



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

## Chapter A18

### DETERMINATION OF STREAM REAERATION COEFFICIENTS BY USE OF TRACERS

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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,  $\phi_z$  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;  $\Delta Q_z$  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  $\phi$  approaches 1.00.

The data requirements to compute  $\phi_z$  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  $\phi$  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  $\phi$  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  $\phi$ . 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  $\phi$  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,  $\Delta H$  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  $\phi$  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  $\mu\text{m}$  (micrometers) in diameter has been used successfully. Crawford (1985) used a series of Zimpro passive diffusers having a 1.5- to 2.0- $\mu\text{m}$  pore size mounted in

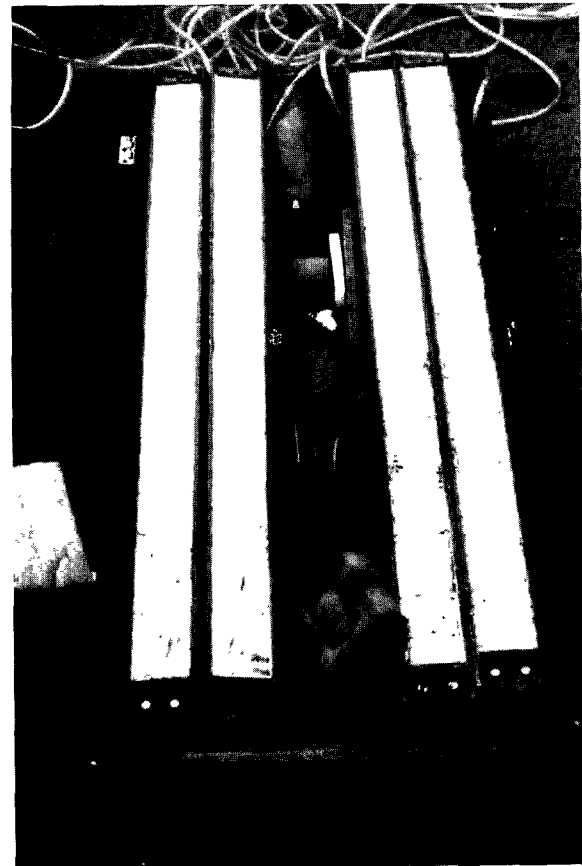


Figure 6.—Ceramic diffuser plates stored and transported in custom-made box.

