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Waste Disposal and
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2350
MIXING AND SAMPLING ENRICHED U-235 FLUID IN
CYLINDRICAL STORAGE CYLINDERS (U)
(A Progress Report)

James E. Harrell

RELEASED FOR ANNOUNCEMENT
IN NUCLEAR SCIENCE ABSTRACTS

UNION CARBIDE CORPORATION
NUCLEAR DIVISION
OAK RIDGE Y-12 PLANT

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ABSTRACT

The intermixing of fluid contained in cylindrical safe-geometry tankage, as found in nuclear fuel processing plants handling solutions of fissionable material, has been investigated. Utilizing an approximation to pulse-type tracer injection methods, experimental data were collected for four and six-inch-diameter single tank loops, two-in-parallel tank loops, and complex-flow-path tank loops mixed by pump recirculation, and for a six-inch-diameter single vertical tank mixed by air sparging.

A defined mixing time (mixing period needed to dispose a tracer pulse to near homogeneity with tank-loop contents) was measured for each type system and found to vary linearly with the recirculation rate when plotted on full logarithmic paper. For single tank loops, mixing time for both completely and partially fill conditions ranged between 10 and 625 minutes for recirculation rates between 1 and 100 gpm. The nature of mixing in parallel-tankage loops was considered by varying the ratio of flow through two identical tanks at aggregate flows between 10 and 100 gpm; an optimum flow split ratio where mixing time is minimized was found to exist at about 0.7. Some of the mixing characteristics for series-parallel flow through a single tank loop were studied; mixing time data for several loop systems were analyzed. In addition, the relationship between dispersion intensity which embodies the effective rate of mixing and Reynolds number was studied for several single tank loops. The relationship was found to be linear when plotted on full logarithmic paper and to deviate significantly at low Reynolds numbers from published data for very long pipelines.

Preliminary mixing-time data obtained for the air-sparged tank varied between 11 and 31 minutes at air rates between 0.12 and 5.0 scfm.

A theory for the recirculation mixing of fluids contained in cylindrical-tankage loops was developed based on the dispersion model and on the tanks-in-series model. Because either an analog or a digital computer solution is required for each theoretical treatment, only the single-tank-loop theory has yet been tested with experimental data. For this type of loop, when using an experimentally measured dispersion intensity and at Reynolds numbers greater than about 10,000, the predicted mixing times were found to agree within $\pm 30\%$.

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INTRODUCTION

In a nuclear fuel processing plant where a significant portion of the total fuel inventory is held in recycle solutions, the mixing of liquids in subcritical (safe-geometry) tankage is accomplished by procedures established through trial-and-error experiments. For some tankage systems where composition and concentration of the liquid contents is nearly homogeneous, little if any mixing might be required to reduce the liquid composite to homogeneity. For other systems, with greater initial liquid inhomogeneity due to differing feed materials and control of process variables, a greater mixing intensity and duration might be required. Mixing procedures for such systems are not likely to be interchangeable, and if conditions governing the relative homogeneity of a system are severely altered, mixing procedures for that system may no longer be adequate.

Solutions held in safe-geometry tankage can be mixed to any predetermined small degree of inhomogeneity and can, in most cases, be representatively sampled for nuclear fuel inventory providing the mixing characteristics of the tankage are known and utilized. A research program is in progress that was designed to study the various parameters associated with mixing and sampling liquids of different composition and concentration which might possibly contain some solid material and which are stored in cylindrical safe-geometry tankage. This report summarizes the progress made in this activity through November 1965 and reviews current and future objectives.

In a preliminary report, ⁽¹⁾ a resumé of the state of the technology for mixing and sampling liquids contained in cylindrical storage tankage was presented. Results were also presented of an extensive literature search, an inspection of safe-tank facilities of eight AEC plants, and of contacts with various personnel concerned with problems in this area. Due to the unique nature of mixing in and sampling from safe tanks, no prior work of general utility was uncovered excepting that of Rushton and Hillestad⁽²⁾ in the area of isokinetic sampling of well-mixed liquid-solid mixtures.

In a subsequent report, ⁽³⁾ a review of the program's experimental phase for the first half of Fiscal Year 1965 was given which included a general discussion of the experimental facility, procedures, and methods of data evaluation. Data were presented graphically for five, horizontal safe-tank systems mixed by recirculation. It was shown that a linear fit to logarithms of the mixing time-recirculation rate data was an intuitively acceptable relationship to the physical mixing system, and that all data excepting that collected at relatively low recirculation rates justified this relationship.

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SUMMARY

A research program requested by the Division of Nuclear Materials Management of the United States Atomic Energy Commission for a study of the mixing and sampling characteristics of cylindrical nuclear safe-geometry tankage has been undertaken at the Y-12 Plant. A program combining the measurement of some safe-tank mixing characteristics with a theoretical analysis for a generalization of these characteristics is in progress.

For simulation of both vertically and horizontally orientated tankage, an experimental facility equipped with analytical components for flow measurement and solution-concentration measurement has been assembled. Data have been collected for recirculation-mixing experiments conducted in twelve tank systems of different geometric similarity and configuration. These data, a defined mixing time and the dispersion intensity, have been treated by least-squares techniques and are presented graphically as a function of the recirculation rate. For six-tank systems, the effect of the degree of fullness upon these data was observed, treated, and presented in the same manner. Both mixing-time and dispersion-intensity data were found to be linearized when plotted as a function of the recirculation rate on full logarithmic paper.

A theoretical analysis of safe tank mixing has been made which provides a tool for treating both simple and complex tankage systems. By a combination of the series of ideally mixed tanks model and the dispersion model, mixing time for single horizontal tanks has been predicted; a comparison of the predicted times with some of those determined by experiment has also been included. Equations for the prediction of mixing time for multiple-parallel tankage and for combinations of parallel and series tankage have been developed and are outlined.

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ACCOMPLISHMENTS

GENERAL

An experimental installation has been built that simulates the construction of vertically and horizontally oriented nuclear-safe storage tanks as used in uranium and plutonium processing plants. The installation consists of modular four and six-inch-diameter horizontal tanks for single or parallel-tank recirculation-mixing experiments, and of six-inch-diameter vertical tanks for air-sparge mixing and for single or parallel-tank recirculation-mixing experiments. Each system has been equipped with flow meters and electrical conductivity recorders for a continuous analysis of the degree of liquid homogeneity as a function of time for a specified set of conditions. By using these recorders, the response of a safe-tank system whose contents are being mixed to homogeneity with a highly conductive aqueous sodium chloride tracer can be measured and recorded on strip charts.

Arrangements have been made with recognized authorities in the field of fluid agitation and mixing to serve as consultants, namely: J. H. Rushton of Purdue University and Octave Levenspiel of the Illinois Institute of Technology. Their advice and review of the experimental program and of methods for treating and analyzing of data have proved to be valuable.

The research program has been divided into three general areas: (1) mixing by recirculation of safe tank contents; (2) mixing of vertical safe tank contents by air sparging; and (3) representative sampling of liquid-solid mixtures contained in a safe tank. Although some preliminary air-sparge mixing experiments have been conducted, the program has been primarily concerned with the recirculation-mixing problem for simple and complex tankage systems.

