of injection, sampling, and analysis, and on techniques for computing 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 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 dissolved oxygen, are used to calculate waste-load allocations for the stream so that dissolved-oxygen concentration standards are not violated. If the reaeration coefficient used in a model is smaller than the actual coefficient for the stream, 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 for the stream, the degree of waste treatment indi-

cated by the model results will be insufficient and dissolved-oxygen standards may be violated. Management of the dissolved-oxygen 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 dissolved-oxygen 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, E.C. 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 of less than 200 ft³/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, R.E. Rathbun (Rathbun and others, 1975; Rathbun and others, 1978) modified the technique (hence, it is frequently called the "modified method"): 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 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 *slug* injection of the gas tracer into the stream and subsequent measurement of its desorption as it moved and dispersed downstream. To be consistent with other tracer manuals and with 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) and Parker and Gay (1987), which features *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 longitudinal dispersion is not complete. Although preliminary, the field techniques and methods of analysis are presented in this manual to encourage their use and further development.

The authors wish to acknowledge the many contributions of others to the development of the techniques presented in this manual. In particular, we are indebted to E.C. Tsivoglou for providing the basic theory and techniques for indirectly measuring stream reaeration; his work has spawned many similar reaeration measuring techniques as well as broadened our understanding of gas transfer at water surfaces. More specifically, we are indebted to Merritt Blalock for developing the supporting computer programs and to Frederick Gay, David Stedfast, James Smoot, Kenneth Taylor, and numerous others for their data as well as helpful comments on equipment and procedures.

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 background reference, 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 is vital to their successful performance. For continuity and convenience, some of the information available in these reports is presented again. For consistency, symbols and definitions are 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 measures necessary for an adequate analysis to meet the intended use. For example, background reference 2 suggests low and high levels of study commensurate with the objectives of the study for time-of-travel tests. Conversely, background 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

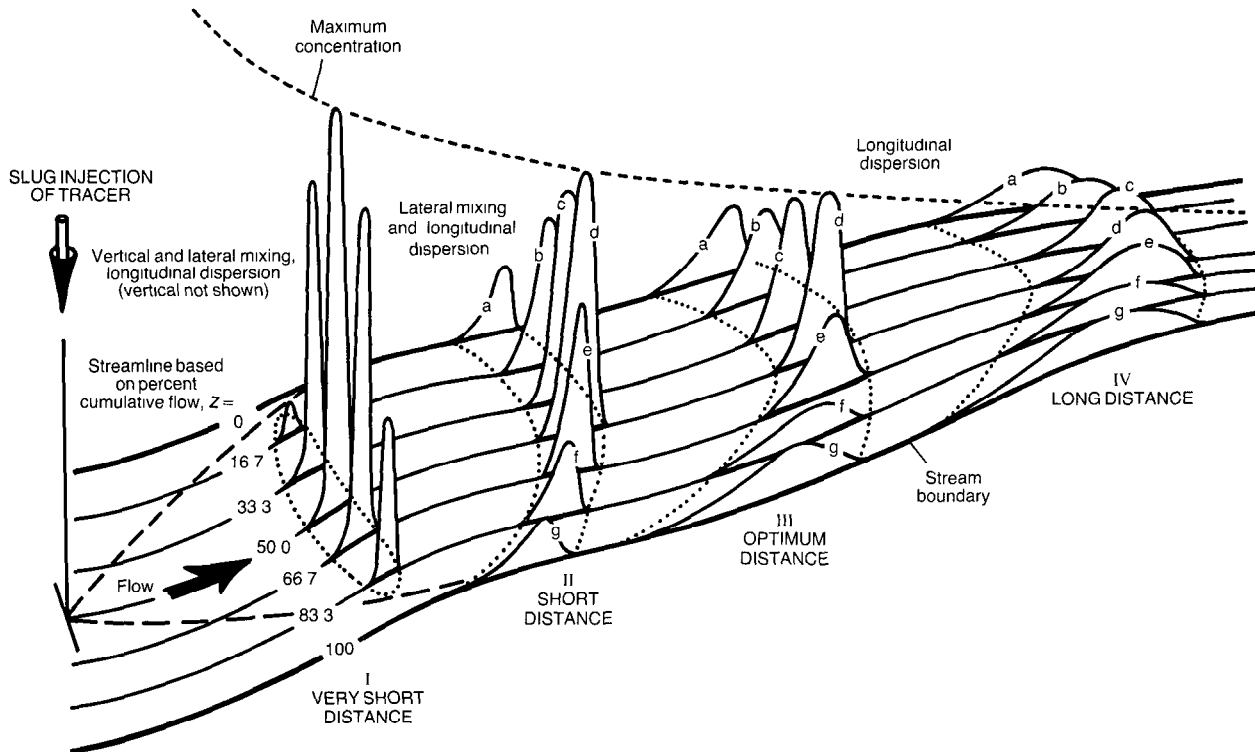


Figure 1.—Lateral mixing and longitudinal dispersion patterns and changes in distribution of concentration downstream from a single, center slug injection of tracer.

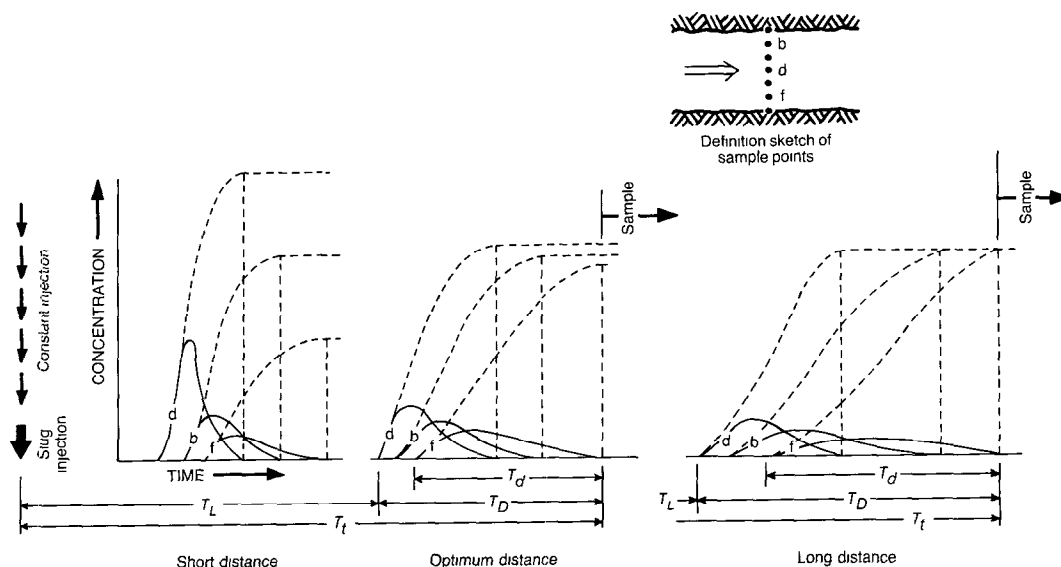
reaeration tests. Figure 1 depicts the downstream behavior of a tracer injected as a slug in the center of flow. Note that in figure 1 the response curves are shown as concentration versus longitudinal distance and not versus time. In figure 1, the stream has been arbitrarily divided laterally into six stream tubes of equal discharge; these are defined by 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). It 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 to wide streams.

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 are referred to in a general way as "mixing." The elongation of a tracer response cloud longitudinally is referred to as "longitudinal dispersion." Vertical mixing is normally completed first, and lateral mixing later, depending on the width of the stream and on velocity variations. Longitudinal dispersion, having no boundaries, continues indefinitely. Thus at section I (fig. 1), 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), while lateral mixing is still in progress. At section II, 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. Therefore, mixing and dispersion in two dimensions exists between sections I and II.

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

An optimum mixing distance, section III, is reached when the tracer-response curves as observed laterally, a, b, c,...g, have about the same area, even though the individual response curves may vary considerably in shape and dimensions; dispersion is approaching the one-dimensional state. Nevertheless, peak concentrations in the center of the channel may be considerably greater than peak concentrations along the banks, while curves along the bank are



NOTE Only the duration of passage, T_d , of the longest response curve is labeled

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. Abbreviations are defined in text and in list of "Symbols and Units."

longer both physically and in time of passage. Also, the tracer cloud may be skewed, advancing faster in the center of the flow than at the channel banks. As shown in figure 1, the tracer cloud may not be uniformly 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, section 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 to measure reaeration by the SI method, a stream reach is sought wherein both vertical and lateral mixing can be essentially complete. A test reach normally consists of an upstream and a downstream measuring section. An effort is made to select an injection site a sufficient distance upstream that, as a minimum, optimum mixing is obtained in the first measuring section (the upstream section) of the reach. It is essential that an accurate measurement and adjustment for dye losses be made, and this can be more accurately done if lateral mixing is essentially complete in the test reach. Complete lateral mixing is not

a factor when using the SI method with radioactive tracers because the radioactive dispersion tracer is essentially conservative over the stream reaches and times employed and because loss of this tracer is not a factor in 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 in which optimum mixing has been obtained.

Characteristics of response curve

The conventional manner of illustrating the response 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 centerpoint 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 sampled at just 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.

As will be seen, it is the single longest duration response curve 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

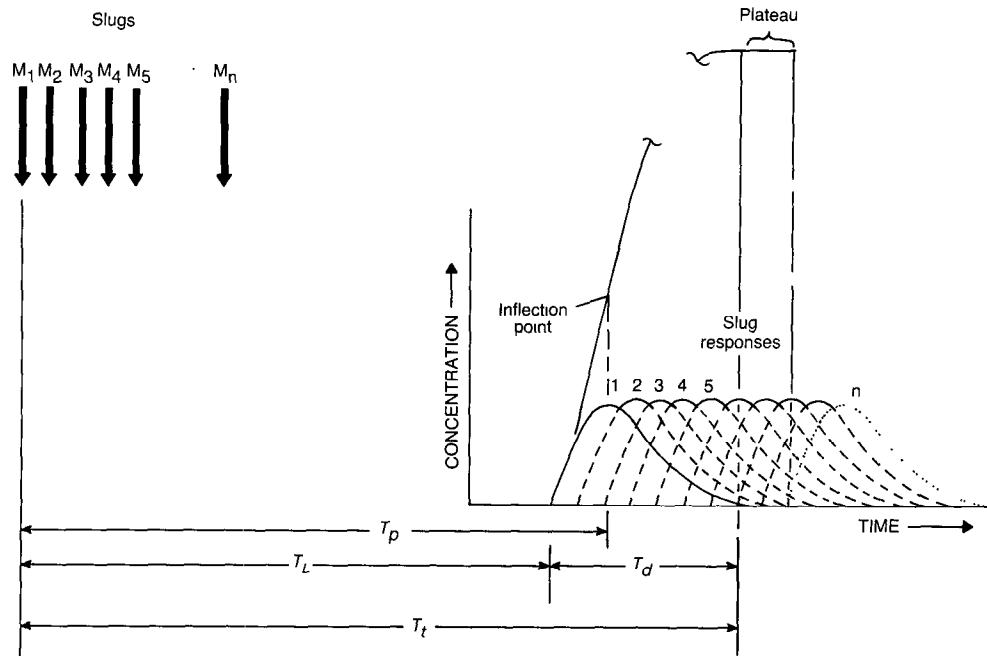


Figure 3.—Superposition of slug-response curves to simulate constant-injection buildup to a plateau at one location in stream section. Abbreviations are defined in text and in list of "Symbols and Units."

time-concentration response curve is essential to performance of the CRI method and can be best understood by using the superposition principle.

Superposition principle

A continuous, constant-rate injection of tracer can 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 edge, respectively, of this response curve. Assuming that streamflow is steady, continuing to inject a series of tracer slugs of equal amounts (M_2, M_3, \dots, 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 cannot 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 T_t , the time when the trailing edge of the first slug response passes 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 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 can 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 distance¹, the plateaus laterally tend to converge to about the same concentration, indicating that mixing is adequate. Note that the tracer would need to be injected continuously for at

¹The 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 background reference 3 (Kilpatrick and Cobb, 1985).

least a time equal to the longest duration of passage at any location *across the channel between points b and f* at that distance (see fig. 2) to just produce a stabilized plateau. Of course, it would be necessary to inject tracer for a slightly greater duration 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 the duration of the slowest moving tracer along one bank or the other. It is therefore advisable not to sample too close to one bank or the other and to be suspicious of any near-bank samples that yield low concentrations of tracer.

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 also applies to the long-distance superposition. Most important, it is the longest duration of passage *for the most downstream site* that 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 farther 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 when the CRI method of reaeration measurement is to be used. 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 as a result of a continuous, constant-rate injection of gas upstream. A CRI reaeration test should be designed to avoid sampling along 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 injection of a tracer gas into the streamflow and subsequent measurement of its desorption as it is transported downstream (Rathbun and others, 1975; Rathbun and Grant, 1978). The amount of desorption is determined 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 that is injected at exactly the same location and undergoes the same dispersion and dilution as the gas tracer.

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

ily because the dye tracer used in the latter is not totally conservative, in contrast to the tritiated water used in the former. 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 SI method using hydrocarbon gas is best performed in a stream reach in which 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 time-concentration 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 $\mu\text{g/L}$ (microgram per liter), whichever is larger. The remainder of the curve should be extrapolated to zero. Under no circumstances should the time-concentration curves be truncated at 10 percent of the peak concentration, as is suggested for time-of-travel studies. Information about the total mass of dye passing the measuring section is desired, and hence the best measurement of the *total* areas of the time-concentration curves is necessary. The dye recovery ratio, R_r , at any measuring section is expressed by the equation

$$R_r = \frac{W_r}{W_d} \quad (1)$$

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

$$R_r = 1,699 \frac{QA_c}{V_I CS_G} \quad (2)$$

where

Q = stream discharge, in cubic feet per second;
 A_c = representative *total* area under the observed dye time-concentration curve, in micrograms per liter times *minutes*. If three or more time-concentration 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 that also considers the specific gravity, S_G , of the dye solution (see background reference 1, Wilson and others, 1986);
 V_I = volume of dye injected, in liters having a concentration C ;

C = concentration of the injected solution, in micrograms per liter (20 percent = 20×10^7 $\mu\text{g/L}$); and S_G = 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, if 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

$$R_r = 1,699 \frac{\sum(\Delta Q_z A_z)}{V_I C S_G} \quad (3)$$

where

ΔQ_z = portion of total stream discharge applicable to streamline, in cubic feet per second; and

A_z = area of the observed dye concentration-time response curve measured on streamline z .

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

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

using the recovery ratio for the upstream and downstream measuring sections, which together make up 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 can be examined. In practice, the recovered amount 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 is 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 time-concentration curve at fewer 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—specifically, 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 that have involved careful concurrent measurement of oxygen absorption and gas desorption for the hydrocarbon gases ethylene and propane have been performed by Rathbun (Rathbun and others, 1978) and Rainwater and Holley (1983, 1984). 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 (R_e) and propane (R_p) are

$$R_e = \frac{K_2}{K_e} = 1.15 \quad (5)$$

and

$$R_p = \frac{K_2}{K_p} = 1.39 \quad (6)$$

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 removal of the gas is by desorption only and that no other physical or chemical processes interfere. Experience (Holley and Yotsukura, 1984) indicates that 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 from industrial or domestic sewage-treatment plants (Stedfast and Draper, 1986). Therefore, propane has become the more commonly used hydrocarbon gas in reaeration tests.