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

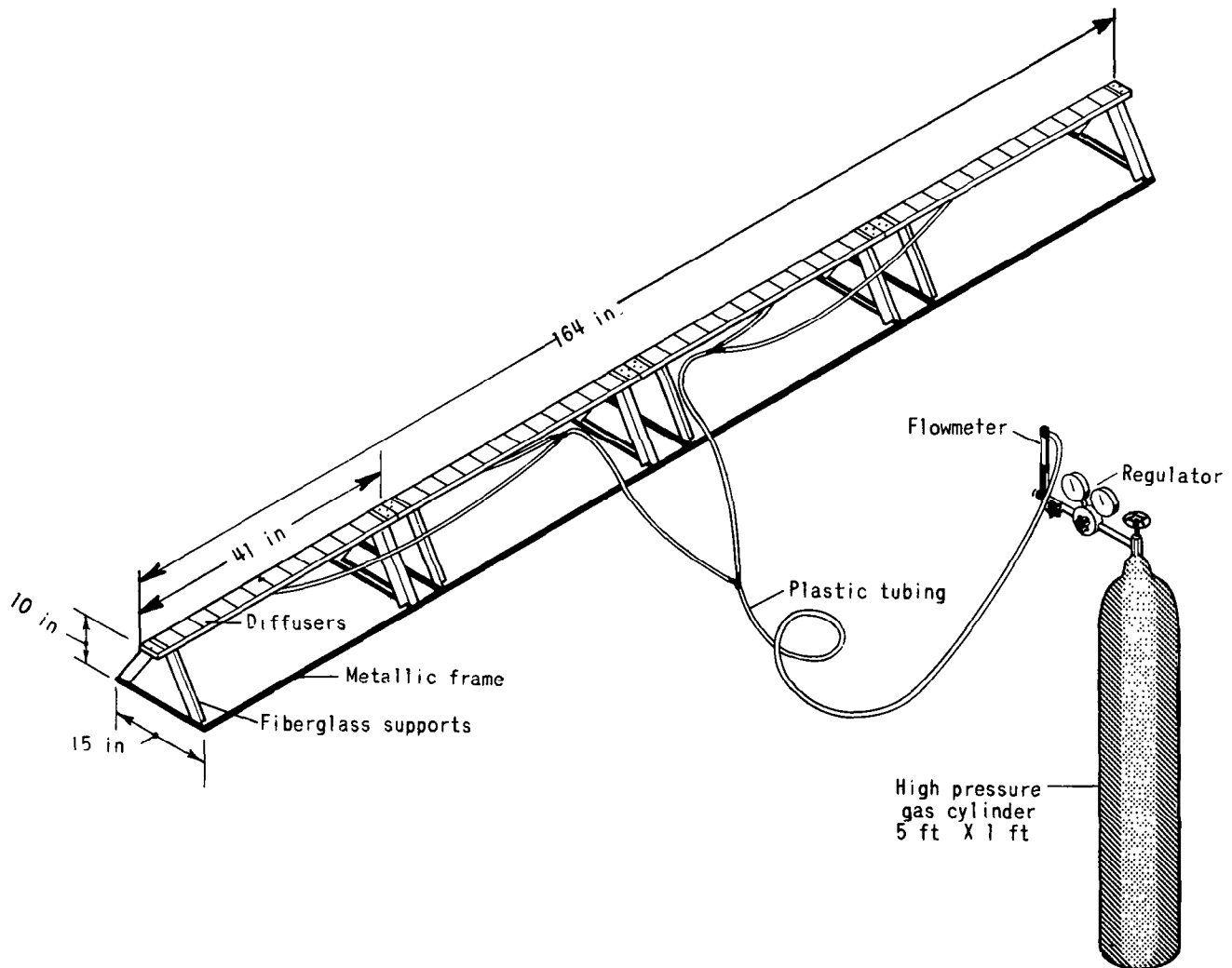


Figure 7.—Gas-injection apparatus using flat-plate porous ceramic diffusers epoxied into channels to form four racks. (From Crawford, 1985.)

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. ft<sup>3</sup>/s, cubic feet per second]

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

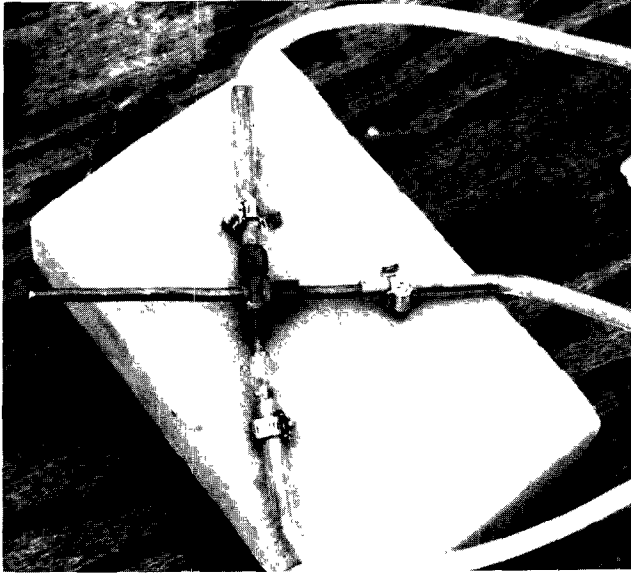


Figure 8.—Three-way manifold used to supply gas to diffusers from one gas cylinder.

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 ft<sup>3</sup>/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 CO<sub>2</sub> (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;