EXPERIMENTAL

Pulse-type tracer mixing experiments have been conducted in twelve safe tank systems constructed of four or six-inch-diameter Pyrex pipe with length-to-diameter ratios between 29 and 80. The experimentation has consisted of a total of 502 runs divided among 38 experimental series for measurement of the tank-system mixing time or dispersion intensity. These measurements were made at recirculation rates between 1 and 100 gpm for single and two-in-parallel, recirculation-mixed tank systems; and at air-sparge rates between 0.12 and 5.0 scfm for preliminary evaluation tests of a vertical air-sparge mixed tank. For an analysis of varied safe-tank mixing conditions, the character of recorder strip-chart conductivity-time curves have been used. These curves approximate exponentially decaying sine curves for recirculation-mixing experiments or exponentially asymptotic curves for air-sparge mixing experiments.

Mixing-time determinations have been made for most experimental series. This time measurement for recirculation mixing relates two entities: (1) the delay period required to disperse and mix a relatively small volume of tracer with bulk tank contents to (2) a nearly homogeneous condition which has arbitrarily been defined to exist when the ratio of the minimum-to-maximum tracer concentration for any complete recirculation of tank contents is equal to or greater than 0.998. Conversely, the mixing time is the duration of mixing needed to disperse the tracer so that the concentration deviation (maximum value-minimum value) throughout the tank system is no greater than 0.2% of the maximum concentration for that circulation.

For air-sparge mixing, a comparable mixed condition defining mixing time is used; but, since there is no recirculative liquid flow past the measurement probe that would generate readings with periodic concentration maxima and minima on a strip chart, these mixing-time measurements were less accurately determinable.

Experimentally determined mixing times for seven, single tank systems mixed by recirculation are reported in Appendix A (Table A-1) as a function of the recirculation rate and at the indicated degree of tank fullness. For these systems, at recirculation rates between 1 and 100 gpm, the mixing time ranged between 10.5 and 622 minutes. As these data are linearized for most of the range of recirculation rate studied when plotted on full logarithmic graph paper, they have been treated by a least-squares fit of the form:

$$\log T = A - B \log Q, \quad (1)$$

where:

T represents the mixing time and

Q the recirculation rate.

A and B are constants of the least-squares data fit.

These graphs are presented in Appendix A (Figures A-1 through A-18).

Values of the constants for these data fits, their standard error, and the variance of estimate for the linearized fits are given in Table A-2. Confidence limits have been shown on each figure as an upper and lower line surrounding the linear least-squares fit. These limits give the maximum and minimum mixing time that would be expected to occur for a single experiment at a given flow rate within the flow range considered and at a probability level of 97.5%.

Mixing times determined for a two-in-parallel tank system were measured to reflect the effect from the influent flow splitting between identical tanks and the subsequent effluent flow combination at the tank outlets. For this system at several flow-split conditions and at recirculation rates between 10 and 100 gpm, the mixing time

varied between 5.8 and 116.0 minutes. These data, which manifest for certain ranges of the flow-split ratio, a significant mixing-time reduction over comparable single tank experiments were also found to fit Equation 1 when plotted logarithmically for a fixed-flow split ratio (ie, ratio of flow through one tank to the flow through the other tank). A compilation of these data is given in Appendix B (Table B-1) and graphed logarithmically in Figures B-1 through B-11. Values of the constants for these linear least-squares fits, their standard error, and the variance of estimate of the fits are given in Table B-2. Confidence limits have been shown on each figure as for single tank data. A cross plot of these data, which gives mixing time as a function of the flow-split ratio for several values of the total recirculation rate, is given in Figure B-12. From this plot it appears that a flow-split ratio of about two to three optimizes the mixing efficiency for two identical parallel tanks mixed by recirculation.

Mixing-time measurements were made for complex-flow-path, safe tank systems where the tank contents are recirculated through a coaxial inner tube (termed mixing tube) with selected axially positioned flow outlets. Data are compiled in Appendix C (Table C-1) for mixing in a system of this type where both parallel and series flow circuits exist, and where four flow patterns were considered. At recirculation rates between 2.1 and 79.0 gpm, mixing time was found to vary between 3.0 and 111.0 minutes. In an analogous manner to the treatment of data for other systems, these data were fitted to Equation 1 and plotted in Figures C-1 through C-4. Values of the constants for these fits, their standard error, and the variance of the estimate for the linearized fits are given in Table C-2. It has been demonstrated by these experiments that an indiscriminate location of flow outlets can lead to a less-than-optimum mixing system.

Preliminary mixing-time measurements were made for an air-sparged tank. For air-sparge rates between 0.12 and 5.0 scfm, mixing time varied between 10.4 and 32.1 minutes. These data, tabulated in Appendix D (Table D-1), and plotted in Figure D-1, are presented at this time for rough comparison with recirculation-system mixing-time data.

During the mixing-time investigations, measurements of the dispersion intensity were made for some of the systems considered. As this variable embodies the virtual recirculation-mixing diffusion coefficient, its value must be readily available for use in any theoretical, generalized treatment of either a simple or complex recirculation-mixing system.

For three single tank systems, the dispersion intensity was determined. This variable, which is evaluated from an interrelationship between several measured variables and is dimensionless in form, is presented graphically in Figure A-19. As in the case of mixing-time data, it was linearized when plotted on full logarithmic paper; hence, a separate fit for each system studied was made using least-squares techniques and a linear form:

$$\log (D_i) = A - B \log (Re), \quad (2)$$

where:

D_i represents the dispersion intensity and

Re the Reynolds number.

A and B are constants of the least-squares data fit.

THEORETICAL

Methods have been outlined for predicting the mixing-time requirements of recirculation-mixed tankage systems. These methods utilize either the dispersion model or the tanks-in-series model and the equivalence of the models allowing use of measured generalized dispersion intensity data. Although the most valuable mixing model is the tanks-in-series model, mixing time for single tank systems has been predicted for the single tank experiments by the dispersion model. A comparison of these predicted theoretical mixing times with those determined by experiment and fit by a least-squares curve has been made and is presented in Table A-3. Within the range of the recirculation rate that would be recommended (Reynolds numbers of about 10,000) for these systems, the relative error of this estimate is about $\pm 30\%$. It is shown that the mixing time for any single tank system can be predicted by the use of relatively simple calculational procedures.

Although methods for the theoretical treatment of parallel and mix-tube tank systems have been suggested, a comparison of these treatments with experimental data has not been made. These methods are currently being programmed for digital computation.

DISCUSSION

THEORY

Literature Review

It has been shown in the literature that some of the problems associated with fluid intermixing during flow can be handled analytically. The most widely used methods for treating the problem use a diffusional model (generally referred to as the dispersion model) or a tanks-in-series model, although several statistical models have been applied. A frequent requirement for the treatment of mixing in a system by these models is for the system to be devoid of stagnant regions where mixing and flow conditions are significantly different from those of any other region of the system. This requirement is one that is frequently demanded by theoretical analyses or when a set of experimental data for one system are used for predicting the properties of some other system; hence, this requirement should not be regarded as excessively restrictive.

In these literature articles, the objective has been to provide a set of equations for predicting the concentration of a tracer material (injected some place upstream) as a function of time at some position downstream from the injection point, or for use in evaluating the "virtual diffusion coefficient" for the tracer material in the system at some set of dynamic flow conditions. The utility of these solutions for treating safe tank systems is subtle, since the literature treated the mixing of a fluid for one pass through the mixing equipment while the problem to be solved for the recirculation-mixing operation of safe tank contents calls for many passes through a safe tank system, which is itself the mixing equipment.

The discussion which follows gives a review of the dispersion model and the tanks-in-series model which will be used as a basis for treating the various recirculation-mixing problems associated with safe-tank-system configurations.