Temperature corrections

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

$$K_{T_{20}} = K_{T_Y} (1.0241)^{(20-Y)} \quad (7)$$

where K_{T_Y} is the desorption coefficient as measured by a tracer gas at stream temperature Y . Similarly, the reaeration coefficient at 20 °C when propane is the tracer gas can be expressed as

$$K_{20} = 1.39 K_{P_Y} (1.0241)^{(20-Y)} \quad (8)$$

Gas desorption

All methods of measuring stream reaeration involve injecting a tracer gas into the streamflow and subsequently measuring 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 *desorb* the gas; this ability is then related to the capacity of the same stream reach to *absorb* oxygen. It may be assumed that the desorption of the tracer gas through the stream surface is a first-order process of the form

$$\frac{dC_g}{dt} = -K_T C_g \quad (9)$$

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 calculated by measuring the loss of the gas tracer between two or more sections downstream from the injection. Equation 9 can be integrated and applied to a stream reach delineated by upstream and downstream measuring sections to give

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

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, 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 actual gas desorption, it is necessary to inject a conservative tracer and the gas tracer *concurrently* so that they undergo *identical dispersion and dilution*. Therefore, the dye tracer must be slug-injected in an identical manner as the gas, that is, in 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

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

in which both the gas-tracer concentration and the dye-tracer concentration, C_d , are measured at a characteristic time on the upstream and downstream response curves. As shown in figure 4, the most commonly used characteristic time is that for peak concentration; 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 can be resolved by adjusting the measured dye concentrations using the dye recovery ratios measured at each section such that for the "peak method"

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

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

If the dye-loss correction factor, J , is used

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

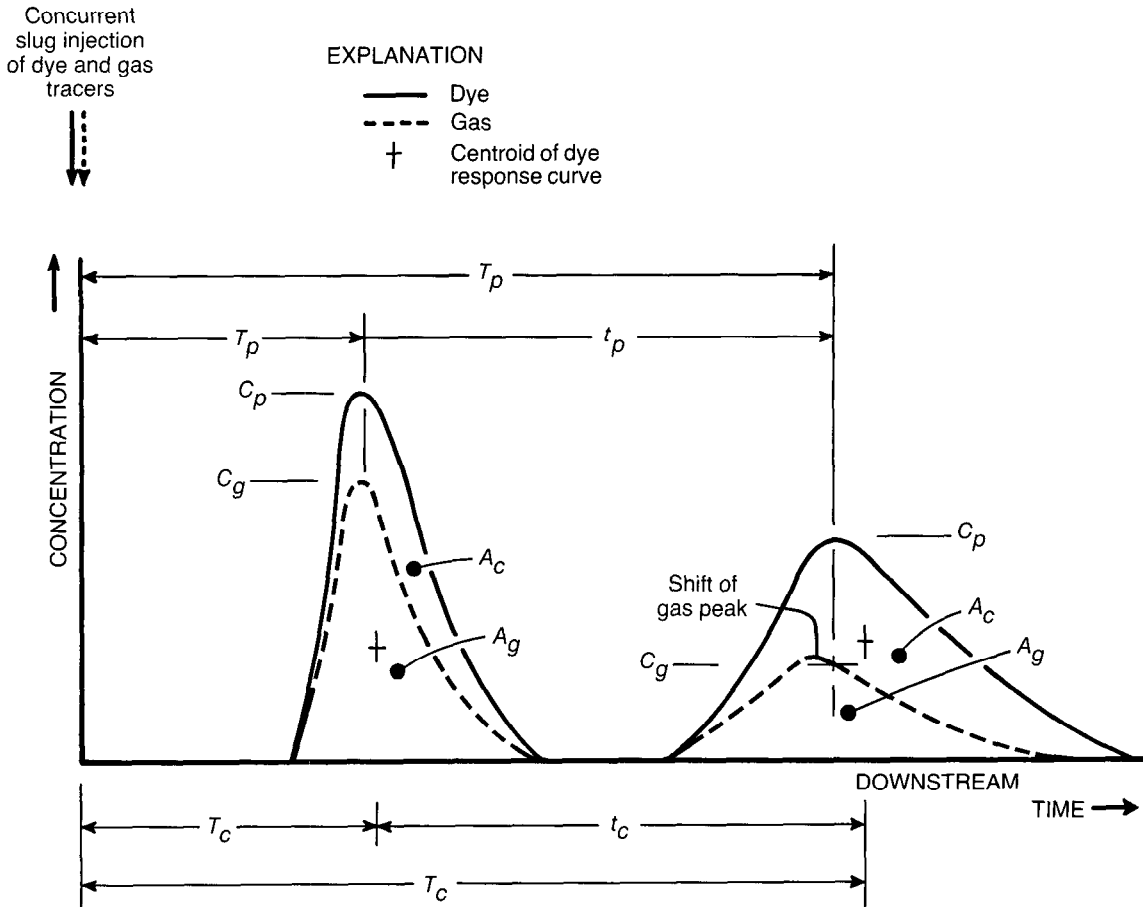


Figure 4.—Definition sketch of slug-injection type of reaeration measurement. Abbreviations are defined in text and in list of "Symbols and Units."

where t_p is the traveltime from the upstream to the downstream peaks of the dye-response curves, C_p is the observed peak dye concentration, and C_g is the gas concentration observed at the same time as the dye peak. 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 so 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 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

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

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 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. Although the area method avoids the requirement to evaluate dye-tracer recoveries accurately, 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 of the dye-tracer response curves. The elapsed time to the centroid (T_c) of each dye-response curve is needed and is 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 can be expressed as

$$T_c = \frac{\int_{t=0}^{t=\infty} C_d t dt}{\int_{t=0}^{t=\infty} C_d dt} \quad (15)$$

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 can 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 , can be determined either by planimetry 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 U.S. Geological Survey Office of Surface Water in Reston, Va.

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 are 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 (assuming the tracer has moved 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

$$Q = q \frac{C}{\bar{c}} \quad (16)$$

where

q = rate of tracer injection, assumed to be very small relative to Q^2 ;

C = concentration of the tracer being injected; and

\bar{c} = 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 if mixing is 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, \bar{c}_g , with distance downstream, as depicted in figure 5. If gas injection lasts long enough, longitudinal dispersion ceases to be a factor in determining concentration levels; only dilution by flow accrual, if any, will reduce plateau levels below the level caused by the desorption of the gas. Thus, an *approximate* solution for the gas desorption coefficient is

$$K_T = \frac{1}{t_c} \ln \frac{(\bar{c}_g Q)_u}{(\bar{c}_g Q)_d} \quad (17)$$

This equation is approximate as it is based (Yotsukura and others, 1983) on the assumption that the stream channel is straight and prismatic. The product, $\bar{c}_g Q$, may be thought of as the gas mass in transport at a section. In this instance, \bar{c}_{g_u} and \bar{c}_{g_d} are the weighted average plateau concentration of the gas at the upstream and downstream measuring sections, respectively. As was the case 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 *dye-tracer* response cloud. These data are normally acquired by the instantaneous *slug* injection of the dye tracer into the streamflow at the same location and time as the continuous gas injection.

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

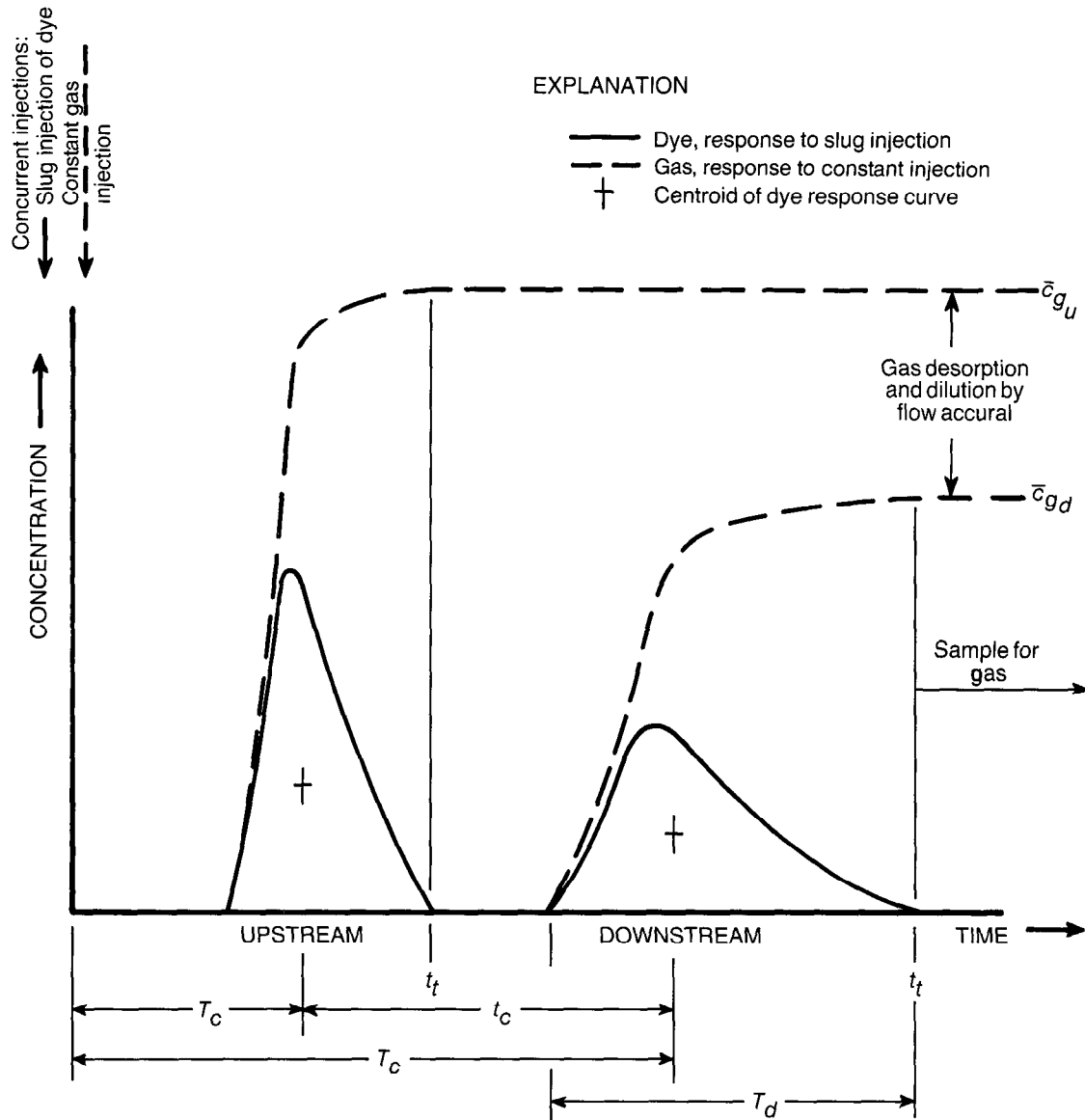
A more exact solution for the desorption coefficient is obtained by the trial solution of the equation

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

in which the left term is the ratio of the upstream gas mass in transport to the downstream gas mass in transport. 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 the upstream and downstream measuring sections. Normalizing a given set of dye time-concentration data is done by dividing by the area of that response curve such that

$$f(C_d, t) = C_d(t) / \int C_d dt \quad (19)$$

²For clarity, units are ignored here.



NOTE: T_d is minimum duration of constant 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 of reaeration measurement. Abbreviations are defined in text and in list of "Symbols and Units."

The solution of equation 18 involves numerical integration calculations employing a number of trial K_T values estimated from the value determined by equation 17. When the ratio on the right side of equation 18 agrees with the ratio of observed data on the left, the trial K_T is considered 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. 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 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 of passage of the dye-response curve provides exact information on how long a gas injection must be, and its

time of final departure, t_f , provides the exact time to sample the gas-concentration plateau.

It should be noted that thus far the approach has been 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 far enough downstream 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 calculate values 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, 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 from time of travel 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 former because the nonconservative gas tracer must be desorbed to accomplish the measurement. From a practical standpoint, only a small amount of the gas (such as propane or ethylene) initially injected into the flow is actually absorbed by it. This, coupled with the desired desorption, limits the length of reach that can be measured and the levels of gas concentration that can still be measured accurately.

Furthermore, most field tests have been on small streams, as it was desirable to perform the measurement in a reach where vertical and lateral mixing of the tracers was 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 reach length, and this may result in gas concentrations too small to measure. In effect, for wide rivers, the distance required to achieve 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. Although this

technique is new and its performance in the field is 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. This injection section is located upstream from an upstream and a downstream measuring section which constitute 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 measurements are made for gas concentration, as was described previously when applying the CRI method to narrow streams. The primary difference 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, at 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 parallel streamlines. Obviously, using the CRI method in a wide stream means that 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 were far enough downstream from the 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 equations 17 and 18 that applies the CRI method to the two-dimensional non-uniform plume situation and to measurement along a given streamline, z , is

$$\left[\frac{(\bar{c}_g Q)_d \phi_d}{(\bar{c}_g Q)_d \phi_u}_z \right] = \frac{\int_{t=0}^{t=\infty} f(C_d, t) \exp(-K_T t) dt_u}{\int_{t=0}^{t=\infty} f(C_d, t) \exp(-K_T t) dt_d}_z \quad (20)$$

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 as well as at the section upstream chosen for the injections. From plots of cumulative discharge versus lateral distance, common streamlines are chosen for the measurements. Plateau gas concentrations, \bar{c}_{g_u} and \bar{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

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

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 A_{c_z} in equation 21 by the plateau gas concentrations gives

$$\phi_z = \frac{\bar{c}_{g_z}}{\sum \bar{c}_{g_z} \frac{\Delta Q_z}{Q}} \quad (22)$$

If possible, the gas injection should be sufficient to yield measurable concentrations near the streambanks, where they might be expected to be 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 determining ϕ is to perform a continuous dye injection long enough to establish steady-state plateau concentrations and to 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 of dye injection because as much as a day or more 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 in most cases, the following is recommended: (1) a slug injection of dye tracer at a point on a source streamline at the injection section, with complete sampling of the response curves on the same streamline and on the two adjacent streamlines at the two downstream sections; (2) concurrent with or within a short time following, 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 kept in mind that equation 20 is the general equation applicable to the two-dimensional situation, whether on a narrow or a 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 can 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 is 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, or maybe two or more flow durations, will probably be desirable.

In contrast, if evaluation of the change in reaeration capacity with stream stage on a certain reach of a stream is an objective, several reaeration measurements at different flows may be necessary.

As can be deduced from the previous sections, successful performance of tracer-type reaeration studies requires considerable planning and careful execution. 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 must be 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. When using the CRI method in wide streams, a current-meter measurement must also be made at the injection section to enable the selection of a streamline.
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 the upstream and downstream sections that make up the test reach.
3. Stream test reaches and the corresponding measuring sections should be chosen so that tracer mixing and residence times between sections are adequate. The exception is the case of two-dimensional nonuniform mixing where sufficient data must be collected to account for the nonuniformity.

Reach selection

Selection of the test reach may be based on the need to evaluate permissible waste loading below a discharge point. More commonly, the study 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 in hydraulic properties such as roughness and cross sectional area. 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 and 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 kept in mind. Accessibility to

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

[Note: $E_z = 1.13d^{3/2}s^{1/2}$. ft/ft, foot per foot]

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.

the injection site is most important, as pressurized gas cylinders must be placed close to the bank and diffuser lines and plates must be placed in the stream.

Mixing length requirements

Except for the case of wide rivers, for which it is accepted that it will not be feasible to obtain complete lateral mixing in the test reach, selection of the injection site relative to the downstream test reach must take into account distance to the upstream measuring section to ensure an adequate distance for mixing.

Repeating from background reference 3 (Kilpatrick and Cobb, 1985), the optimum distance, L_o , in feet, required for adequate lateral mixing of a tracer injected in the middle of the streamflow can be estimated by the equation

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

where

v = mean stream velocity, in feet per second;

B = average stream width, in feet; and

E_z = lateral mixing coefficient, in feet squared per second.

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 *minimum* distance between the point of tracer injection and the first measuring section; greater distances will be to advantage if feasible. Furthermore, from the standpoint of gas injection, it

is preferable that the distance to the first section where gas is to be sampled be at least 1 h (hour) traveltime from the point of gas injection to ensure that all the gas is truly in solution (R.E. Rathbun, written commun., 1987).

Adequacy of residence time

As can be seen from equations 10, 13, 14, 17, 18, and 20, a logarithmic relation exists between tracer concentrations and the desorption coefficient. Thus, the computation of K_T may be subject to increasing error as the ratio of upstream to downstream gas concentrations drops significantly below 2.72 or, conversely, the product of K_T and t_c drops below 1.0. There must be sufficient gas residence time between sampling sections so that the ensuing computation will be accurate. *This is probably the most important criterion 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 straightforward 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 kept 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 reaches of the pool-and-riffle type having slopes, s , ranging from 0.00012 to 0.0057 ft/ft (foot per foot), the equation is

$$v_p = 0.38 Q^{0.40} s^{0.20} \quad (24)$$

where v_p is in feet per second and Q is discharge in cubic feet per second. For reaches of the channel-control type having slopes ranging from 0.00016 to 0.0023 ft/ft, the equation is

$$v_p = 2.69 Q^{0.26} s^{0.28} \quad (25)$$

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

$$K_2 = 0.054 \Delta H / t_c \quad (26)$$

seems best for stream reaches having a slope greater than 0.003 ft/ft. 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)

$$K_2 = 0.906 v^{0.67} / d^{1.85} \quad (27)$$

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

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

$$K_p = 0.039 \Delta H / t_c \quad (28)$$

and

$$K_p = 0.651 v^{0.67} / d^{1.85} \quad (29)$$

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 from 20 °C, it may be desirable to adjust K_p using the equation

$$K_{pY} = K_{p20} (1.0241)^{Y-20} \quad (30)$$

where Y is 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 can 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 that make up a greater portion of many stream reaches. If estimates or measurements of B and v are available, mean depth can be estimated from the equation

$$d = \frac{Q}{Bv} \quad (31)$$

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

Having estimates of t_p and K_p , their product is calculated; the units used should yield a dimensionless number. If the product is less than 1.00, it is desirable to move the measuring sections farther 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 to use the CRI two-dimensional dispersion 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 discharge measurements should be made at the injection site and at the two sections that make up the test reach. If there are changes in stage during the reaeration measurement, additional current-meter measurements should be made at the two downstream sections. 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 streamlines common to the two measuring sections that make up the test reach. If boat traffic exists, lightweight string may be suspended safely across the channel, with suitable bright tape marking the sampling locations.