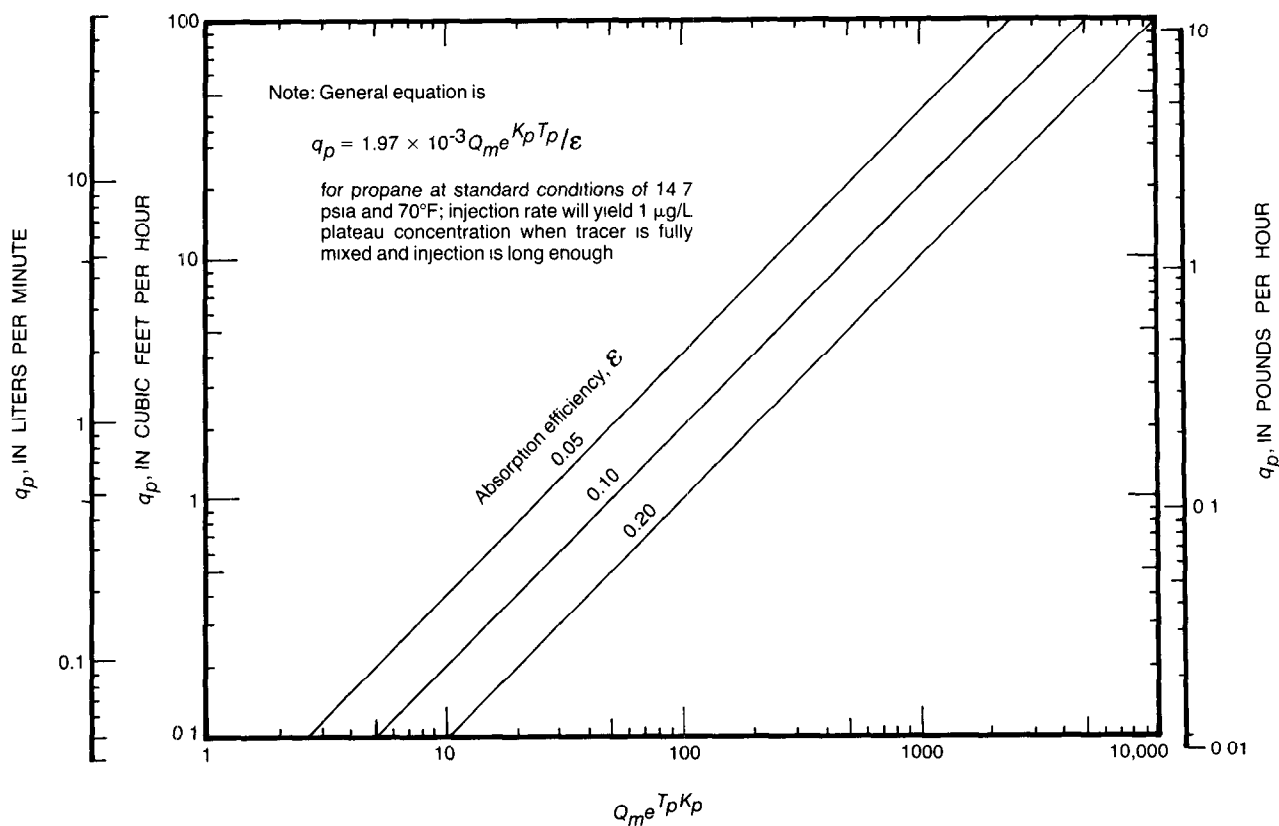


Figure 11.—Graph used to aid in selecting propane gas injection rates. Abbreviations are defined in text and in list of "Symbols and Units."

$e =$  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  $\text{hour}^{-1}$  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 µg/L. It is advisable to plan for concentrations of 2 µg/L or larger, considering the uncertainties in the various estimates. Larger concentrations should be sought when tests on wide rivers are being performed and gas concentrations may be zero along the streambanks. Furthermore, the injection rate should be based on 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