Tanks-in-Series Model - The tanks-in-series model has received considerable attention in the literature since articles were published by Ham and Coe⁽⁴⁾ and by McMullin and Weber.⁽⁵⁾ Later, Kandiner,⁽⁶⁾ Katz,⁽⁷⁾ Masa and Pivet,⁽⁸⁾ and Young⁽⁹⁾ were among those who studied the model and demonstrated its utility. As discussed by Levenspiel⁽¹⁰⁾ in a review, the equations to be solved for this model are those for tracer material passing through a series of ideally mixed tanks, as depicted by Figure 1. The material-balance equation to be solved simultaneously for each of the equally sized tanks in the series is:

$$\text{Input of Tracer} - \text{Output of Tracer} = \text{Accumulation of Tracer in Tank.}$$

For a series of tanks initially at zero tracer concentration and whose first tank is instantaneously injected with a pulse of tracer, the material balance for the first

Figure 1. A SERIES OF IDEALLY MIXED TANKS.

tank and the i th tank is respectively:

$$C_0 V \delta(t) - g C_1 = V \frac{dC_1}{dt}, \text{ and} \quad (3)$$

$$g C_{i-1} - g C_i = V \frac{dC_i}{dt}, \quad (4)$$

where:

C_0 represents the concentration of tracer if mixed homogeneously through the tank system,

V the volume of each of the ideally mixed tanks,

$\delta(t)$ the delta function of time (equals 0 for $t \neq 0$ and equals 1 for $t = 0$),

g the volumetric flow rate between each ideally mixed tank, and

t the time.

The solution of these equations, as given by Levenspiel,⁽¹⁰⁾ is obtained by Laplace transform techniques, dimensionlessized for simplicity, and is for the N th tank of a series. The equation is:

$$C_N = \frac{N^N}{(N-1)!} \theta^{N-1} \exp(-N\theta), \quad (5)$$

where:

C_N represents the dimensionless concentration of the N th tank,

θ the dimensionless time, and

N the tank number in the series of tanks.

It will later be shown that the primary significance of this equation for our purpose was to determine the first and second moment of the concentration distribution for the Nth tank. The dimensionless mean and variance found from these moments are respectively:

$$\mu = 1, \quad (6)$$

and

$$\sigma^2 = \frac{1}{N}. \quad (7)$$

Dispersion Model - The dispersion model was suggested by Taylor as appropriate for use in treating the axial mixing of a tracer pulse. He demonstrated that for the laminar flow regime⁽¹¹⁾ and for the turbulent flow regime,⁽¹²⁾ a tracer pulse is distributed in a near-Gaussian form about a point at the pulse center which moves with the mean fluid speed, and that this axial dispersion of the tracer can be described by using a diffusion equation analogy with a virtual diffusion coefficient. Further, Taylor derived relationships for the prediction of these coefficients for both flow regimes. Levenspiel⁽¹³⁾ compiled published experimental data, calculated a dimensionless ratio embodying the diffusion-like coefficient and termed it "dispersion intensity", and correlated these data in dimensionless form as a function of the Reynolds number.

Levenspiel and Smith⁽¹⁴⁾ treated the axial dispersion of a tracer moving through an infinitely long, cylindrical pipeline by a second-moment analysis. Van der Laan⁽¹⁵⁾ derived expressions relating mixing number, P , and tracer concentration variance in finite vessels with several types of vessel closures. Since in each of these treatments the injected tracer was assumed to be a perfect delta function with zero variance (eg, a finite amount of tracer injected in an infinitesimal time). Aris,⁽¹⁶⁾ later corrected by Bischoff,⁽¹⁷⁾ showed that two measurement points could be used downstream from an injection point for the measurement of any arbitrary injected tracer form to determine the mixing number. It should be pointed out that the latter treatments have taken into account the effect of the tank ends on the dispersion equations; yet, the complex flow patterns prevailing at the tank ends which might greatly affect these measurements were neglected.

Equations relating the concentration of a tracer pulse at some position downstream from the injection point have been derived by numerous authors.^(18, 19, 20, 14, 21) These equations relate tracer concentration at some downstream axial position to the time lapse since pulse injection and to the mixing number. One of the

simplest was derived by Levenspiel and Smith⁽¹⁴⁾ as a solution to the following differential material balance for a cylindrical vessel:

$$\frac{\partial C}{\partial X} - P \frac{\partial^2 C}{\partial X^2} + \frac{\partial C}{\partial \theta} = \delta(X - X_0) \delta(\theta), \quad (8)$$

and

$$P = (Di) \left(\frac{d}{L} \right), \quad (9)$$

where:

- C represents the dimensionless concentration,
- X the dimensionless axial position,
- θ the dimensionless time,
- P the mixing number,
- $\delta(X - X_0)$ the delta function of the location for the tracer-pulse input (equals 0 for $X \neq X_0$ and equals 1 for $X = X_0$),
- $\delta(\theta)$ the delta function of time for the tracer pulse input (equals 0 for $\theta \neq 0$ and equals 1 for $\theta = 0$),
- Di the dispersion intensity,
- d the tank inside diameter, and
- L the tank length.

The solution given for this material-balance equation at an axial position where $X = 1$ (say at the outlet of a continuous-flow pipeline mixer) is:

$$C(\theta) = \left(\frac{1}{4 \pi P \theta} \right)^{1/2} \exp \left[- \frac{(1 - \theta)^2}{4 P \theta} \right]. \quad (10)$$

From first and second moments of the concentration distribution, the dimensionless mean and variance were shown respectively to be:

$$\mu = 1 + 2P, \quad (11)$$

and

$$\sigma^2 = 2P + 8P^2. \quad (12)$$

Equations 10, 11, and 12 provide added tools for the treatment of complex safe-tank mixing problems.

Properties of Mixing Models

Levenspiel⁽²²⁾ has pointed out two properties of mixing models that are needed for the treatment of complex mining problems: (1) the equivalence relationship between the tanks-in-series model and the dispersion model, and (2) the additive property of a series of distinct mixing regions.

For any single, distinct mixing region that could be represented by either mixing model, an equivalence relationship between the models can frequently be used to relate model parameters. When the equivalent number of ideally mixed tanks in series for a mixing region is large (at least > 10) and/or the mixing number, P , for the mixing region is small (< 0.1), the dimensionless mean and variance for each model approach limiting values. For the mean, the limiting value of Equations 6 and 11 is unity. When Equations 7 and 12 are compared and simplified to reflect the limiting value approached for each model, the following relationship between model parameters is observed:

$$\frac{1}{N} = 2P,$$

or

$$N = \frac{1}{2P}. \quad (13)$$

When the model-equivalence criteria are met and either P or N is known or determinable, the other is available through Equation 13. This property will be extensively used in complex flow systems to transform values for P for a distinct mixing region to values of N , so that the tanks-in-series model can be used.

A second property discussed by Levenspiel is the additive property for a series of distinct mixing regions. In order to characterize mixing in a series of distinct mixing regions where any combination of tanks-in-series regions and/or dispersion regions exists, an overall model parameter for the series combination of regions is needed. Since the additive properties only treat dimensioned means and variances, the relationship between these dimensioned and dimensionless variables becomes:

$$\theta = \frac{t}{\bar{t}}, \quad (14)$$

and

$$\sigma^2 = \frac{\sigma_t^2}{\bar{t}^2}, \quad (15)$$

where:

- θ represents the dimensionless time,
- t the dimensioned time,
- $\bar{t}$ the mean residence time (equal to the region ratio, V/Q),
- σ^2 the dimensionless variance, and
- σ_t^2 the dimensioned variance.