For tests on wide rivers, for which planning is more critical, current-meter discharge measurements may best be made in advance of the reaeration measurement so that injection source and sampling streamlines and sections may be selected and suitably identified. In such cases, buoys 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. Adaptation of these gases as nonconservative tracers required devising means of forcing enough gas into a 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 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 pores 2 μm (micrometers) in diameter has been used successfully. Crawford (1985) used a series of Zimpro passive diffusers having a 1.5- to 2.0- μm pore size mounted in

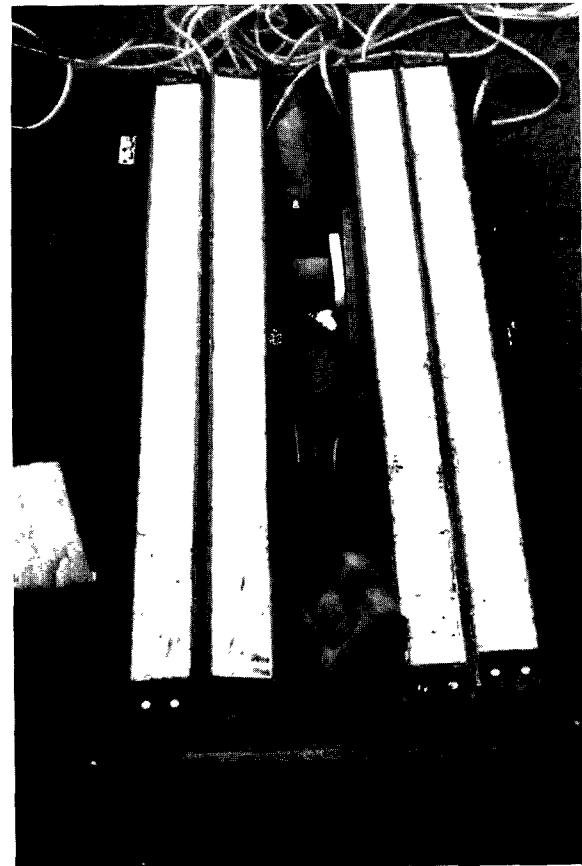


Figure 6.—Ceramic diffuser plates stored and transported in custom-made box.

a series of racks, as shown in figure 7. The number of diffusers used in a test depends primarily on the stream discharge being tagged. Several diffusers can be fed from one gas tank using manifolds such as those 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 square inches. Table 2 provides guidelines for the number of diffusers to use for ranges of stream discharge. If the diffusers are placed in water significantly deeper than 1 ft, fewer diffusers may be required; conversely, more diffusers may be needed if the gas injection is in shallower water.

Regardless of the type or brand of gas diffuser used, it must be placed to duplicate the dye injection as nearly as possible. This becomes particularly important when applying the CRI method to a wide stream where any differences in tracer source configurations between gas and dye could be reflected in the concentration response curves 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 those

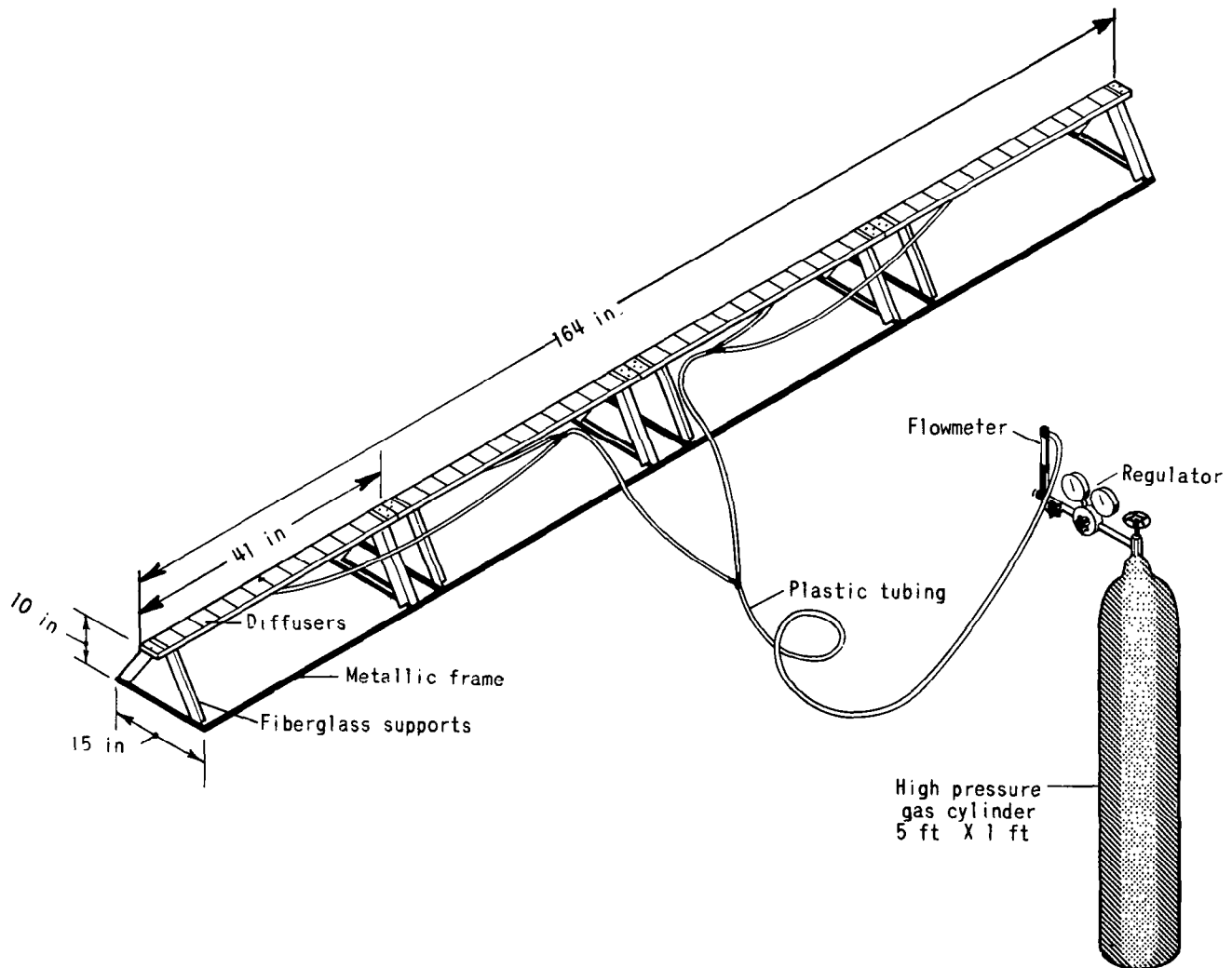


Figure 7.—Gas-injection apparatus using flat-plate porous ceramic diffusers epoxied into channels to form four racks. (From Crawford, 1985.)

shown in figure 7), they should be aligned longitudinally in the channel, *parallel to the flow*.

The diffusers should be placed in the deepest water 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 the point of injection or a short distance downstream from that point. As a rule, the most upstream sampling section should be at least 1 h time-of-travel downstream from the gas-injection point to ensure that the gas is truly in solution. The efficiency of the gas injection is

Table 2.—Number of diffusers to use to inject gas into different stream discharges

[Diffuser plates are assumed to be 2 micrometers in pore size, 75 square inches in surface area, and placed in 1 foot of flowing water. ft³/s, cubic feet per second]

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

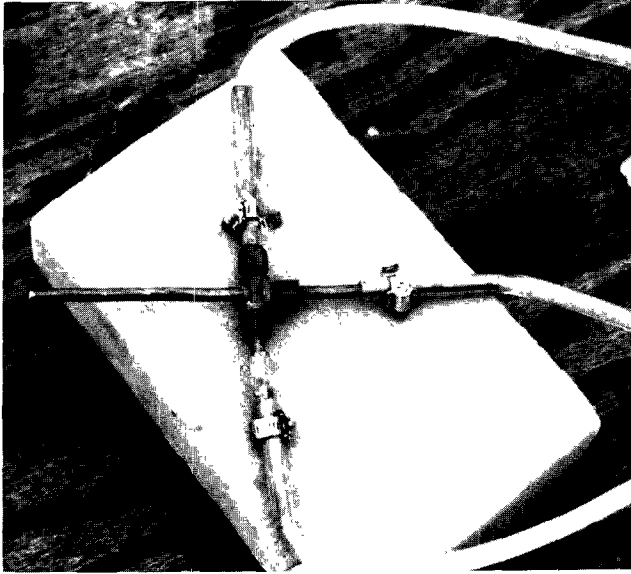


Figure 8.—Three-way manifold used to supply gas to diffusers from one gas cylinder.

largely a function of the depth of the flow over the diffusers, the size of the bubbles produced by the diffusers, and the temperature of the water, which affects gas solubility and hence is 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 taking care to expose the diffusers to river water as short a time as possible and, upon removal, by 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 diffusers and recommended a preliminary period of gas injection and observation to make certain injection rates are stabilized.

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 (pound) tanks (see fig. 9) up to 100-lb commercial cylinders. A



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

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 ft³/h (cubic feet per hour). Large tanks also are preferred when performing the CRI type of test, which may require as long as 48 h 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 tank may also be rented.

Rates

To ensure and measure a constant rate of gas injection, a flow regulator and flowmeter (see figs. 7, 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 CO₂ (carbon dioxide) type of 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



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

diffusers, it is necessary to continuously inject the hydrocarbon gas tracer for 1/2 to 2 h when using the SI method and up to 48 h when using the CRI method. With the SI method, the short-duration injection may be considered a “quasi-slug” injection. No attempt is made to produce plateau concentrations downstream; 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.

Stability of the continuous gas injection is vital to successful performance of a CRI type of reaeration measurement. As a check on the flow rate and, more important, on 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 scales are available from most laboratory supply houses for approximately \$50 and will weigh up to 250 lb 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

Table 3.—Typical costs of 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

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 the length of time the rate 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- $\mu\text{g/L}$ plateau concentration could be related to diffuser efficiency, stream discharge, and the first-order desorption of the propane by a general equation of the form

$$q_p = 1.97 \times 10^{-3} [Q_m e^{T_p K_p}] / \epsilon \quad (32)$$

where

q_p = constant-rate gas injection, in cubic feet per hour at standard conditions of 70 °F and 14.7 psia;
 Q_m = maximum stream discharge, usually at the most downstream section, in cubic feet per second;

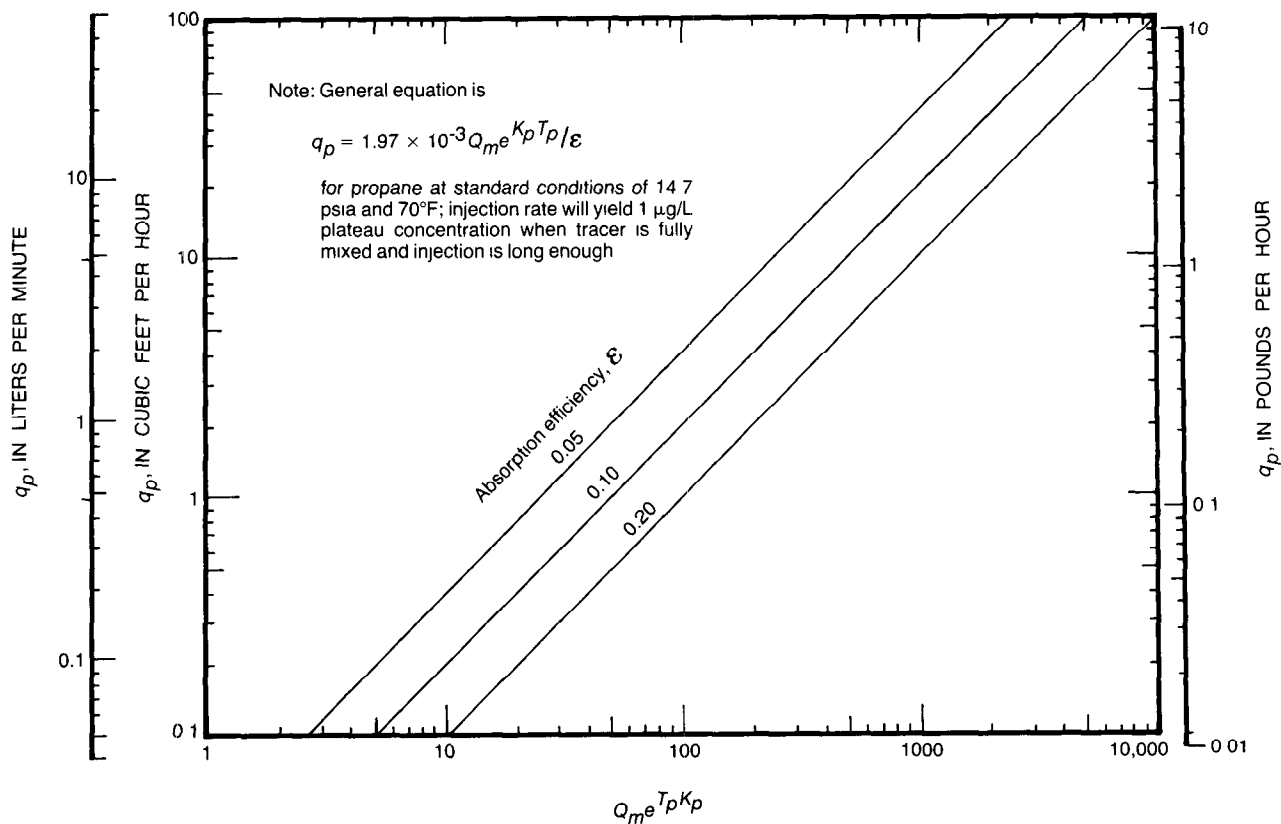


Figure 11.—Graph used to aid in selecting propane gas injection rates. Abbreviations are defined in text and in list of "Symbols and Units."

$e =$ a constant, 2.72;

$T_p =$ elapsed time to the peak concentration at the most downstream section, in hours;

$K_p =$ desorption coefficient for propane, in hour^{-1} at 20 °C; and

$\epsilon =$ 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 $\mu\text{g/L}$. It is advisable to plan for concentrations of 2 $\mu\text{g/L}$ 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 the expected efficiency of the injection system. 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.

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 the size of tank needed for performing the CRI type of reaeration measurement. It can 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 fivefold 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. Excessive gas escape from 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 latter is suggested because manipulating the gas injection rate at the start of a test may result in 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

$$q_a = q_p \sqrt{\frac{14.7}{14.7 + p_g}} \sqrt{\frac{460 + Y_g}{530}} \sqrt{\frac{44}{29}} \quad (33)$$

where p_g and Y_g are the pressure, in psig, and the 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; it 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; it normally varies from 50 to 60 psig for the Marox diffusers. The metering temperature, Y_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 $Y_g=32$ °F), equation 33 simplifies to

$$q_a = 0.44 q_p \quad (34)$$

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

$$q_a \approx 10^{-2} Q_m e^{K_p T_p} \quad (35)$$

Note that this is the rate to yield a gas plateau of 1 $\mu\text{g/L}$; the rate must be increased proportionally to obtain larger plateau concentrations. Equation 35 is for $p_g=55$ psig, $Y_g=32$ °F, and $\epsilon=0.087$ and should not be used if conditions, especially metering pressure and diffuser efficiency, are considerably different. 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 1/2 to 2 h is usually necessary for the SI method. The longer times should be used when

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 on "Theory," it is shown that the longest duration of passage of any of the dye-response curves 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, 3). Kilpatrick (written commun., 1987) analyzed a large amount of time-of-travel and reaeration 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 in figure 12, 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 that 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. Use of the last 20 percent of tank volumes should be avoided.