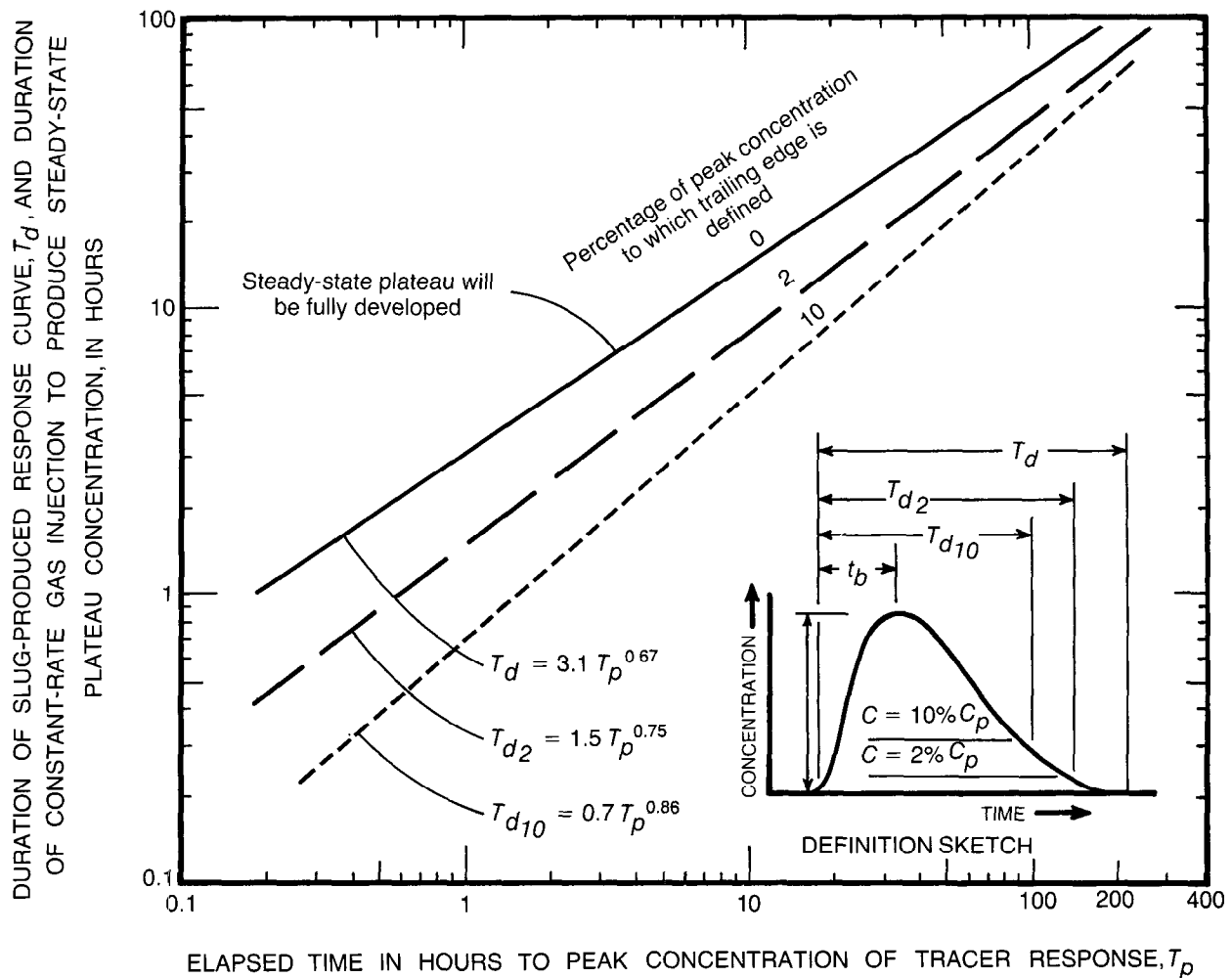


Figure 12.—Graph used to estimate duration of slug-produced response curves as defined to different trailing edge concentrations and to estimate duration of constant-rate gas injection required to develop steady-state plateau concentration for different peak traveltimes. Abbreviations are defined in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