The overall model parameters are then found by the use of the following relationships:

$$(\bar{t})_{\text{overall}} = \bar{t}_1 + \bar{t}_2 + \dots + \bar{t}_i = \sum_{i=1}^i \bar{t}_i, \quad (16)$$

$$(\sigma_t^2)_{\text{overall}} = (\sigma_t^2)_1 + (\sigma_t^2)_2 + \dots + (\sigma_t^2)_i = \sum_{i=1}^i (\sigma_t^2)_i, \quad (17)$$

and

$$(\sigma^2)_{\text{overall}} = \frac{(\sigma_t^2)_{\text{overall}}}{(\bar{t})_{\text{overall}}^2}, \quad (18)$$

where subscripts refer to each mixing region in the series from 1 to i .

Mixing Time Prediction for Recirculation-Mixed Systems

Single Tank Systems - The mixing time for a single tank system mixed by a recirculation of the tank contents through loop piping, such as shown in Figure 2, can be predicted by the use of either of these mixing models. To demonstrate the utility of the dispersion model, it was selected for treatment of this problem.

Figure 2. REPRESENTATIVE ARRANGEMENT FOR HORIZONTAL SINGLE TANK EXPERIMENTAL LOOPS.

One of the simplest solutions for the dispersion of a delta function-type tracer pulse during convective flow was suggested by Levenspiel and Smith.⁽¹⁴⁾ The solution, Equation 10, gives the concentration of a tracer pulse downstream from the injection point at a dimensionless axial position of unity. Although the solution assumes a doubly infinite pipe (extending to infinity in both directions), it can be applied to the recirculation-mixing operation of a single tank system.

The distribution of the tracer for the first pass through a safe tank system can be predicted by a direct use of Equation 10. Physically, this means that the spread of a tracer injected at the tank entrance is measured at the tank outlet as a function of time, and that the tank outlet is located at a dimensionless axial position of unity.

For the prediction of a tracer distribution for the second pass, a modification of Levenspiel's result can be used. This modification is simply one of relocating the measurement point in the doubly infinite pipeline to a dimensionless axial position of two. In this case, the tracer distribution is measured at a position in the infinitely long pipeline that is equivalent in displacement from the injection point to two circulations of the contents of a safe tank system. In a like manner, the distribution for the j th pass is measured at an axial position of j . In general, the

distribution can be calculated for any pass through the tank system from the following equation:

$$C(i, \theta) = \left(\frac{1}{4 \pi P \theta} \right)^{1/2} \exp \left[- \frac{(i-\theta)^2}{4 P \theta} \right], \quad (19)$$

where the variables are as previously defined.

Up to now, the effect of intermixing the tracer during recirculation has been neglected. It becomes obvious that after several passes the tracer concentration distribution during any single pass will be spread over a greater extent than the safe tank system volumetric equivalent of an infinitely long pipeline. This situation must occur for the tracer pulse to disperse evenly throughout the tank system.

This intermixing of tracer can be handled by simply summing the contributions of each of the i concentration curves as a function of time. Thus, combined dispersion for at least the pass numbers up to $i/2$ can be written as:

$$C(\theta) = \sum_{i=1}^i \left(\frac{1}{4 \pi P \theta} \right)^{1/2} \exp \left[- \frac{(i-\theta)^2}{4 P \theta} \right]. \quad (20)$$

Hence, the concentration-time relationship is derived for the measurement at the safe tank outlet. Using this equation, with a mixing number of 0.00842 for example, a theoretical curve was determined by using an IBM 7090 digital computer and a Benson-Lehner plotter combination. This curve is given in Figure 3. The periodic character of this curve, which resembles that of an exponentially decaying sine curve, provides a convenient definition of the mixing time. The system concentration when homogenized, C_0 , can be evaluated from Equation 20 by allowing the number of passes to increase to some large value (say about 200) and finding the limiting value of C_0 . By comparing the periodic maximum tracer concentration to C_0 for increasingly larger numbers of tracer passes through the system beginning with the first, a condition of relatively small degree of inhomogeneity can be used for defining the mixing time. Thus, the system is mixed at the N th maximum concentration to $(100.0 - \gamma) \%$ of the homogeneity if the following definition is used:

$$\gamma \geq \left| 1.0 - C_{\max}(N, \theta) \right|, \quad (21)$$

where:

$C_{\max}(N, \theta)$ represents the dimensionless concentration maximum for the N th tracer pass whose value approaches 1.0 for large θ .

Figure 3. DIMENSIONLESS TRACER CONCENTRATION AS A FUNCTION OF THE DIMENSIONLESS TIME PREDICTED BY THE USE OF EQUATION 22 FOR A MIXING NUMBER OF 0.00824.

The time lapse to the Nth concentration maximum is the mixing time in dimensionless units. To convert to real time, multiply this dimensionless mixing time by the ratio of system volume to recirculation rate.

As Equation 20 requires only that the system mixing number be specified for the calculation of tracer concentration maxima, and Equation 21 requires specification of the homogeneity parameter, γ , mixing-time calculations have been made on an IBM 7090 digital computer. At mixed conditions of 90.0, 95.0, 99.0, 99.5, 99.8, and 99.95%, and for mixing numbers ranging between 0.001 and 4.0, mixing times were determined. These data have been tabulated in Table A-4. Over the range of mixing numbers that safe tank systems will most likely be operated (ie, mixing numbers < than ~ 0.1), a full logarithmic plot of the dimensionless mixing time as a function of the mixing number is linear. As a consequence, a linear least-squares fit of the logarithms of these data was made for each homogeneity parameter. A plot of these data is given in Figure A-20. The constants for each fit, their standard error, and the variance of the estimate for each fit is given in Table A-3.

Parallel Tank Systems - The mixing characteristics of a parallel tank system, such as shown in Figure 4, are more complex than those for a single tank system. In a single tank system, mixing takes place by dispersion about the center of a tracer pulse moving with a mean fluid velocity. For a parallel tank system, where flow through the tanks is unequal, the system content is also mixed by the splitting of an influent stream between the tanks and the combination of the effluent streams at the tank outlets. The effect of the latter type of mixing can be very effective in reducing the mixing time for a given quantity of stored liquid. Due to the complexity of this type of system mixing, and the availability of high-speed digital computation, the tanks-in-series model was developed for this case.

A parallel safe-tank system can be represented by a series of ideally mixed tanks, as shown in Figure 5. By a use of the relationship between the dispersion model and the tanks-in-series model, given by Equation 13, the number of equally sized, ideally mixed tanks in series that would be equivalent both in dispersion characteristics and in total volume to each of the parallel safe tanks can be found.

For a given parallel-tank system consisting of an M number of safe tanks, the following must be specified:

$Q(J)$, $J = 1, 2, \dots, M$

$L(J)$, $J = 1, 2, \dots, M$

$d(J)$, $J = 1, 2, \dots, M$

Figure 4. REPRESENTATIVE ARRANGEMENT FOR A PARALLEL TANK EXPERIMENTAL LOOP.

where $Q(J)$, $L(J)$, and $d(J)$ represent, respectively, the volumetric flow rate through, the tank length of, and the inside diameter of the J th safe tank. In addition, the average density and viscosity of the system contents must be specified for a Reynolds number calculation.