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

The curves in figure 12 are approximate and should be used for planning purposes only. In practice, when using the CRI method, a slug of dye is injected simultaneously with the start of continuous gas injection or shortly afterward when the gas rate is observed to be constant. Observation of the slug-produced dye-concentration response curves at the two downstream measuring sections not only produces data needed for the computation of K_T , but also should be used to guide decisions about 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 gas-tracer concentrations caused by flow

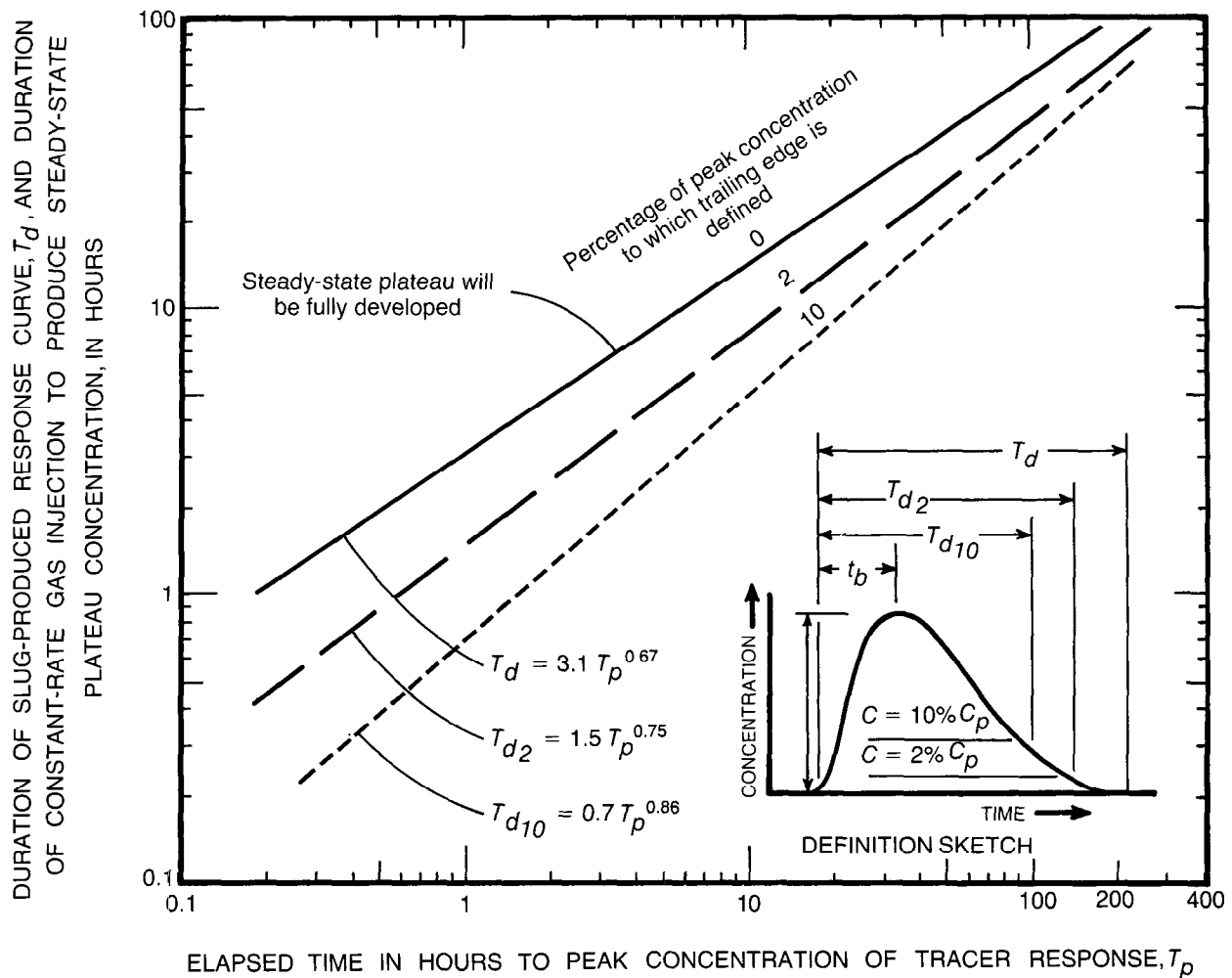


Figure 12.—Graph used to estimate duration of slug-produced response curves as defined to different trailing edge concentrations and to estimate duration of constant-rate gas injection required to develop steady-state plateau concentration for different peak traveltimes. Abbreviations are defined in text and in list of "Symbols and Units."

accrual and dispersion over and above the desired measurement of reduction due to gas desorption.

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 (Kilpatrick and Cobb, 1985) and is 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 and 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 mL/min (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 gas injection, rate constancy is more important than exact rate.

Injection rates

The dye-dilution discharge equation (continuity equation)

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



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.

was used to develop the family of curves shown in figure 15 for selecting dye-injection rates and concentrations to yield approximately a 10- $\mu\text{g}/\text{L}$ plateau concentration at the most upstream section for a range of stream discharges. In equation 36 and figure 15

Q = discharge of the stream, in cubic feet per second;
 q = rate of injection of the tracer, in milliliters per minute;

C = concentration of the dye solution injected into the stream, in micrograms per liter; and

\bar{c} = equilibrium, or plateau concentration, in micrograms per liter, averaged or weighted across the sampling section.

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

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.

Constant-rate-injection method

In seeming contradiction, 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 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 $\mu\text{g}/\text{L}$ at the most *downstream* measuring section. The distance, L , and the discharge, Q , should therefore be for the most downstream section. In figure 16,

V_s = volume of rhodamine WT 20-percent dye, in milliliters;

Q = stream discharge at the downstream section, in cubic feet per second;

L = distance to the downstream section, in feet;

v = mean stream velocity, in feet per second; and

C_p = peak concentration at the downstream sampling site, in micrograms per liter.

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

[$\mu\text{g/L}$, micrograms per liter]

Desired concentration C in $\mu\text{g/L} \times 10^7$	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.

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

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 ensure accurate injection of the amount measured.

Just before withdrawing the concentrated dye, about 10 L (liters) of river water should be measured accurately into a container (most buckets readily hold 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 to allow standards to be prepared from it; 100 mL (milliliters) 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 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 on the basis of cumulative discharge and should be 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 sampling point locations for a given test to represent various discharge increments. More sampling points are recommended for wider and shallower streams.

Dye

Scheduling sampling

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

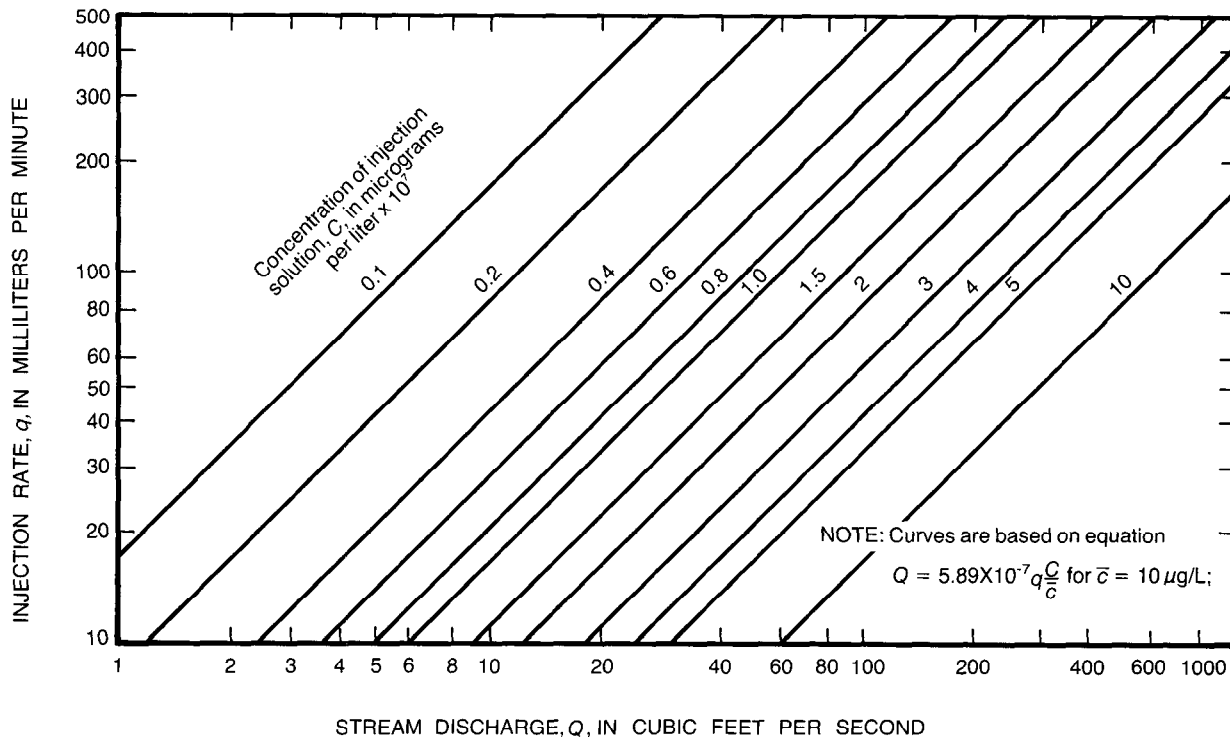


Figure 15.—Graph used to estimate rates of dye injections for different stream discharges and concentrations of injection solutions.

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

which may be simplified to

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

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 can 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 *through* the peak and less frequent sampling toward the trailing edge is 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 also be involved in dye sampling because of the potential for contamination of samples.

In most cases, sampling can be performed by wading into the stream and lowering the bottle slowly toward the bottom as it fills. Sampling from boats may be necessary on larger streams. The floating syringe type of 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, table 5) discharge points. Occasionally, samples should be taken at the boat to confirm 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 at night. The best practice is to visit the one or more floating samplers, collect check samples, and, if possible, note the time when the sampler is collecting a given sample. The latter helps confirm the timing of the automatic sampler.

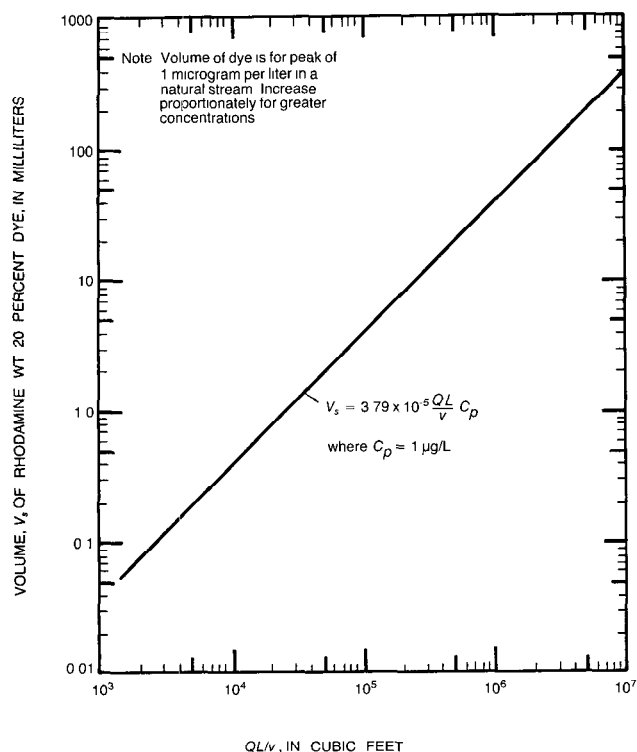


Figure 16.—Graph used to determine quantity of rhodamine WT, 20-percent dye required for slug injection to produce a peak concentration of 1 microgram per liter ($\mu\text{g/L}$) at a distance downstream, L , at a mean velocity, v , and with a discharge, Q , in the reach.

Flow-through 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 aspects of reaeration measurement is the gas sampling procedure. The objective is to deliver to the laboratory a sample that 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) injection of a small quantity of formalin to prevent biological degradation during storage, (2) use of borosilicate glass sample bottles tightly 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.

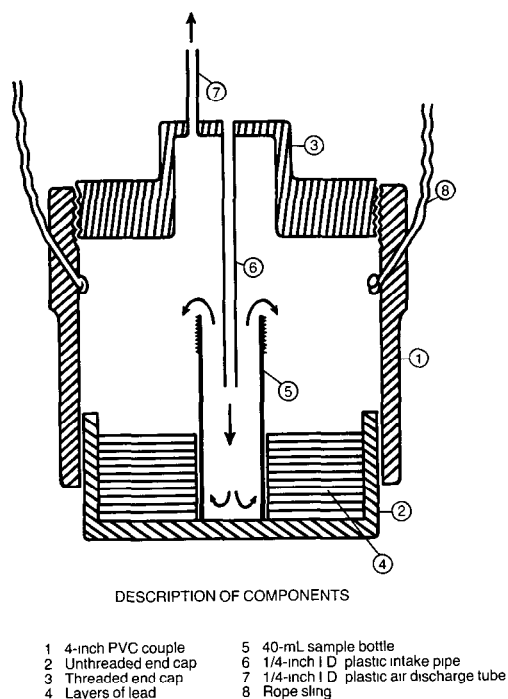


Figure 17.—Design sketch of gas sampler (requires approximately 40 seconds to fill).

Scheduling sampling

In the SI method, the gas and dye are injected simultaneously and continuously from the *same location* and for the *same duration*, $\frac{1}{2}$ to 2 h. Sampling of 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 of samples 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 that are believed to be adequate for defining the gas concentration-time curve should be 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 a

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

40-mL glass bottle. The bottle can be obtained from the Geological Survey Central Laboratory. Important features are as follows:

1. The sample bottle is flushed many times in the process of filling.
2. The sample bottle is kept submerged while the formalin is injected and the Teflon-lined cap is placed on the bottle.
3. The container is large enough to permit capping of the bottle with the fingers and easy removal of the bottle.

Samplers similar to that sketched in figure 17 are suggested, as they are inexpensive and effective in obtaining representative gas samples.

Figure 18 shows the 40-mL glass bottle in place; the intake tube must project into the bottle 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 (fig. 21) while still covered with water, with the Teflon surface *facing the inside of the sample bottle*. Gas sample bottles are then placed in an insulated cooler and their caps checked for tightness. 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 should be 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 illustrates by example the techniques and analysis procedures suggested for performing an SI reaeration measurement. The example involves a State Environmental Control Board's concerns with the waste loading entering Rath Creek just upstream from Highway 1 and its need to know the reaeration capabilities of the downstream reach (see fig. 22). Of particular concern was the extent of natural purification and the level of dissolved oxygen at a water supply withdrawal point 4 mi (miles) downstream. Data were 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 for 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. The initial plan 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 ft; mixing of the tracers would be accomplished in the 12,000 ft down to the Highway 2 bridge crossing. The measurement reach would be the 8,000 ft of channel down to the State park. The downstream section was to be located just upstream from a significant inflow from Bun Creek, as it was recognized that poor mixing conditions would exist downstream from this inflow. The motel and the covered pavilion would



Figure 18.—Placement of 40-milliliter sample bottle in holder.



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

serve as sites for the fluorometer when sampling at the upstream and downstream sections, respectively.

Reach slope

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



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

Traveltimes

This is a pool-and-riffle type of stream, so equation 24 was used to compute a peak velocity:

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

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 earlier as part of a low-flow study. The slower velocity was thought



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

to be more accurate because 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 were estimated as

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

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

Therefore, the traveltime of a peak, t_p , through the test reach is $13.89 - 8.33 = 5.56 \text{ h}$.

Mixing length

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

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

While this was just an estimate, 12,000 ft would be available from Highway 1 to Highway 2 and, hence, mixing was expected to be more than adequate.

Residence time

The decision was made 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 was used to estimate the desorption coefficient for propane:

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

thus, $K_p t_p = 0.098/\text{h} \times 5.56 \text{ h} = 0.54$, which is significantly less than 1.00. A longer test reach was needed.

Inspection of figure 22 revealed that mixing should be more than adequate at an old road crossing upstream, at a distance 4,000 ft downstream from the injection point. The traveltime to this section was computed as before and was approximately 2.78 h; thus, the time of travel of a peak in this longer test reach was $13.89 - 2.78 = 11.1 \text{ h}$ and $K_p t_p = 0.098/\text{h} \times 11.1 \text{ h} = 1.09$. While this evaluation was based on numerous estimates, the actual field test was expected to result in 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 ft. Based on a downstream discharge of 42 ft³/s and table 2, two diffusers, supplied by one gas tank, were used; gas injection for 1 h should be sufficient.

Using the curves in figure 11 (or eqs. 32, 35), $Q_m e^{T_p K_p}$ was computed for the stream conditions described in figure 22 and previously estimated, applicable to the most downstream section:

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

From figure 11, it was determined that a constant gas injection rate of 3.23 ft³/h was needed for a plateau of 1 μg/L, assuming an absorption efficiency of 10 percent. Since this was to be a 1-h-long "slug injection," a plateau of 5 μg/L or more was planned for, knowing that lesser concentrations would actually result at the most downstream section. Thus, $5 \times 3.23 = 16.15 \text{ ft}^3/\text{h}$. An injection rate of approximately 16 ft³/h, which from figure 11 is equivalent to less than 2 lb of propane for the 1-h test, was planned for. A 20-lb propane tank was more than sufficient for the test.