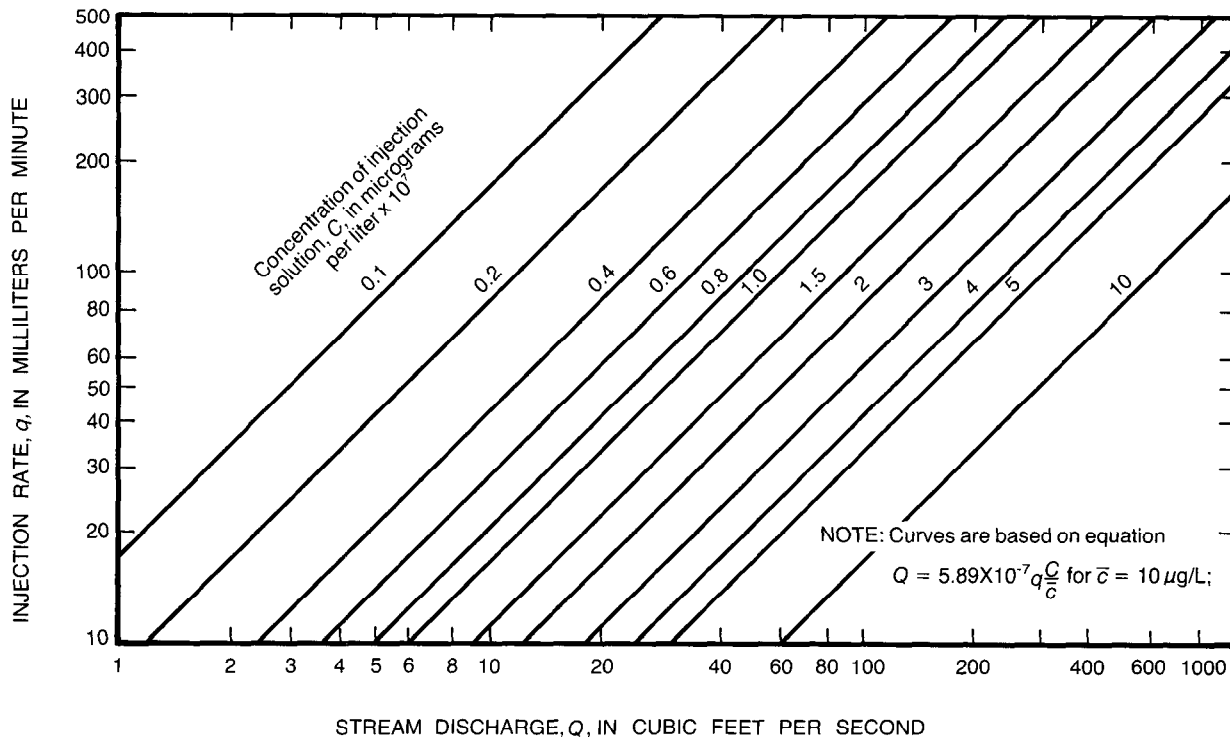


Figure 15.—Graph used to estimate rates of dye injections for different stream discharges and concentrations of injection solutions.

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

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.

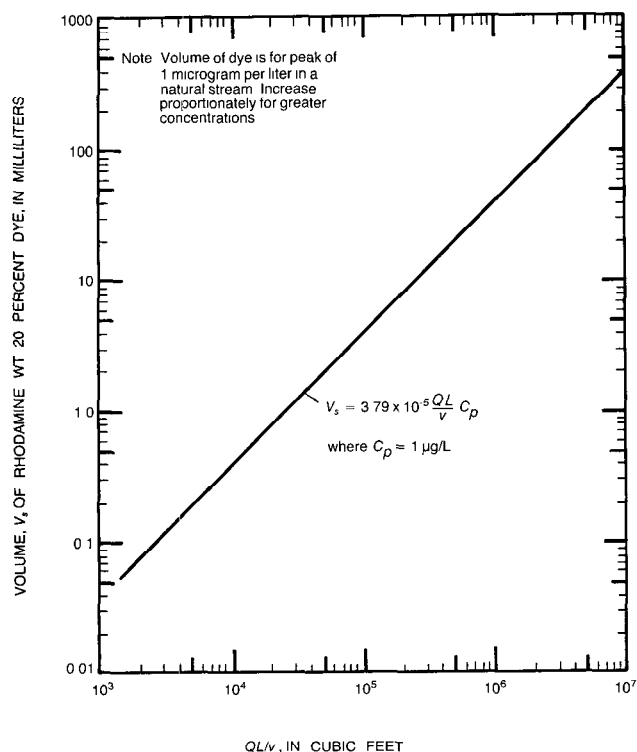


Figure 16.—Graph used to determine quantity of rhodamine WT, 20-percent dye required for slug injection to produce a peak concentration of 1 microgram per liter ( $\mu\text{g/L}$ ) at a distance downstream,  $L$ , at a mean velocity,  $v$ , and with a discharge,  $Q$ , in the reach.

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.

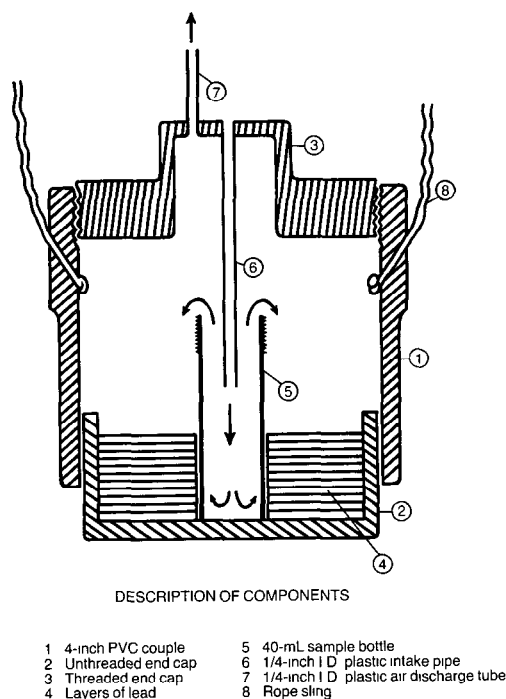


Figure 17.—Design sketch of gas sampler (requires approximately 40 seconds to fill).

### 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