For the J th safe tank, the equivalent number of ideally mixed tanks in series and time constant for these ideally mixed tanks must be determined. By use of the relationship between Reynolds number and dispersion intensity (Equation 2), the mixing number is obtained by multiplying the dispersion intensity by the tank length-to-diameter ratio. Then,

$$P(J) = \left[Di(J) \right] \left[\frac{d(J)}{L(J)} \right]. \quad (22)$$

From Equation 13, the equivalent number of equally sized, ideally mixed tanks-in-series arrangement representative of the J th safe tank is:

Figure 5. REPRESENTATIVE ARRANGEMENT OF A PARALLEL SAFE TANK SYSTEM BY THE USE OF A TANKS-IN-SERIES MODEL.

$$N(J) = \frac{1}{2P(J)} \quad (23)$$

As only integral values for $N(J)$ are meaningful, $N(J)$ must be rounded off to the nearest integer. The time constant for each of these $N(J)$ tanks, which is the mean residence time for each tank, is found by:

$$\tau(J) = \frac{V(J)}{Q(J) N(J)} \quad (24)$$

where $\tau(J)$ is the time constant, and $V(J)$ the total volume of the J th safe tank. Each ideally mixed tank of a system, as shown in Figure 5, must be identified. This identification can be accomplished by letting $T(K, J)$ denote the K th ideally mixed tank of the J th safe tank, where:

$$1 \leq K \leq N(J)$$

$$1 \leq J \leq M(J)$$

defines the array of ideally mixed tanks.

For pulse-type tracer mixing-time calculations it is assumed that initially the tracer concentration of each tank is zero, except for each $T(1, J)$ tank and its respective volume. For example, at $\theta = 0$:

$$C(1, J, 0) = \left[\frac{Q(J)}{\sum_{J=1}^M Q(J)} \right] \left[\frac{N(J)}{V(J)} \right] \quad (A), \quad (25)$$

where $C(1, J, 0)$ is the initial concentration of the $T(1, J)$ tank, $\sum_{J=1}^M Q(J)$

is the total system recirculation rate, and A is the total amount of tracer added to the system.

The transient concentration of each element of the ideally mixed tank array is found by simultaneously and numerically solving an array of material balance equations for the $T(K, J)$ tanks:

$$C(K-1, J, \theta) - C(K, J, \theta) = \tau(J) \frac{d}{d\theta} [C(K, J, \theta)], \quad (26)$$

where $\frac{d}{d\theta} [C(K, J, \theta)]$ represents the derivative of the concentration for the $T(K, J)$ tank with respect to time. The following relationships must also be used:

1. For combined stream concentration at the tank outlets:

$$C(Z, \theta) = \frac{\sum_{J=1}^M \{C[N(J), J, \theta]\} [Q(J)]}{\sum_{J=1}^M Q(J)}. \quad (27)$$

2. For the $T(1, J)$ tanks:

$$C(Z, \theta) - C(1, J, \theta) = \tau(J) \frac{d}{d\theta} [C(1, J, \theta)], \quad (28)$$

where $C(Z, \theta)$ is the combined stream concentration at the tank outlets.

By comparing the maximum and ultimate value of $C(Z, \theta)$ for each integral time interval equal to these greatest residence time for any of the J safe tanks, a mixing time analogous to that used for single tank systems can be defined. The time interval would be the largest value of the following ratio:

$$\Delta T_{\max} = \frac{V(J)}{Q(J)}, \quad (29)$$

where $\Delta T_{\max}$ is the time interval corresponding to the greatest residence time for any of the $M(J)$ safe tanks in the system. Mixing time would then be defined by the following criteria similar to Equation 21:

$$\gamma \geq \left| 1.0 - C_{\max}(Z, \theta) \right|, \quad (30)$$

where:

$C_{\max}(Z, \theta)$ represents the dimensionless concentration maximum at a tank outlet whose value approaches 1.0 for large θ .

A program is to be written to treat this problem but has not yet been completed. It will be reported later.

Series-Parallel Tank Systems - The advantage of pumping unequal flow rates through parallel flow paths has been considered. It was pointed out that the mixing time can be significantly reduced by a judicious selection of a set of unequal flow rates through a parallel tank system. The mixing time reduction results directly from splitting up the "plug-like" flow that exists in single tank systems or in-parallel tank systems with equal tank flow rates; for in these cases mixing occurs solely by dispersion. By the use of a combination of series and parallel flow paths such as that shown in Figure 6 for a mixing-tube system, even greater mixing efficiencies can be obtained. Although a complete treatment of the mixing-tube system has not yet been made, a method of approach has been proposed. An outline of this approach is presented in the discussion that follows.

Using the tanks-in-series model, a set of differential material balance equations can be written which should reasonably well predict the concentration-time curve for a series-parallel flow system. For a single tank-mixing tube system where the tank contents are circulated through an inner coaxial tube into the safe tank at selected axial positions, a tanks-in-series representation like Figure 6 should be appropriate. Since it has been shown experimentally (discussed on Page 54) that an indiscriminate set of equally sized mixing-tube hole locations located uniformly along the tube axis would be relatively inefficient, and it can also be argued from a theoretical standpoint that a large number of equally sized and spaced holes would be highly ineffective, a mixing-tube system with well-placed, equally sized holes at a few locations will be considered.

The analysis of the system is simplified if equal flow out of the mixing tube at each axial hole position is assumed. This condition can be reasonably well attained for

Figure 6. REPRESENTATIVE ARRANGEMENT OF A SERIES-PARALLEL FLOW PATTERN FOR A MIXING-TUBE SYSTEM BY THE USE OF A TANKS-IN-SERIES MODEL.

equally sized holes along the tube axis if the differential pressure for flow through the holes is held relatively high. The holes become orifice like and their flow rate is primarily dependent upon the differential pressure at that axial position.

Between each set of holes there exists a parallel flow of fluid for the coaxial inner tube and the annular space surrounding the inner tube. For both parallel flow regions, a treatment similar to that given for parallel tank mixing can be made. With the flow rate and volume of each region specified, calculation of the number of and the time constant for ideally mixed tanks in series in each region is performed as before. At the next axial hole location, such as depicted in Figure 7, an equation taking into account the series-parallel flow condition must be used. For the tank receiving flow from the mixing tube, this equation is:

$$NC_A(S, \theta) + C_T(R, \theta) - (N + 1) C_A(S + 1, \theta) = \tau(S + 1) \frac{d}{d\theta} [C(S + 1, \theta)], \quad (31)$$

where:

- N represents the number of upstream hole locations,
- $C_A(S, \theta)$ the concentration of the upstream annular tank, S ,
- $C_A(S + 1, \theta)$ the concentration of the annular tank receiving mixing tube discharge,
- $C_T(R, \theta)$ the concentration of the mixing tube ideally mixed tank at the tube discharge position, and
- $\tau(S + 1)$ the residence time of the $(S + 1)$ th annular tank.

By simultaneously solving a set of material-balance equations such as those outlined for a pulse-type tracer input using an analogous end condition to that proposed for parallel tank systems, a computerized mixing-time prediction can be made. An appropriate end condition would test the concentration of the first ideally mixed annular tube tank with the ultimate tank concentration.

EXPERIMENTAL FACILITY

The simulated safe tank systems were constructed of standard four or six-inch-diameter flanged Pyrex pipe (5 and 10-foot-long sections as needed) due to the desirability for safe tank flow visualization. These systems were supported about five feet above the floor level in an angle-iron framework where horizontal systems were inclined about 1/5 inch per foot to facilitate drainage.