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

$$q_a = (0.44)(16 \text{ ft}^3/\text{h}) \approx 7 \text{ ft}^3/\text{h}$$

Dye Injection

The dye injection was to be for 1 h duration at the same location as the gas injection. Examination of figure 15 indicated that for a stream discharge of 42 ft³/s, a dye solution having a concentration, C , of $2 \times 10^7 \text{ μg/L}$ would yield a 10 μg/L plateau concentra-

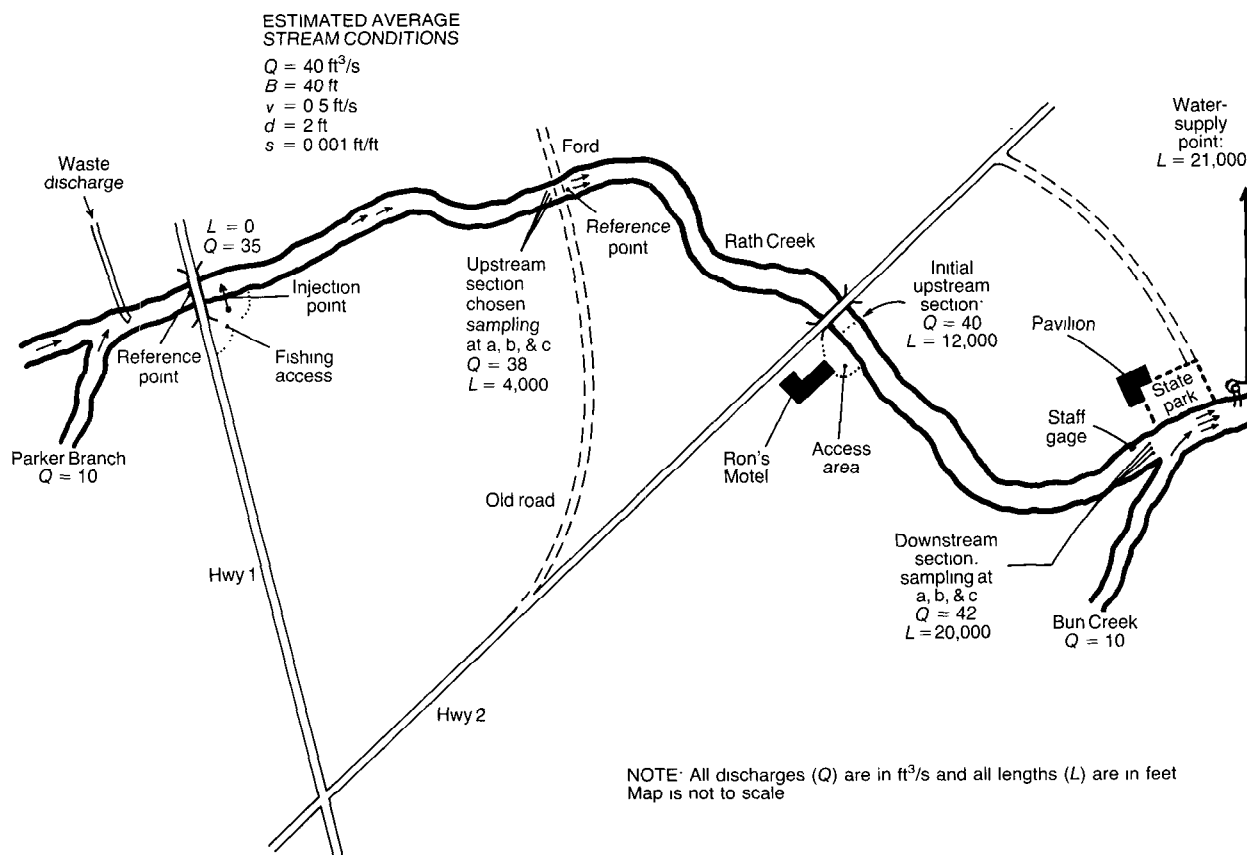


Figure 22.—Sketch of stream reach used in examples of reeration measurements.

tion if injected at a rate of 34 mL/min. While a $10 \mu\text{g}/\text{L}$ concentration might not exist at the downstream section, dye concentrations as low as $1 \mu\text{g}/\text{L}$ would be acceptable; thus a considerable margin existed for the dye plateau to be reduced by longitudinal dispersion and still be adequate for accurate fluorometric measurement. It was important, too, that dye concentrations be less than $10 \mu\text{g}/\text{L}$ at the water supply intake (Hubbard and others, 1982).

An injection rate of 34 mL/min for 1 h would require a total dye solution volume of approximately 2 L or 1/2 gal. Table 4 provided the volumes of dye and water to mix together for preparing approximately 5 gal of solution. Additional tests on other streams were planned in which stream discharges were to range from 20 to 50 ft^3/s , so a large volume of $2 \times 10^7 \mu\text{g}/\text{L}$ solution was deemed useful. Using table 4, approximately 2.5 gal of $2 \times 10^7 \mu\text{g}/\text{L}$ solution was prepared 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 it was thoroughly mixed, the dye solution was retained and a 100-mL bottle of the solution was stored 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 h and 13.9 h for the upstream and downstream sections, respectively. Figure 12 was used to estimate other properties of the dye-response curves at the upstream and downstream sections to provide a means of scheduling tracer injection and sampling. These estimates were tabulated (table 6) and depicted visually (fig. 23) to aid planning. As can be seen, the first arrival of the dye was estimated to be at 2.2 and 11.8 h at the upstream and downstream sections, respectively, from the time injection started. The last dye was estimated to depart the upstream and downstream sections at 9.4 and 29.8 h elapsed time, respectively, allowing for the 1 h of injection.

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, it is

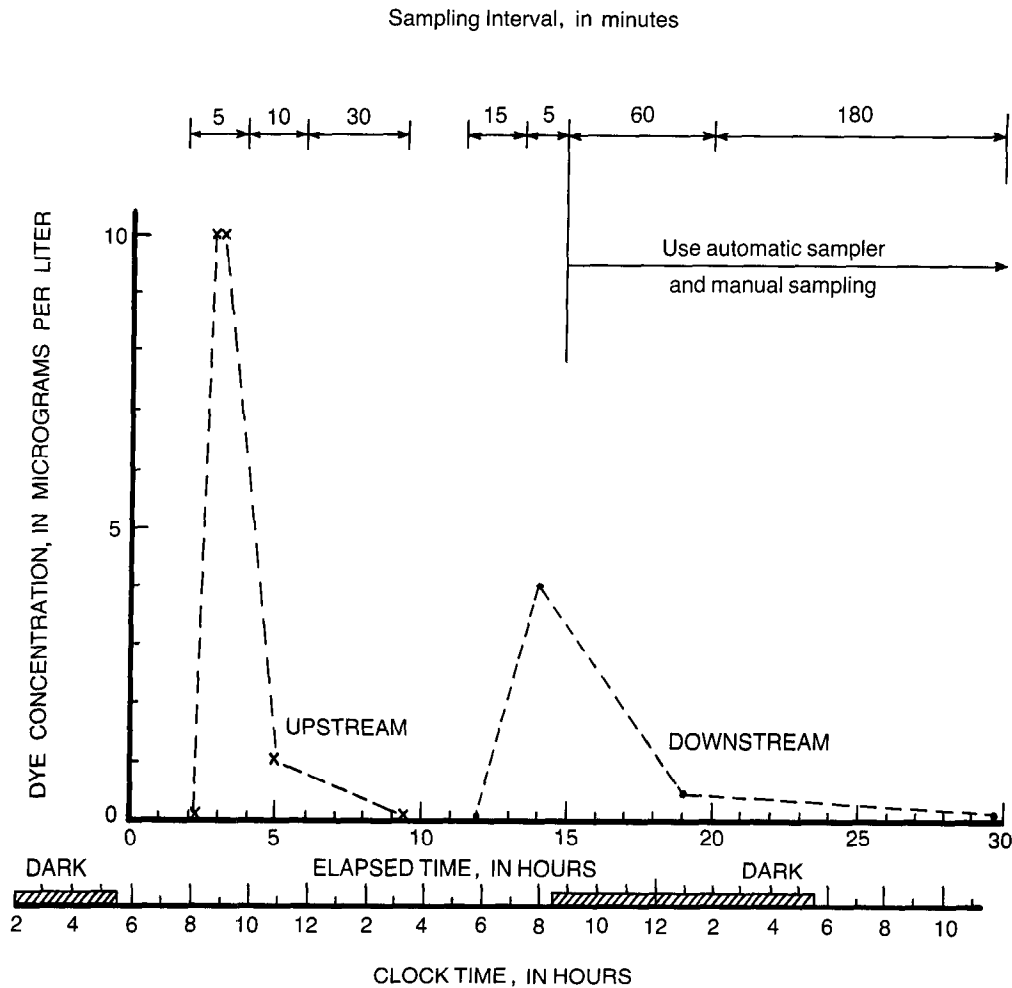


Figure 23.—Sketch of estimated response curves for guidance in scheduling slug-injection type of field reaeration test.

hoped, 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 used, only dye samples will have to be acquired the second day. Samples from a 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 *actual sampling must always be guided by real-time field results.*

Field test—Peak method

Preliminary preparation made the afternoon before the actual test included the following:

1. Reference points were established at the injection and upstream sections and a temporary staff gage was placed 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 was located distancewise from the left bank. Stage 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.

Table 6.—*Estimated properties of slug-response curves for scheduling sampling for slug-injection type of reaeration test*[Note: Duration of dye injection, 1 hour. All times in hours. C_p , observed peak dye concentration]

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_{d10}	1.7	6.2
3. Buildup from leading edge to peak, t_b : $t_b = \frac{T_{d10}}{3}$	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_t , at 0 percent C_p : (4) + (6) + 1 hour	9.4	29.8

*From figure 12

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

4. Gas and dye injection was begun at 6 a.m.; this time corresponded 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 rates³, the other measured stage both before and after making the current-meter measurement at the upstream section of the test reach.
6. At $t=1$ h, background samples were collected at the upstream section and gas and dye injection was terminated at the injection site. The injection apparatus was removed immediately, and the dye pump and line and the gas line and diffuser were flushed with tap water.
7. Upon completion of the current-meter measurement, the tagline was left in place and the locations corresponding to the 16.7-, 50-, and 83.3-percent cumulative discharge points were flagged (see table 5).

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

8. The fluorometer was set up in a vehicle and dye sampling was begun at the centerpoint at $t=2$ h. Samples were analyzed immediately and plotted

on a graph similar to figure 24; stream water temperatures were measured and recorded.

9. With the first appearance of dye at the upstream section, dye sampling proceeded at approximately 5-min intervals at all three sampling points.
10. The immediate analysis and plotting of the dye concentrations continued until values approached about 7 $\mu\text{g/L}$ (knowing that a brief plateau of about 10 $\mu\text{g/L}$ was likely), at which time gas samples were collected at 5- to 10-min intervals through the dye peak. (Judgment should be exercised to sample for gas several times at each point just prior to the dye peak and as the peak occurs.)
11. Stage measurements were 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 continued at a less frequent rate, the fluorometer being used to immediately analyze samples and the data plotted concurrently.
13. The dye samples were retained and stored out of direct light.
14. The gas samples were checked, caps tightened, and those containing gas bubbles discarded; the remainder were stored in ice chests to maintain them at approximate stream temperature. Large

³See figure 17 in background reference 3 (Kilpatrick and Cobb, 1985).

bottles of stream water were placed in the ice chests to help maintain them at the original stream temperature.

15. Except for checking injection rates, steps 5 through 14 were repeated at the downstream section, with the sampling schedule being altered as necessary on the basis of the results of the dye concentration-time plots at the upstream section.
16. Dye samples were taken manually at 1/2-h intervals until 9 p.m. ($t=15$ h), after which the automatic sampler anchored in the center was used. Manual dye samples were 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 12th sample taken by the floating sampler, which had been geared to sample every 45 min starting at 9 p.m.
17. All samples were returned to the office. Fluorometer dye standards were prepared from a sample of the 2×10^7 - $\mu\text{g/L}$ dye mixture that was injected. All dye samples, standards, background samples, and stream samples were analyzed at one temperature. These dye concentration-time data were plotted, and 12 gas samples, 4 from each point, were selected on the basis of their proximity to the dye peak. Twelve gas samples were also selected for downstream, and all 24 samples shipped to the laboratory. The laboratory was 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 were 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 $t=2.5$ h elapsed time and was essentially gone at $t=6.5$ h; thus, its duration was 4.0 h. Had the dye injection been an instantaneous slug injection instead of one lasting 1 h, the duration would have been 3 h.

Thus, at this specific section and point, dye and (or) gas tracer would have to be injected for a minimum of 3 h for a steady-state plateau to develop. As the data show, the dye curve is climbing toward the plateau level of $10 \mu\text{g/L}$ 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 h instead of 3 h. 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); instead, it should be realized that this last 2 h, during which the dye would be climbing toward a plateau, is a mirror image in shape of 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 indicate a response duration of about 8 h (if 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 planimetry or mathematically using a numerical integration scheme such as that employed in computing a current-meter discharge measurement. A program available from the Geological Survey Office of Surface Water will 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 attempt 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 kept 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 response curves are 577 and 466 $\mu\text{g/L} \times \text{minutes}$, respectively. The reduction in the areas of the downstream dye-response curves is due to dilution by a $4\text{-ft}^3/\text{s}$ 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 were computed for the upstream and downstream sections, respectively.

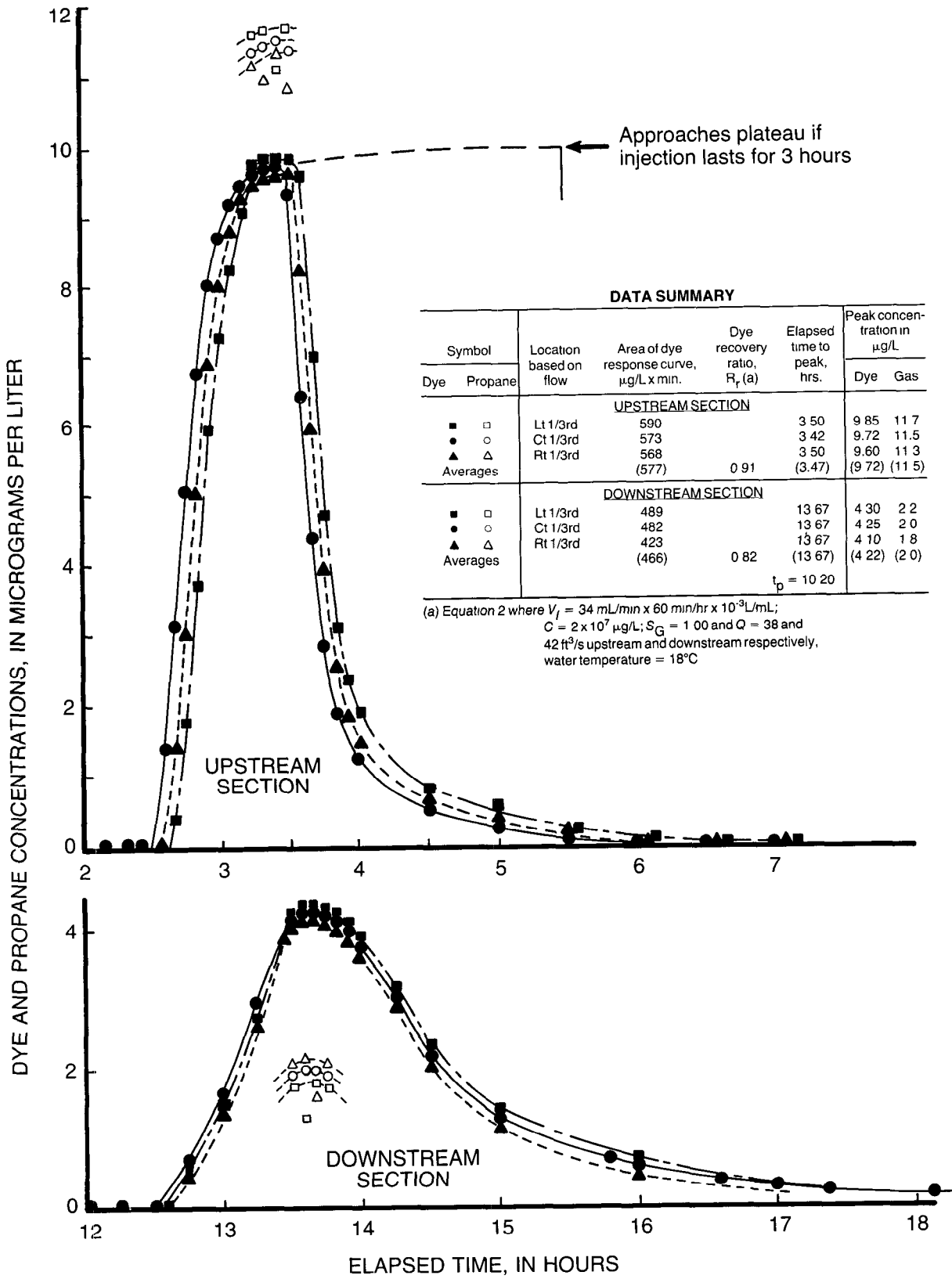


Figure 24.—Tracer data acquired for slug injection, peak method of reaeration measurement.