Figure 7. SERIES-PARALLEL FLOW PATTERN AT A MIXING-TUBE HOLE LOCATION.

Recirculation-Mixed Systems

For smooth flow transition at the tank ends, the tank closures were composed of flanged Pyrex pipe reducers to two-inch-diameter Pyrex pipe. For several special experiments in the six-inch-diameter systems, the cells were located some distance away from these closures and mounted in six by six by two-inch tees. These cells^(a) were mounted at end closures immediately inside or immediately outside the tank, or were mounted in a six by six by two-inch tee, as indicated in Figures 8 through 10.

Loop piping connecting a safe tank assembly to the prime mover (centrifugal pump) suction and discharge was fabricated from 2 and 1 1/2-inch Schedule 40 pipe. In the discharge piping, a section five feet long was provided for tracer admission. This section could be isolated by closing 1 1/2-inch ball valves at each end. After the section was drained, it could then be filled with tracer from an upper level head tank by manipulation of 1/2-inch fill and drain valves, as shown in Figure 11.

Recirculation rate control was achieved by adjusting a 1 1/2-inch globe valve immediately downstream from the pump while observing the rotameter reading. To extend the range of flow for the rotameter, ^(b) a light and a heavy float were used to cover the 1 to 100 gpm range.

Air Sparge-Mixed System

This vertical tank system was closed at the base with a special flange assembly which utilized a two-dimensional, coiled, 0.25-inch-diameter, stainless steel tube with about 80 randomly spaced holes (0.037 inch in diameter) to provide an

(a) Industrial Instruments, Inc; Model CEL-II (SS) X1-02.

(b) Brooks Instrument Company Model 1110.

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Figure 8. MOCKUP OF A CONDUCTIVITY CELL ATTACHMENT IMMEDIATELY INSIDE A SAFE TANK.

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Figure 9. MOCKUP OF A CONDUCTIVITY CELL ATTACHMENT IMMEDIATELY OUTSIDE A SAFE TANK.

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Figure 10. MOCKUP OF A CONDUCTIVITY CELL ATTACHMENT WITHIN A SAFE TANK TEST SECTION MOUNTED IN A SIX BY SIX BY TWO-INCH TEE.

117212(U)

Figure 11. TRACER ADDITION PIPING SECTION OF A FOUR-INCH-DIAMETER SAFE TANK FACILITY.

even air distribution across the tank base. Oil-free air at 15 psig was metered through parallel rotameters^(c) and needle valves to cover a flow range of from 0.07 to 7.0 scfm. A 0.25-inch-diameter tracer admission tube was run from an upper level head tank through a six by six by two-inch Pyrex tee to provide tracer near the tank base for the mixing experiment initial condition. The air-supply piping, tracer-admission tubing, and flange assembly are pictured in Figure 12.

Two electrical conductivity cells^(d) with companion temperature compensators^(e) were mounted within the tank. As shown by Figure 13, a 0.75-inch-diameter stainless steel tube centered within the tank by two steel hoops was used for positioning the cells and compensators.

Each of the tank systems studied have been diagrammed, and following is a listing of these diagrams:

Number of Tanks in System	Tank Inside Diameter (inches)	Tank Lengths Studied (feet)	Representative Arrangement (figure number)	Orientation
1	4	15, 25	2	Horizontal
1	6	15, 20, 25, 26, 40	2	Horizontal
1	6	20	14	Vertical
1	6	20	15	Horizontal
2	4	25	4	Horizontal
1	6	20	16	Vertical

A tabulation of the aggregate piping lengths and component volumes for the tank systems which reflects the degree of fullness considered is given in Table 1.

Figure 17 pictures the facility.

(c) Brooks Instrument Company Model 1110 and Fisher and Porter Company Model M6767.

(d) Industrial Instruments, Inc; Model CEL-VHX.

(e) Specials provided by Industrial Instruments, Inc,

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Figure 12. BASE FLANGE ASSEMBLY INSTALLED IN THE AIR-SPARGED TANK FACILITY.

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Figure 13. ATTACHMENT OF THE LOWER CONDUCTIVITY CELL AND TEMPERATURE COMPENSATOR WITHIN THE AIR-SPARGED TANK.

Figure 14. REPRESENTATIVE ARRANGEMENT FOR A VERTICAL, SINGLE TANK EXPERIMENTAL LOOP.

EXPERIMENTAL PROCEDURE

At the outset, all analytical components to be used in the experimental program were calibrated. The rotameters for air and for water flow rate measurement were calibrated at the Plant Standards Laboratory by collecting the throughput stream for a measured time. These data collected over the full range of flow for each rotameter-float combination were compiled and fit to a polynomial curve of the form:

$$Q = A + BS + DS^2 + ES^3, \quad (32)$$

where:

Figure 15. REPRESENTATIVE ARRANGEMENT FOR A HORIZONTAL, SINGLE TANK LOOP ADAPTED WITH A MIXING TUBE.

Q represents the flow rate and

S the rotameter scale reading.

A , B , D , and E are constants of the least-squares data fit.

For these fits the greatest standard deviation of fit for the water meters used was 0.305 gpm and for the air meters, 0.0294 scfm.

Conductivity measuring equipment was calibrated by measuring at room temperature the conductivity of salt water samples made from measured weights of dried, reagent-grade sodium chloride and demineralized water. As the relationship between conductivity and concentration for dilute solutions is linear when plotted on full logarithmic paper, a fit of these data was made to an equation of the form:

$$\log K = A + B \log C, \quad (33)$$

where:

K represents the solution electrical conductivity, and

C the solution concentration.

A and B are constants of the least-squares data fit.

Figure 16. REPRESENTATIVE ARRANGEMENT FOR THE VERTICAL AIR-SPARGED TANK.

The greatest standard deviation of fit for the three conductivity measuring units was 0.0578. These data were found to compare favorably with that published in the literature.^(23, 24)

Tracer solution was made for the experimental program by adding about 300 milliliters of 20% byweight aqueous sodium chloride to about 12 gallons of demineralized water in the upper-level head tank. A small quantity of fluorescein disodium salt^(f) was added to give the tracer a greenish color and to assist in flow visualization.

(f) Dye Number 735, manufactured by Eastman Kodak.

Table 1
SAFE TANK SYSTEM PIPING LENGTHS AND COMPONENT
VOLUMES FOR DESIGNATED EXPERIMENTAL SERIES

Series Number	Tank Diameter (inches)	Tank Length (feet)	Tank Fullness (%)	Tank Volume (gals)	Two-Inch Pipe		1.5-Inch Pipe		Pump Volume (gals)	Miscellaneous System Volumes (gals)	Total System Volume (gals)
					Length (feet)	Volume (gals)	Length (feet)	Volume (gals)			
1	4	15	100.0	9.7	15.6	2.7	22.1	2.33	0.22	1.16	16.21
2	4	15	97.7	9.5	15.6	2.7	22.1	2.33	0.22	1.16	15.98
3	4	25	100.0	16.3	16.7	2.9	22.1	2.33	0.22	1.08	22.85
4	4	25	98.5	16.0	16.7	2.9	22.1	2.33	0.22	1.08	22.61
5	4	25	79.6	12.9	16.7	2.9	22.1	2.33	0.22	1.08	19.52
6	6	15	100.0	22.0	7.9	1.3	20.4	2.16	0.34	1.81	27.73
7	6	15	98.5	21.7	7.9	1.3	20.4	2.16	0.34	1.81	27.39
8	6	20	100.0	29.3	16.7	2.9	14.6	1.54	0.34	1.81	35.97
9	6	20	98.9	29.0	16.7	2.9	14.6	1.54	0.34	1.81	35.64
10	6	20	85.2	25.0	16.7	2.9	14.6	1.54	0.34	1.81	31.62
11	6	25	100.0	36.7	16.7	2.9	20.4	2.16	0.34	1.81	43.93
12	6	25	99.1	36.4	16.7	2.9	20.4	2.16	0.34	1.81	43.61
13	6	25	88.2	32.3	16.7	2.9	20.4	2.16	0.34	1.81	39.59
16	6	20	100.0	29.3	16.7	2.9	14.6	1.54	0.34	1.81	35.97
17	6	20	100.0	29.3	16.7	2.9	14.6	1.54	0.34	1.81	35.97
18	6	26	100.0	38.1	16.7	2.9	20.6	2.18	0.34	1.81	45.42
19	6	26	100.0	38.1	16.7	2.9	20.6	2.18	0.34	1.81	45.42
22	6	20	100.0	29.3	16.7	2.9	14.6	1.54	0.34	1.81	35.97
24	6	40	100.0	58.7	66.3	11.5	6.3	0.67	0.22	2.51	73.72
25	6	20	100.0	29.3	17.9	3.1	15.9	1.68	0.34	1.81	36.33
26	6	40	100.0	58.7	66.3	11.5	6.3	0.67	0.22	2.51	73.72
27	6	20	100.0	29.3	17.9	3.1	15.9	1.68	0.34	1.81	36.33
28	6	20	100.0	29.3	56.7	9.8	21.8	2.31	0.22	4.53	46.32
29	6	20	75.0	22.0	56.7	9.8	21.8	2.31	0.22	4.53	38.98
30	6	20	50.0	14.6	56.7	9.8	21.8	2.31	0.22	4.53	31.63
31	6	20	100.0	29.3	17.9	3.1	15.9	1.68	0.34	1.81	36.33
32-42	4	25	100.0	26.0	22.4	3.9	25.4	2.69	0.22	3.33	36.14
46	6	20	76.7	22.5	0.0	0.0	0.0	0.0	0.0	0.0	22.53

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Figure 17. THE EXPERIMENTAL FACILITY.

The small quantity of dye added only slightly to the solution conductivity; thus a saline tracer with a concentration of a few thousand parts per million by weight with comparable conductivity was made available.

In preparation for a series of experiments on one of the safe tank systems, the system was filled with demineralized water to a predetermined fullness. This water, having an initial conductivity of about one micromho per centimeter (equivalent to a concentration of about $1/2$ ppm of sodium chloride tracer), was recirculated or air sparged as appropriate at a high flow rate to homogeneity. The conductivity recorder was read, the tank content's initial conductivity recorded, and chart drive mechanism stopped. Notation was then made on the recorder strip chart of the experimental run being conducted and the exact pen location marked for future reference.

Recirculation-Mixed Systems

As a recirculation-mixing experiment begins from a static condition after tracer has been added to a segregated section of loop piping, the recirculation rate was set by adjustment of the flow control valve to a specified rotameter reading before stopping the pump. Tracer material was added to the segregated section of the pump discharge piping, as shown by Figure 11, from an overhead tank by closing the isolating $1\frac{1}{2}$ -inch ball valves, draining the contents, and refilling with tracer by manipulating the $1/2$ -inch drain-and-fill valves. After tracer addition, the isolation valves were opened and preparation for the experiment completed.

The run was initiated by starting a stopwatch and the recorder strip-chart drive simultaneously, and quickly starting the pump for recirculation. The timed experiment continued until the salt tracer was homogeneously dispersed throughout the safe tank system. After this condition was attained, the strip-chart drive and stopwatch were stopped. Run time and final system conductivity were recorded and the strip-chart pen point location exactly marked.

Air Sparge-Mixed System

For the air sparge-mixing experiments, an initial-static condition within a vertical tank similar to that used in the recirculation-mixing procedure was used. After filling the tank with demineralized water and air-sparge mixing to homogeneity, the air flow rate would be set to a preassigned value for the next run by adjusting a flow control valve downstream from the air rotameter. After closing a quick-opening ball valve in the air supply line, tracer from an overhead tank was added at the base of the vertical safe tank for about three minutes by the manipulation of tracer fill valving. The run was subsequently begun by simultaneously starting a stopwatch, starting the recorder strip-chart drive, and opening the air-flow ball valve. The timed experiment continued until the salt tracer was homogeneously dispersed throughout the safe tank system. After this condition was attained, the strip-chart drive and stopwatch were stopped. Run time and final system conductivity were recorded and the strip-chart pen point location exactly marked.

RESULTS

Experimental determinations of the mixing time and/or dispersion intensity have been made for twelve cylindrical, recirculation-mixed, safe tank systems. Preliminary measurements of the mixing time for a cylindrical, vertical, air-sparged safe tank have also been made. A listing of the experimental series that were conducted, summarizing the systems evaluated, and pertinent details for each experimental series is given in Table 2. A comparison of the data collected in the experimental series with the published data for dispersion intensity, and with the theoretical mixing model predicted mixing time for single tank systems, is made in the discussion that follows.

Dispersion Intensity

Using an approximation to the pulse-type tracer techniques where tracer concentration as a function of time was continuously measured at the safe tank outlet, the relationship between dispersion intensity and Reynolds number for three single tank systems, as depicted in Figure 2 and characterized in Tables 1 and 2, was studied. It was found that these data could be fit by a linear logarithmic equation over the full Reynolds number range investigated, which extended from the region of complete turbulence down into the laminar flow region (for Reynolds numbers less than 2100). Although the linear logarithmic relationship was expected for the turbulent-region experiments which would correspond to Taylor's prediction⁽¹²⁾ for a smooth

Table 2
SUMMARY DATA OF THE EXPERIMENTAL PROGRAM

Series Number	System Safe Tank		Type Experiment	Number of Runs Conducted	
	Diameter (Inches)	Length (Feet)		Mixing Time	Dispersion Intensity
1	4	15.0	Single Tank	7	7
2	4	15.0	Single Tank	7	0
3	4	25.0	Single Tank	7	6
4	4	25.0	Single Tank	7	0
5	4	25.0	Single Tank	6	0
6	6	15.0	Single Tank	12	12
7	6	15.0	Single Tank	11	0
8	6	20.0	Single Tank	35	29
9	6	20.0	Single Tank	16	9
10	6	20.0	Single Tank	15	10
11	6	25.0	Single Tank	12	13
12	6	25.0	Single Tank	11	11
13	6	25.0	Single Tank	11	8
16	6	20.0	Single Tank	0	18
17	6	20.0	Single Tank	0	18
18	6	26.0	Single Tank	0	19
19	6	26.0	Single Tank	0	12
22	6	20.0	Single Tank with Mixing Tube	11	0
24	6	40.0	Single Tank	28	0
25	6	20.0	Single Tank with Mixing Tube	20	0
26	6	40.0	Single Tank	26	0
27	6	20.0	Single Tank with Mixing Tube	22	0
28	6	20.0	Single Tank	23	0
29	6	20.0	Single Tank	10	0
30	6	20.0	Single Tank	10	0
31	6	20.0	Single Tank with Mixing Tube	11	0
32-42	4	25.0	Parallel Tanks	131	0
46	6	20.0	Air Sparge Tank	10	0

- (1) All series numbers except 46 were recirculation-mixed experiments.
 Series 46 was an air-sparge mixed experiment.
 Series 22, 25, 27, and 31 denote mixing-tube experiments with one, two, three, and five-hole sets, respectively.
 All experimental facilities were horizontal except for Series 28, 29, 30, and 46.

pipe and agree with published data compiled by Levenspiel, (13) the extension of linearity through the transition region and into the laminar region was unexpected. These characteristics are depicted in Figure A-19 where a curve representing previously published transition region data as given by Levenspiel, a curve representing Taylor's turbulent region prediction, and curves representing data collected in this experimental program are plotted together for the full Reynolds number range investigated.