The traveltime between the peaks can be calculated 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" in 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 they 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 are greater than the dye concentrations at the upstream section but, because of desorption, are less than the dye concentrations at the downstream section.

Computations

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

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

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

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

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

$$K_{220} = 1.39 K_{pY} (1.0241)^{(20-Y)}$$

$$K_{220} = (1.39)(0.10/\text{h})(1.0241)^2 = 0.15 \text{ h}^{-1}$$

Field test—Area method

The reaeration coefficient can 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 can 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, a subsequent plot of the dye-concentration data would indicate that only definition of the gas-response curve just in the center of the flow at the downstream section would be 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. The 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.

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 eq. 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 , the numerical integration interval, has been chosen as 5 min, which results in 35 increments and defines the response curve with minimum error. The computer program available from the Geological Survey 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

DATA SUMMARY AND COMPUTATIONS

Location based on flow	Area of Gas Response Curve, $\mu\text{g/L} \times \text{min}$		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

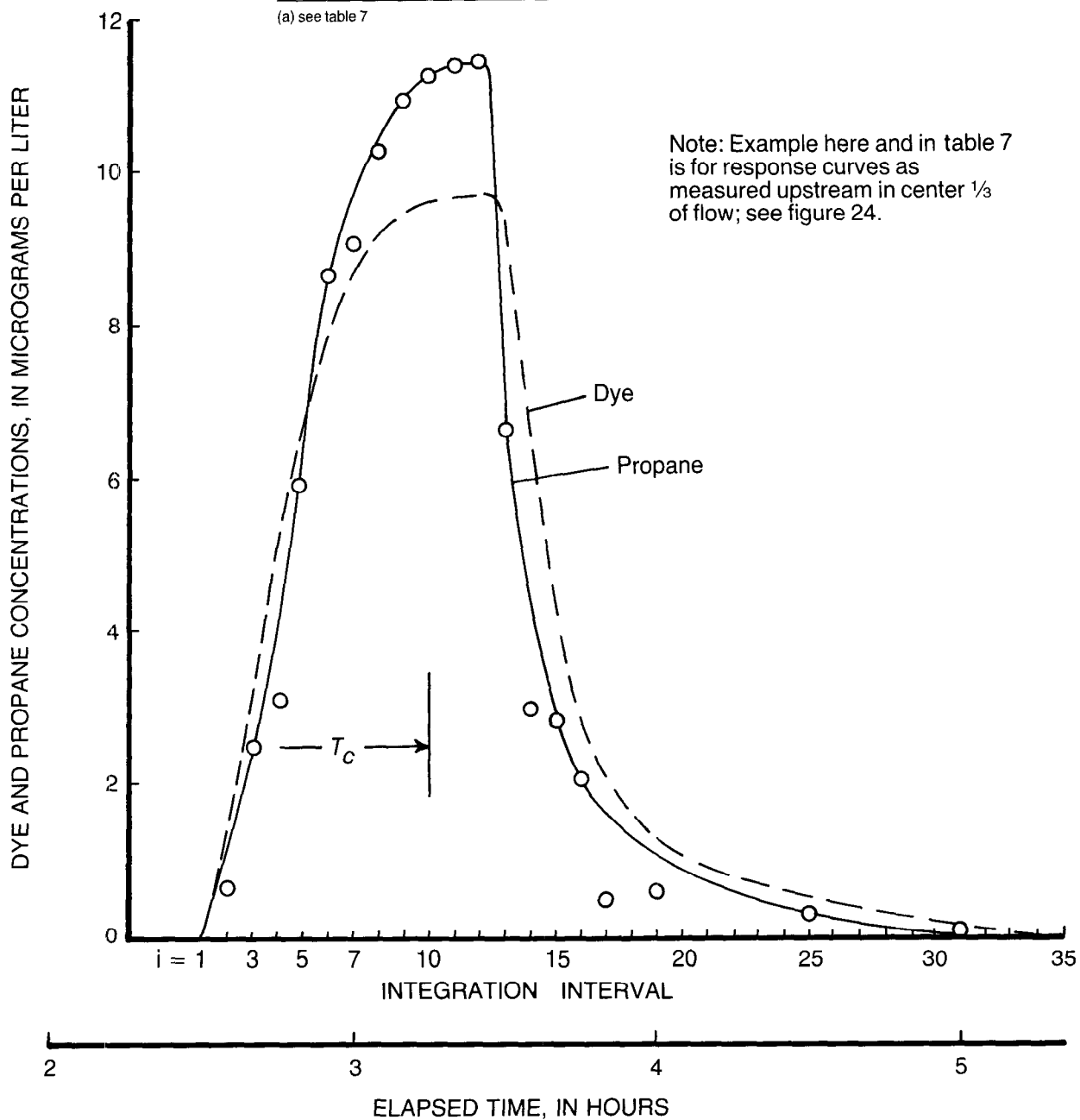


Figure 25.—Preparation of gas-response curve using dye-response curve as a guide and selection of numerical integration interval for computation of curve area and centroid.

Table 7.—Numerical integration of dye-response curve to obtain elapsed time to centroid

[Data are for upstream section at center of channel. $\mu\text{g/L}$, micrograms per liter; h, hours; min, minutes]

i	Elapsed time, t, from t = 0 in hours (1)	Dye concentration C_d , in $\mu\text{g/L}$ (2)	Area increment, $\Delta t \times C_d$ (a) ($\mu\text{g/L} \times \text{h}$) (3)	Incremental moment $t \times \Delta t \times C_d$ (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) $\Delta t = 5 \text{ min} = 0.0833 \text{ h}$ $\Sigma = 9.55 \mu\text{g/L} \times \text{h}$ $\Sigma = 30.889$ $A_C = 573 \mu\text{g/L} \times \text{min}$

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

Computations" table in figure 25 along with other pertinent data for computing the desorption coefficient.

The desorption coefficient can be computed, using equation 14, as

$$K_p = \frac{1}{10.97} \ln \frac{(571 \times 38)}{(185 \times 42)}$$

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

and K_2 at 20 °C can be computed, using equation 8, as

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

Note that in the "Data Summary and Computations" table (fig. 25) 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 for a CRI type of reaeration measurement is 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.

Table 8.—*Estimated properties of slug-response curves for scheduling sampling for constant-rate-injection type of reaeration test*

[Note: Dye injection is instantaneous and gas injection is constant for 20 hours. All times in hours. C_p , observed peak dye concentration]

Description	Upstream section	Downstream section
<u>DYE RESPONSE CURVE</u>		
1. Elapsed time to peak, T_p	2.8	13.9
2. *Duration for truncation at 10 percent C_p : T_{d10}	1.7	6.2
3. Buildup from leading edge to peak, t_b : $t_b = \frac{T_{d10}}{3}$	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_t , at 0 percent C_p : (4) + (6)	8.4	28.8
<u>GAS PLATEAU</u>		
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 one-half hour to bracket 18 hours)	18.0	

*From figure 12

This may influence overall scheduling of the test, in particular the timing of gas sampling.

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

Narrow streams—One-dimensional dispersion

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

Dye injection

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

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

Gas injection and tank size

Using figure 11, $Q_m e^{T_p K_p}$ was computed for the most downstream section as before, and it was determined that a gas injection rate of 3.23 ft^3/h was needed for a plateau of 1 $\mu\text{g/L}$ (assuming an absorption efficiency of 10 percent). Because a plateau concentration of 5 $\mu\text{g/L}$ was desired at the most downstream

section, a rate of $5 \times 3.23 \text{ ft}^3/\text{h}$, or $16.15 \text{ ft}^3/\text{h}$, was necessary. (A rate of about $16 \text{ ft}^3/\text{h}$ 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 h. From figure 12 it was determined that a constant-rate gas injection of approximately 17 h would be necessary to produce a steady-state gas plateau; a 20-h continuous injection was assumed, to allow time for sampling. Thus, a tank containing in excess of 36 lb of propane ($1.8 \text{ lb/h} \times 20 \text{ h}$) was required. A 50-lb tank would be sufficient and not involve using the last 20 percent of the tank.

Preliminary test schedule

In planning the test, the arrival and duration of passage of the dye response was estimated as was done for the SI test. Table 8 is similar to table 6, but for a slug injection of dye and a 20-h continuous injection of propane gas. Figure 26 was prepared from these data to aid in selecting injection and sampling schedules to best use 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 of its appearance 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 were scheduled for sampling exactly as was done for the SI test. Since dye sampling is far more extensive than gas sampling, scheduling should favor this effort. A 6 a.m. slug injection of dye still seemed the best, as it allowed most of the sampling of the downstream dye-response curve to take place during daylight hours; automatic sampling was thought to be sufficient from about 9 p.m. on.

Gas injection was scheduled to start at 6 a.m. ($t=0$) and to terminate 20 h later, at 2 a.m. of the second day. Note that this is 10 h *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 $t=8.4 \text{ h}$ to 22.2 h . It is recommended that gas samples be taken upstream as soon as a stable plateau is known to exist; if the number proves to be excessive, the extra samples 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 was 11.8 h. Therefore, it appeared likely that the upstream gas samples that would be used would

correspond to about $t=18 \text{ h}$, 12 h before gas sampling downstream at $t=30 \text{ h}$. A logical schedule for the upstream site seemed to be to sample for gas every hour starting at $t=9 \text{ h}$ and every $\frac{1}{2} \text{ h}$ at about $t=16 \text{ h}$.

The time at which a steady-state plateau is reached downstream would be apparent from observation when the recession of the dye-response curve reached background levels. This could be well before the estimated 28.8 h. Sampling upstream at $t=9 \text{ h}$ 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 should dictate actual gas sampling.*

Field test—Constant-rate-injection method— One-dimensional dispersion

Preliminary preparation made the afternoon before the actual test included

1. Reference points were established at the injection and upstream sections and a temporary staff gage was placed 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 was located distancewise from the left bank. Stage 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 the next morning.

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

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 $7 \text{ ft}^3/\text{h}$ was set on the rotameter. A platform scale was placed under the gas tank, and weight change with time noted periodically (see fig. 27).⁴ 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.⁵
5. One hydrologist stayed at the injection site until the injection rate was observed to be constant. As can be seen by the data defined by a dashed

⁴See figure 17 in background reference 3 (Kilpatrick and Cobb, 1985).

⁵See section "Alternative Method of Analysis and Computation" in background reference 3 (Kilpatrick and Cobb, 1985).

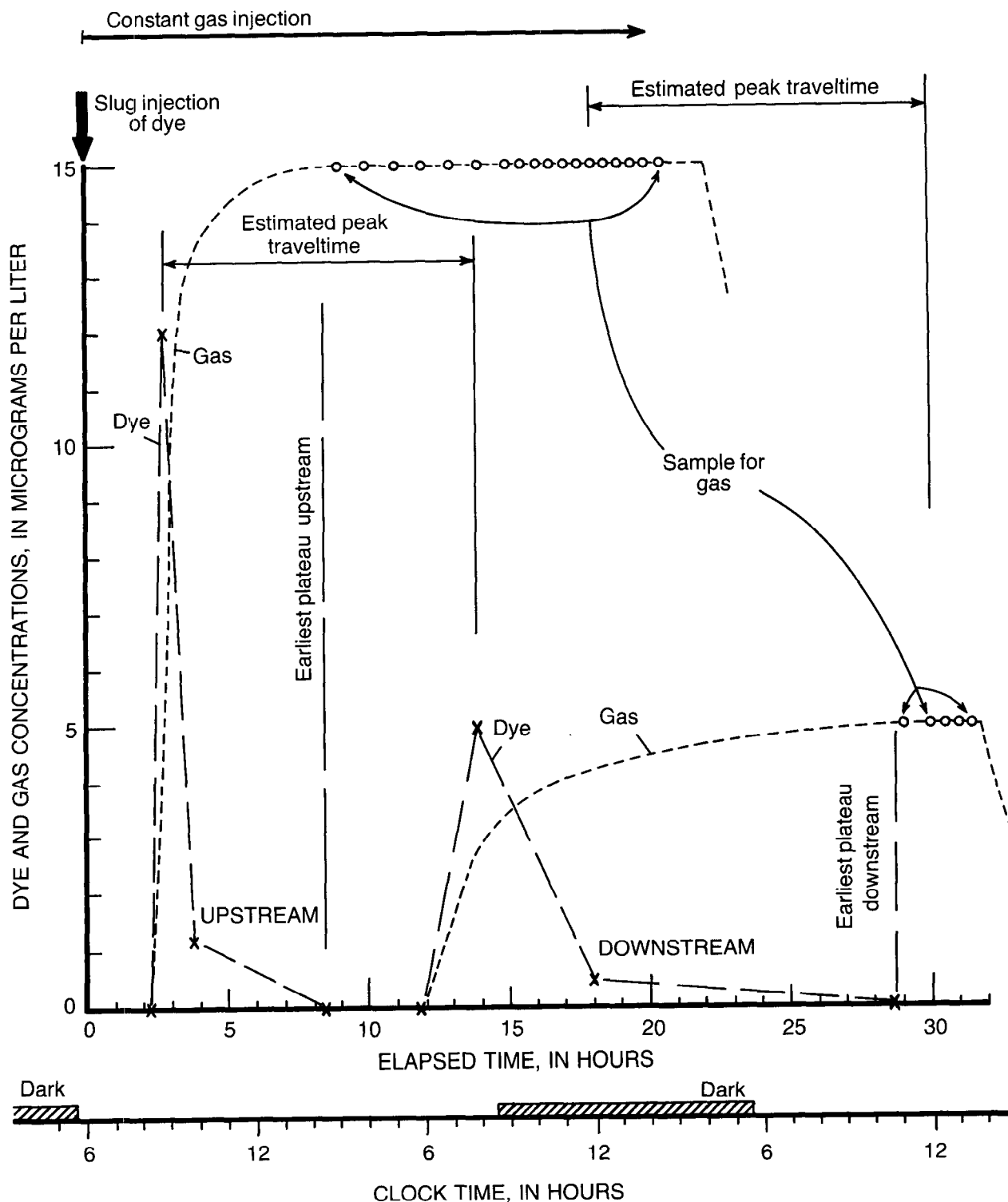


Figure 26.—Sketch of estimated response curves for guidance in scheduling constant-rate-injection type of field reaeration test.

line in figure 27, a constant rate was not attained until 7 a.m. The hydrologist also collected several background samples for use in fluorometric analysis.

6. Another hydrologist proceeded to the upstream section constituting the test reach and made a current-meter discharge measurement and observed stage both before and after.

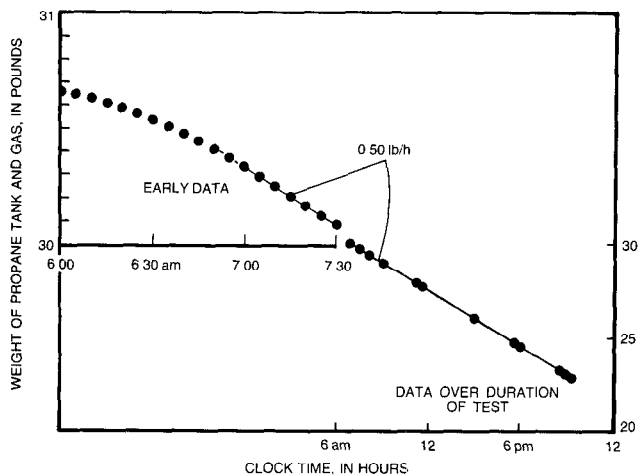


Figure 27.—Determination of rate and constancy of propane gas injection by measurement of weight change with time.

7. Upon completion of the current-meter measurement, the tagline was 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 was set up in a vehicle and dye sampling at 5-min intervals was begun at the centerpoint at $t=2$ h. Samples were analyzed immediately and plotted on a graph such as that shown in figure 28. (Note that fig. 28 is a final data plot based on careful laboratory analyses of dye and gas samples; for brevity it is discussed here as if it were the *field analysis* of the dye data.)
9. Stream water temperature was observed to be 18 °C.
10. With the first appearance of dye at the upstream section, dye sampling proceeded at approximately 5-min intervals at all three sampling points; for clarity, only the center dye-response curve is presented in figure 28.
11. As the dye peak passed, sampling was less frequent.
12. The dye samples were retained and stored out of direct light.
13. The data plot of dye concentration (fig. 28 or dial readings) versus time was examined and used to predict new times of travel to the downstream section.⁶ For example, while the measured leading edge and estimated time of arrival were

identical, the trailing edge was at about $t=5$ h instead of 8.4 h as had been estimated; sampling schedules at the downstream section were modified as necessary.

14. Examination of figure 28 indicated the trailing edge of the upstream dye-response curve to be at $t=5$ h. Since the gas injection was an hour late in stabilizing (see fig. 27), the gas plateau at the upstream section would be fully stabilized at $t=6$ h. Starting at $t=6$ h (12 noon), sets of three gas samples were taken at $\frac{1}{2}$ -h intervals upstream.
15. Stage measurements were made periodically at the upstream section, and no additional discharge measurements were made unless a 10-percent or greater change in discharge had occurred.
16. All equipment was moved to the downstream section and steps 6 through 12 were repeated as newly scheduled.
17. As the downstream dye cloud started to recede, the centroid traveltimes upstream and downstream were estimated as 3 and 14 h, respectively; thus, gas samples taken upstream and downstream 11 h apart represented the same fluid element undergoing gas desorption.
18. As the downstream dye-response curve continued to recede (fig. 28), it was estimated that its duration would be about 6 h (18.5–12.5 h). Furthermore, if the gas injection had been stable initially, a stable gas plateau would be reached at $t=18.5$ h. Since it didn't stabilize until an hour after the start (see fig. 27), a stable gas plateau would be reached at $t=19.5$ h. Since this corresponds to 1:30 a.m. on the second day, a decision had to be made as to whether to complete the test that night or the next morning.

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

If the test was to be completed the next morning, the gas samples could be taken at $t=26$ h (8 a.m.) downstream, and the gas samples collected upstream at $t=15$ h (9 p.m.) could be used as representative matching samples ($t_c=11$ h).

Note that continuous gas injection for 7 h (19.5–12.5 h) would be sufficient to *just* establish a gas plateau at $t=19.5$ h. Thus, if the test was to be completed that night, the gas injection could be terminated at 1 p.m. or if the next morning, at 7:30 p.m. on the first day (26.0 h–19.5 h+7 h=13.5 h, or 7:30 p.m.). In either case, gas injection could be safely terminated well in advance of sampling.

⁶See figure 15 in background reference 2 (Hubbard and others, 1982).

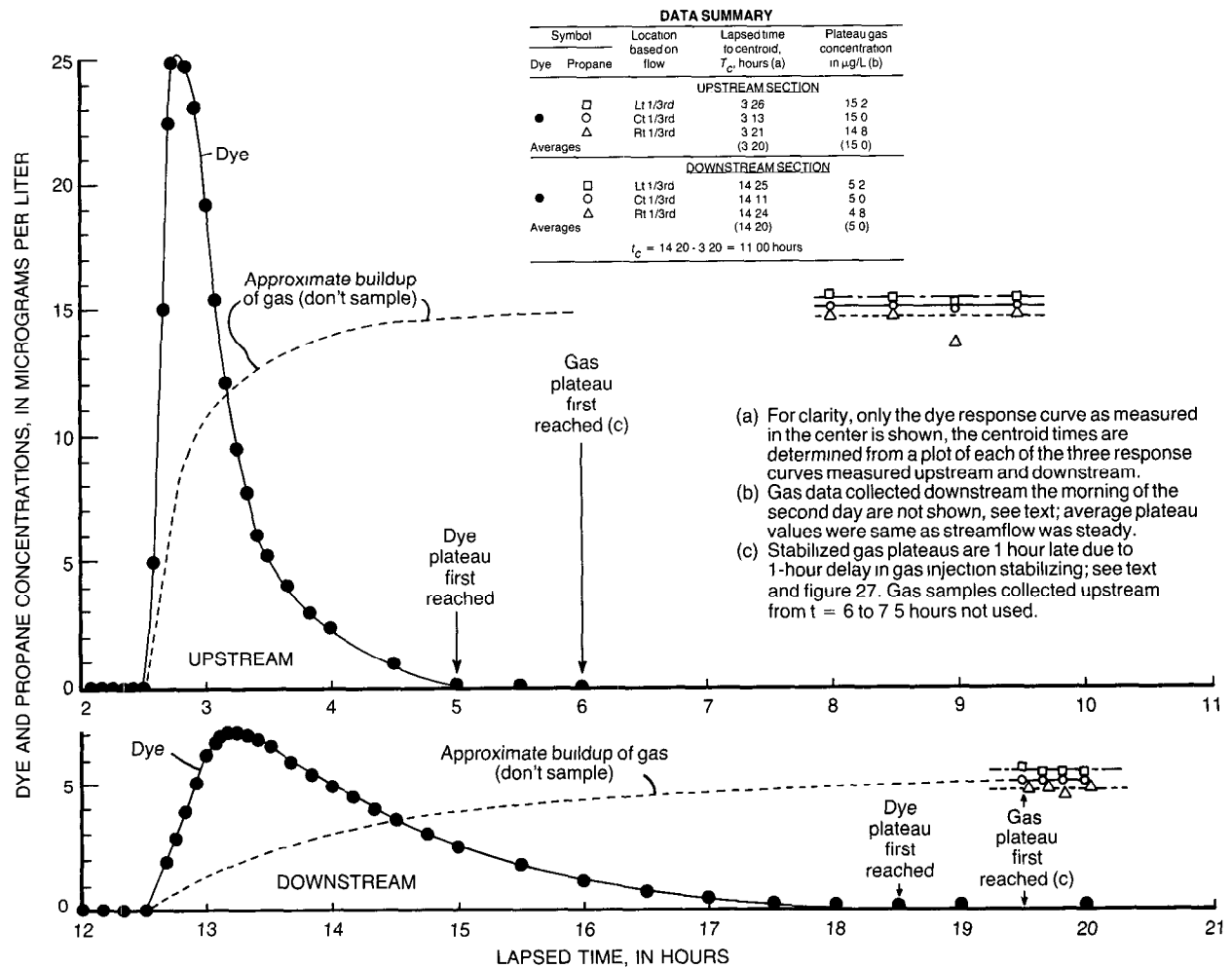


Figure 28.—Tracer data acquired for constant-rate-injection method of reaeration measurement.

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.

19. Since it was necessary to sample the downstream dye-response curve through the night with the automatic sampler and recover the samples the next morning, it was decided to collect gas samples downstream every 10 min for $\frac{1}{2}$ h starting at 1:30 a.m. and 8 p.m., to be matched by 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. on the first day, and several rate checks were made at this time (see fig. 27). This allowed time for sampling; furthermore, it was this hour ($t = 16$ h) before sufficient dye data were available at the downstream section to permit the above decisions to be made.

21. All dye samples were stored out of direct light, gas samples were checked, caps tightened when necessary, and any containing gas bubbles discarded; the remainder were stored in ice chests with little or no chilling as required to maintain them at approximately stream temperature.
22. All samples were returned to the office. Fluorometer dye standards were prepared from a sample of the dye mixture that was injected. Note that the solution injected has a concentration of $0.952 \times 10^7 \mu\text{g/L}$, in contrast to $20 \times 10^7 \mu\text{g/L}$ for straight rhodamine WT.⁷ This shortens the time for preparation of fluorometric standards as well as improves accuracy because the first serial dilution has in effect been made in the field and is the same solution that was injected.
23. All dye samples, standards, background samples, and stream samples were analyzed at one

⁷Using equation 7 in background reference 3 (Kilpatrick and Cobb, 1985).

temperature. These dye concentration-time data were plotted as in figure 28. Since two sets of gas data were collected, 48 gas samples were chosen for shipment to the laboratory. Each data set consisted of 24 samples, 12 upstream and 12 downstream (4 from each of three sampling points). The upstream and downstream samples were taken 11 h apart so 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 were all plotted in figure 28 for both upstream and downstream sections. Just the dye data collected in the center are shown for clarity.

As can be seen in figure 28, the dye concentration-time data plot smoothly, with the peak falling from 25.0 $\mu\text{g/L}$ upstream to 7 $\mu\text{g/L}$ 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 travel-times shown in the "Data Summary" in figure 28. The average time of travel from upstream to downstream sections, t_c , was 11.00 h.

Plateau gas concentrations were found to have dropped on the average from 15.0 $\mu\text{g/L}$ upstream to 5.0 $\mu\text{g/L}$ downstream. These data, along with stream discharges, can be used with equation 17 to compute an estimated propane gas desorption coefficient:

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

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

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

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 piece of data

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 similar 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 min 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, 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 indicated $K_p=0.091 \text{ h}^{-1}$, or the same as estimated by equation 17. A third trial computation using $K_p=0.091 \text{ h}^{-1}$ verified this calculation.

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

Information on a computer program to perform all the computation shown in table 9 is available from the Geological Survey Office of Surface Water in Reston, Va.

Wide streams—Two-dimensional dispersion

Example

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

Preliminary tests, planning, and preparations

It was 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

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

[See text and list of "Symbols and Units" for explanation of variables. $\mu\text{g/L}$, micrograms per liter; hrs, hours; h, hours; ft^3/s , cubic feet per second]

i	Elapsed time, t_i hours	Dye concentration C_d , (a) $\mu\text{g/L}$	Area increment $C_d \Delta t$ (b) $\mu\text{g/L} \times \text{hrs}$	Incremental moment $t_i \times \Delta t \times C_d$ $\mu\text{g/L} \times (\text{hrs})^2$	Trial computation of K_p						
					$\frac{\Delta t}{A_z}$	Trial 1: $K_p=0.090/\text{h}$		Trial 2: $K_p=0.100/\text{h}$		Trial 3: $K_p=0.091/\text{h}$	
						$e^{K_p t_i}$	$\frac{\Delta t C_d}{A_z e^{K_p t_i}}$	$e^{K_p t_i}$	$\frac{\Delta t C_d}{A_z e^{K_p t_i}}$	$e^{K_p t_i}$	$\frac{\Delta t C_d}{A_z e^{K_p t_i}}$
(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
$A_z = \Sigma = 16.81$ $\Sigma = 52.68$					$\Sigma = 0.755$		$\Sigma = 0.732$		$\Sigma = 0.753$		
$T_{C_z} = 52.68/16.81 = 3.13$ 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
$A_z = \Sigma = 13.92$ $\Sigma = 196.40$					$\Sigma = 0.283$		$\Sigma = 0.246$		$\Sigma = 0.278$		
$T_{C_z} = 196.40/13.92 = 14.11$ hrs											

$$\text{Calculated} \left[\frac{\sum_{i=1}^N \frac{\Delta t C_d}{A_z e^{K_p t_i}} \right]_u \bigg/ \left[\frac{\sum_{i=1}^N \frac{\Delta t C_d}{A_z e^{K_p t_i}} \right]_d \bigg|_{z=50} = \frac{0.755}{0.283} = 2.67 \quad \frac{0.732}{0.246} = 2.98 \quad \frac{0.753}{0.278} = 2.71$$

$$\text{Measured} \left[\frac{[\bar{c}_g Q]_u}{[\bar{c}_g Q]_d} \right]_{z=50} = (38 \text{ ft}^3/\text{s} \times 15.00 \mu\text{g/L}) / (42 \text{ ft}^3/\text{s} \times 5.00 \mu\text{g/L}) = 2.71$$

- (a) Dye concentrations are picked from response curves shown in figure 28.
- (b) $\Delta t = 5$ minutes (0.083 hours) for upstream section and 10 minutes (0.167 hours) for downstream section.

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 did 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 was a significant change in discharge by the third day and whether the initial sections chosen proved satisfactory based on analysis and interpreta-

tion of the preliminary dye slug test data. These data would provide true time-of-travel information and might require revision of the sections to obtain sufficient residence time or better mixing.

Selection of test reach

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

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

Table 10.—Summary of desorption and reaeration coefficient computations for constant-rate-injection method—One-dimensional dispersion
[See text and list of “Symbols and Units” for explanation of variables. h⁻¹, per hour]

Streamline z, percent of flow	Measured $\frac{[\bar{c}_g Q]_u}{[\bar{c}_g Q]_d}$ (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

Thus, mixing might be expected to be good at the very end of the 4-mi reach; that is, a nearly one dimensional (longitudinal) dispersion state would be reached. Two-dimensional dispersion (lateral mixing

and longitudinal dispersion) were expected to exist at sections closer to the injection point.

Equation 28 can be used to estimate a propane desorption coefficient for a 15,000-ft reach:

$$K_p = (0.039) \frac{\Delta H}{t_c}$$

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

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

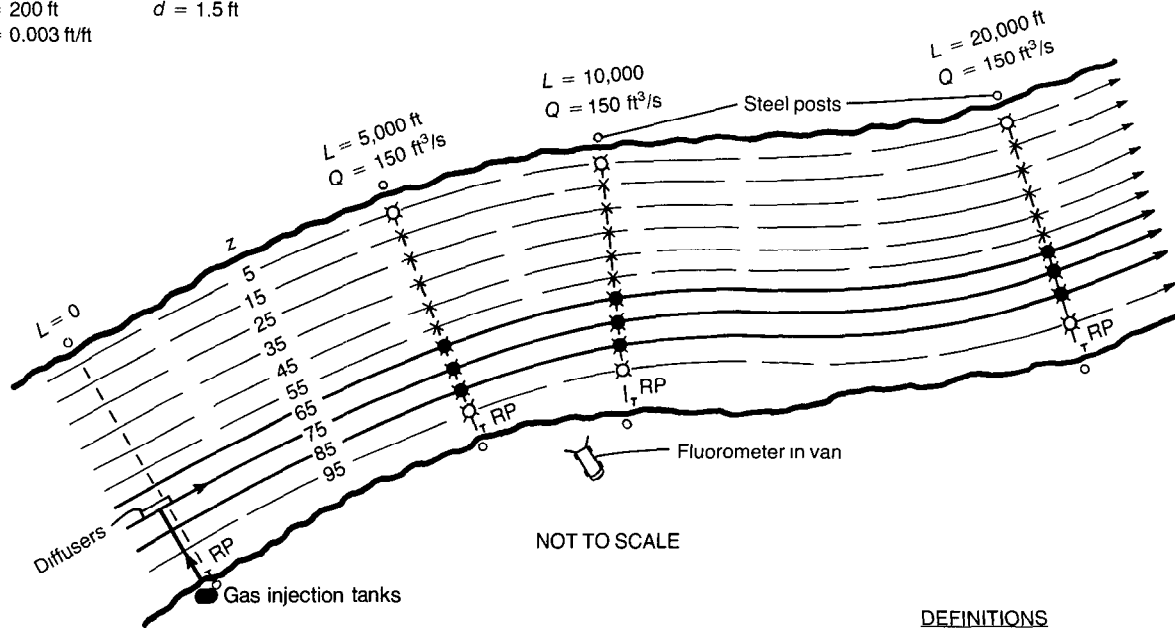
Therefore, if the test were performed in a 15,000-ft reach, $K_p t_c \approx (8.33 \text{ h})(0.21 \text{ h}^{-1}) \approx 1.75$, which is greater than 1.0 and would suggest that a shorter reach could be used. Since these are very approximate estimates, the initial decision was to locate measuring sections at 5,000, 10,000, and 20,000 ft downstream from the injection point located on the most upstream section.

Estimated elapsed times and durations

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

AVERAGE STREAM CONDITIONS

- Q = 150 ft³/s v = 0.5 ft/s
- B = 200 ft d = 1.5 ft
- s = 0.003 ft/ft



DEFINITIONS

- Location to completely sample dye response curves
- Location to sample just trailing edge of dye response curves
- × Location to sample gas plateaus

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

Table 11.—Summary of average dye-response curve properties at three sections in proposed test reach on the Pat River
[ft, feet]

Property	Section at		
	5,000 ft	10,000 ft	20,000 ft
Elapsed time to peak, T_p , hours	2.78	5.56	11.11
Duration of 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_t , hours ($T_e + T_d$)	8.33	14.26	24.69

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 was to begin sampling on streamlines $z = 65, 75,$ and 85 percent at elapsed times of $1.5, 4,$ and 8 h 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 $5 \mu\text{g/L}$ at $20,000$ ft would be $4,500$ mL. An average peak of about $5 \mu\text{g/L}$ should be obtained at the $20,000$ -ft section, with lower concentrations near the left streambanks, especially at the $5,000$ -ft section. For this reason, if in doubt, an amount of dye to produce an average peak of $10 \mu\text{g/L}$ or more could be used if no water-supply intakes existed in the test reach.

Gas injection

Water depths at the point of injection were known to be more than 5 ft. This, and the availability of new diffusers, suggested that the efficiency of the gas-injection system might be as high as 20 percent. An average plateau concentration of $5 \mu\text{g/L}$ at the downstream section was sought, and this value used in computing the gas-injection rate. Using figure 11, with a peak traveltime of 11.11 h (for $20,000$ ft), an estimated K_p of 0.21 h^{-1} , an average gas plateau of $5 \mu\text{g/L}$, and ϵ equal to 0.2 yielded a propane injection rate of $75 \text{ ft}^3/\text{h}$. This exceeds the upper limit of the gas-rate controller. The scale on the right of figure 11 indicates that this rate is equivalent to about 8.5 lb/h . Table 11 indicates a maximum cloud duration of 15.56 h, which is the length of gas injection needed if

preliminary estimates are correct. This amounts to a total of about 132 lb of propane; thus, two 100 -lb tanks would be required, allowing the injection rate for each tank to be about $38 \text{ ft}^3/\text{h}$ of propane. Using equation 34, the air rate to be set on each rotameter was about $17 \text{ ft}^3/\text{h}$.

Performance of test

Preparations

The first day, the four sections making up the test reach were monumented with steel posts on both banks. Stage RP's (reference points) were established on the right bank of all four sections. Taglines were stretched across at the four sections, and conventional boat-type current-meter discharge measurements made; stage was measured concurrently with each discharge measurement. The measurements were computed immediately, with discharge recorded accumulatively. Ten points were then located on each taglined section at the $5,000$ -, $10,000$ -, and $20,000$ -ft distances. As shown in table 5, the 10 points were 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 buoys.

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

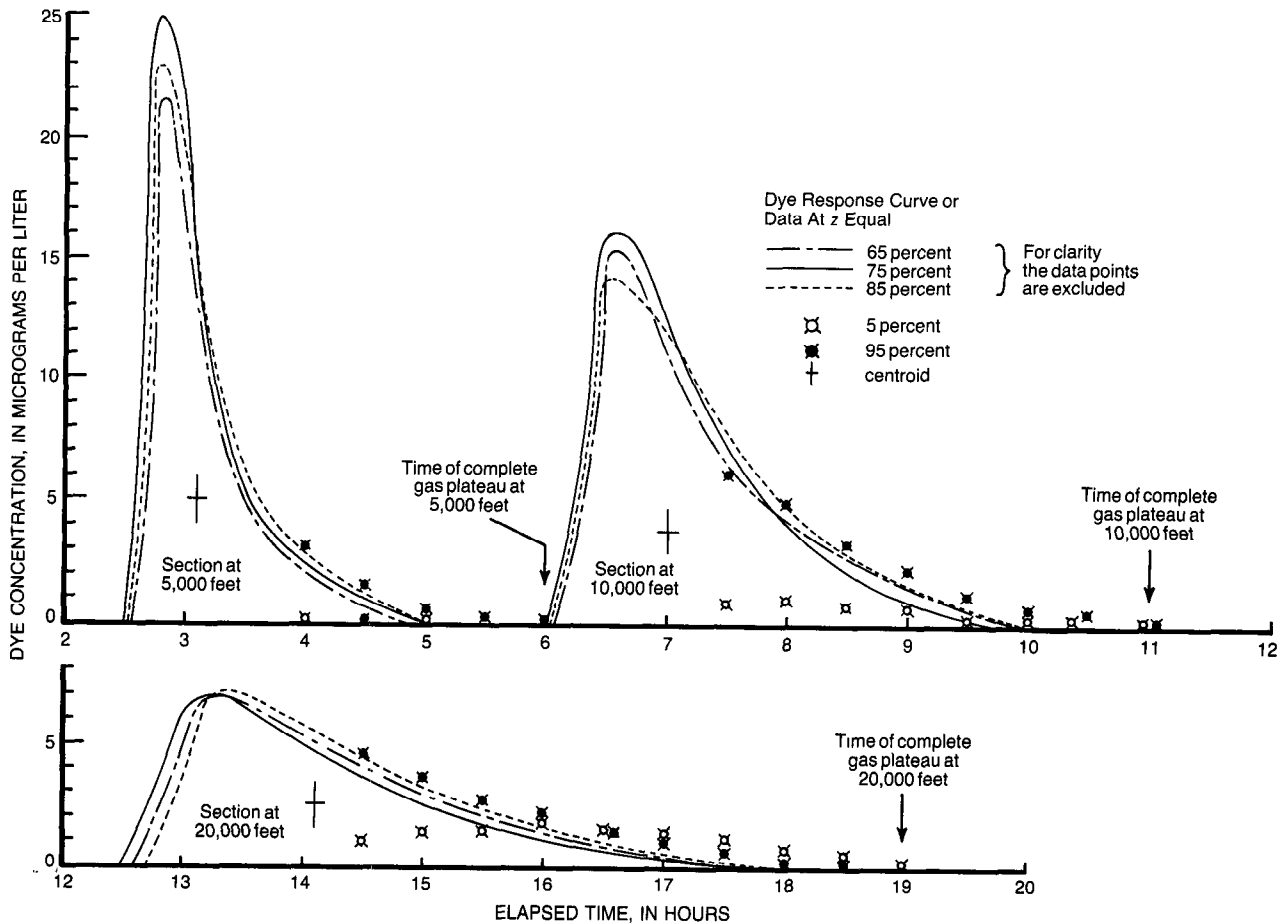


Figure 30.—Graph of dye-tracer response curves and data for constant-rate-injection method of reaeration measurement with two-dimensional dispersion.

Dye test

At 6 a.m. ($t=0$) on 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 h downstream at the 5,000-, 10,000-, and 20,000-ft 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 h, which was considerably slower than estimated in table 11.⁸

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 concen-

trations 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 was made to use all three sections in the gas test; thus, two sets of data were available: 5,000 to 20,000 ft and 10,000 to 20,000 ft.

All dye samples were 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-ft section at $t=10$ h.

Propane test

The dye-response curves and data obtained as a result of an actual slug injection and sampling as

⁸The reader will note that for simplicity and comparison purposes, the dye-response curves used in the previous example are used here as applying to $z=75$ at the 5,000- and 20,000-ft sections, respectively. Furthermore, the data plotted in figure 30 are those obtained later in the laboratory following careful fluorometric analysis but are discussed here as if they were the field-data plots.

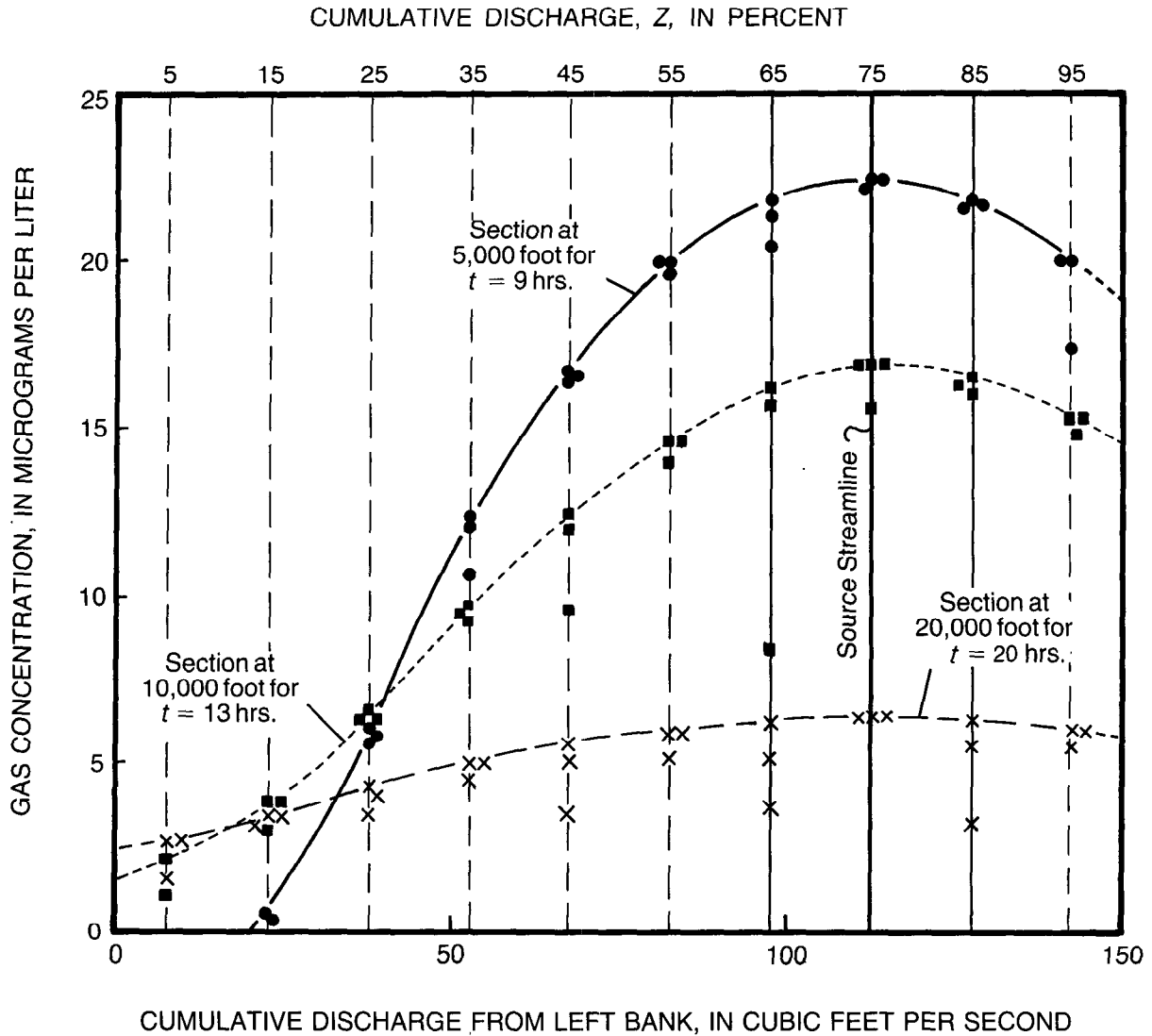


Figure 31.—Graph showing lateral distribution of plateau gas concentrations at the three measuring sections on the Pat River.

shown in figure 30 are extremely valuable in determining *exact* information on the required duration of gas injection and the time at which 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; their uniformity suggests 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-ft section. Similarly, lateral mixing would not be too good even at the

20,000-ft section, as injection at the 75-percent streamline amounts to a partial side injection.

The fully defined dye-response-curve data were 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-ft section. In the example, if gas injection were sufficiently long, stable plateaus would exist at 6.0, 11.0, and 19.0 h elapsed times at the 5,000-, 10,000-, and 20,000-ft sections, respectively.

Inspection of figure 30 indicates centroid travel-times of approximately 11 h between sections 5,000 and 20,000 ft and 7 h between 10,000 and 20,000 ft. Thus, if gas sampling were performed at $t=19$ h at the 20,000-ft section, it should be performed at $t=8$ and 12

h at the 5,000- and 10,000-ft sections, respectively, to represent the same water mass in transport in which gas is being desorbed. Inspection of figure 30 indicates that stable plateaus will have existed for 2 h (8–6 h) at the 5,000-ft section and 1 h (12–11 h) at the 10,000-ft section.

The dye data at the 20,000-ft section also indicate that a *minimum* gas injection of 6.5 h (19.00–12.50 h) would be required. Obviously it would be desirable to inject longer to allow time for sampling the gas at 20,000 ft.

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 ft³/h was started from each tank at 10 p.m. ($t=0$ for the gas data) on the second day; it lasted for 10 h and was discontinued at 8 a.m. on the third day. Gas sampling was performed at $t=9$ h (7 a.m.), 13 h (11 a.m.), and 20 h (6 p.m.) at 5,000, 10,000, and 20,000 ft, 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-ft section at 9 a.m. and at the 20,000-ft section at 5 p.m. No significant changes were noted. Had there been significant change, say ± 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 sent 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 solid, as it is these data for the 5,000-ft and 20,000-ft sections that are 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 bank with cumulative discharge on streamlines. As can be seen, lateral mixing between the injection point and the 5,000-ft section was insufficient to yield any gas concentrations along the left bank and yielded only very

low concentrations at the 10,000-ft section. Similarly, lateral mixing was still not complete at the 20,000-ft section, owing 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 were 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-ft sections. Note that zero concentrations were present at the 5,000-ft section but posed no problems in computing ϕ .

Computation of desorption coefficient

Equation 20 can now be numerically integrated in a manner similar to the numerical integration of equation 18 to yield an equation that includes the ratio of the distribution factors applicable to each streamline:

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

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 are not repeated. As before, an initial value of K_p can be estimated from equation 17 (along streamline $z=75$):

$$K_p = \frac{1}{t_c} \ln \frac{(\bar{c}_g Q)_u \phi_d}{(\bar{c}_g Q)_d \phi_u} \\ = \frac{1}{10.98} \ln \left[22.50 \times \frac{150}{10} / 6.40 \times \frac{150}{10} \right] \left[\frac{1.245}{1.589} \right] \\ K_p = \frac{1}{10.98} \ln [3.52] [0.784] = 0.092 \text{ h}^{-1}$$

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 ratio on the left. Table 13 shows a summary

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

[See text and list of "Symbols and Units" for explanation of variables. $\mu\text{g/L}$, micrograms per liter]

z in percent	\bar{c}_g $\mu\text{g/L}$	$\frac{\Delta Q_z}{Q}$	$\bar{c}_g \frac{\Delta Q}{Q}$	$\phi_z = \frac{\bar{c}_g}{\sum \bar{c}_g \frac{\Delta Q}{Q}}$
5,000-FOOT SECTION				
5	0	0.1	0	0.035
15	0.50	.1	.05	.424
25	6.00	.1	.60	.862
35	12.20	.1	1.22	1.179
45	16.70	.1	1.67	1.412
55	20.0	.1	2.00	1.540*
65	21.8*	.1	2.18	1.589**
75	22.5**	.1	2.25	1.547
85	21.9*	.1	2.19	1.412
95	20.0	.1	2.00	
		1.0	$\Sigma = 14.16$	
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	$\Sigma = 11.41$	
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	$\Sigma = 5.14$	

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

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

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 the gas transport ratios are approximately 2.75, as the residence time was sufficient from 5,000 to 20,000 ft to produce a large desorption of gas. In contrast, from 10,000 to 20,000 ft 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.

Regionalization

As in most hydrologic studies, it is impractical to attempt to measure all streams for their reaeration coefficient; hence, numerous empirical equations have been developed to apply to a given region (Parker and Gay, 1987). 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 empirical 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 wind-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 be possible to estimate reaeration coefficients from photographs of the stream reach. Thus, representative photographs of the stream reach at the flow being tested are advisable.

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

[See text and list of “Symbols and Units” for explanation of variables. h⁻¹, per hour]

Streamline z, percent of flow	Reach 5,000 to 20,000 feet		Reach 10,000 to 20,000 feet		Average K_{20} for 5,000- to 20,000- foot reach h ⁻¹ (c)
	Measured $\left[\frac{[\bar{c}_g Q] \phi}{[\bar{c}_g Q]_d \phi} \right]_z$ (a)	Final K_D as calculated by trial h ⁻¹ (b)	Measured $\left[\frac{[\bar{c}_g Q] \phi}{[\bar{c}_g Q]_d \phi} \right]_z$ (a)	Final K_D as calculated by trial h ⁻¹ (b)	
(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	0.13
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	
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

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, differing in the mode of injection and, hence, the mode of sampling are presented. Both have advantages and disadvantages, and both require greater effort and care in their performance than do most other types of tracer studies if accurate results are to be obtained. However, both are fully within the capabilities of the average hydrologist. Hydrologists should become familiar with routine dye tracer and fluorometry techniques before attempting tracer reaeration measurements; these are well described in the other manuals in this series (Hubbard and others, 1982; Kilpatrick and Cobb, 1985; Wilson and others, 1986).

The equipment required for both types of tests 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. The CRI method may require less gas sampling, although sampling of the dye-response curves is essentially the same for both methods; an exception is 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. Because the test can be performed closer to the point of injection and, hence, in a region where two-dimensional dispersion may exist, longer test reaches can be used, and therefore the greater accuracy that results from the use of greater gas-residence times can be 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 that are 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 Geological Survey 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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