Since the dispersion intensity is a dimensionless variable embodying the dispersion coefficient, its value has been determined from an analysis of the recorder strip-chart data and known properties of the dispersion model. Since strip-chart data consist of a continuous electrical conductivity measurement at a safe tank outlet, a transformation must be made from conductivity to tracer concentration and from

pen position on the chart to time from the start of the experiment. These transformations were made using the following equations:

$$\log C = A + B \log K, \quad (34)$$

and

$$t = \frac{D - D_0}{r}, \quad (35)$$

where:

- C represents the tracer concentration,
- K the measured electrical conductivity,
- t the time,
- D the pen position on the strip chart,
- D₀ the initial pen position on the strip chart, and
- r the strip chart rate.

A and B are constants of the least-squares calibration data fit.

It has been shown that the dispersion intensity is related to the mixing number by Equation 9. It will also be shown that the dispersion intensity for the dispersion model using Equation 12 is given approximately after neglecting the second term on the right side of this equation when the mixing intensity is small as shown by Equation 36. Combining these equations gives the following results:

$$P = (Di) \left(\frac{d}{L} \right) \quad (9)$$

and

$$\sigma^2 = 2P \quad (12, \text{simplified})$$

are combined to give:

$$\sigma^2 = 2 (Di) \left(\frac{d}{L} \right). \quad (36)$$

The transformation to the dimensioned variance:

$$\sigma^2 = \frac{\sigma_t^2}{(\bar{t})^2} \quad (15)$$

combined with Equation 36 gives:

$$\sigma_t^2 = 2(\bar{t})^2 (Di) \left(\frac{d}{L}\right),$$

and by rearrangement:

$$Di = \frac{1}{2(\bar{t})^2} \left(\frac{L}{d}\right) \sigma_t^2. \quad (37)$$

Equation 37 provides the relationship for calculating the dispersion intensity from transformed strip-chart data. The dimensioned variance is calculated by statistical methods from a set of concentration-time data taken at equal time increments from the strip chart. As shown by Levenspiel:⁽²⁵⁾

$$\sigma_t^2 = \sum t^2 C(t) \Delta t - (\bar{t})^2, \quad (38)$$

where:

- t represents the time to $C(t)$ measurement,
- $C(t)$ the average tracer concentration at time t within the time increment,
- Δt the time increment, and
- $\bar{t}$ the mean residence time for the tank system.

To facilitate the treatment of large amounts of strip-chart data, a computer program was written to calculate the dimensioned variance for each experimental run. It was found that, as in the case of published dispersion intensity-Reynolds number data in the turbulent region, dimensioned variance-recirculation rate data could be plotted linearly on full logarithmic paper, but in this case over the full range of the recirculation rate. For this reason, a linear fit of the form:

$$\log \sigma_t^2 = A - B \log Q, \quad (39)$$

where:

σ_t^2 represents the dimensioned variance and

Q the recirculation rate, was made for each set of data collected. As previously,

A and B are constants of the least-squares data fit.

Plots of the data collected in these experimental series, which have been listed in Table A-1, are given in Figures A-21 through A-31. Values of the constants for the constants for these data fits, their standard error, and the variance of the estimate for the linear fits are reported in Table A-5.

Reynolds numbers were calculated from formulas given by Perry.⁽²⁶⁾ Since demineralized water was the bulk safe tank fluid for all experiments, a simplified formula for the Reynolds number calculation was used. After viscosity and density were substituted into a standard formula, the formula modified to consistent dimensions became:

$$Re = \frac{3161W}{d}, \quad (40)$$

where:

W represents the recirculation rate in gallons per minute and

d the equivalent tank diameter in inches.

Using the equation of fit for each data set, the corresponding set of dispersion intensity-Reynolds number data was calculated using Equations 37 and 40.

By this method, less variability is introduced into the final data set than if raw dimensioned variance-recirculation rate data are individually transformed into dispersion intensity-Reynolds number data and subsequently fit by Equation 2.

$$\log (Di) = A - B \log (Re).$$

The added variability comes from the direct substitution of raw data into Equation 37 where the mean residence time which is a function of a measured variable (recirculation rate) is squared.

To study the effect of the measurement position upon the dispersion intensity for a tank, two additional experimental series (16 and 17) were conducted. In Series 16 the conductivity cell was located immediately inside the tank, as shown in Figure 8. For Series 17, the cell was located immediately outside the tank, as shown in

Figure 9. Based on a comparison of the linear logarithmic correlation for these series, as plotted in Figures A-23 and A-24, little difference in the two data sets can be observed. Subsequently, Experimental Series 18 and 19 were conducted in the center section of a tank system. The experimental procedure utilized two measurement probes and methods proposed by Aris⁽¹⁶⁾ and later extended by Levenspiel and Bischoff.⁽²⁷⁾ A variance difference was determined across the 14 1/2-foot center section of a 26-foot-long tank and used in Equation 37 as recommended by these authors. Even though wire grid turbulence promoters were placed across the tank closures for Series 19, little difference was observed in these two data sets when plotted (Figures A-28 and A-31).

Because it is desirable to replace all of the data by a single linear fit, and a transformation of the statistical quantities given in Table A-5 by the use of Equations 37 and 40 distorts their meaning, the latter method of data treatment was used. It was found by an analysis of the variance methods suggested by Lehmann⁽²⁸⁾ that data from each experimental series could be represented by a single slope, $\bar{B}$, and a single intercept, $\bar{A}$. Thus, a single linear data fit representing all data can be statistically justified. Substantiation is given in an analysis of the variance tabulated in Table A-6.

Values of the averaged constants and their standard errors are:

$$\bar{A} = 1.276 \qquad S_{\bar{A}}^2 = 0.210$$

$$\bar{B} = 0.2805 \qquad S_{\bar{B}}^2 = 0.0219$$

Mixing Time

Mixing time has been measured for seven single tank systems; for a two-in-parallel tank system, for four mixing-tube systems (all mixed by recirculation), and for a vertical single tank system (mixed by air sparging). As in the dispersion intensity measurements, pulse-type techniques were used. By mixing a relatively small volume of tracer thoroughly with the contents of a system initially devoid of tracer, a measure of the greatest mixing time can be determined. This mixing time is larger than that required to mix a system that initially was nearly homogeneous; however, since the degree of homogeneity for a system cannot easily be predetermined, the most inhomogeneous initial condition for a system must be treated.

Recirculation-Mixed Single Tank Systems - Mixing time was measured for seven completely filled and five partially filled systems, as shown in Figure 2, at recirculation rates between 1 and 100 gpm. Since the program has been directed primarily at developing experimental data to substantiate the theoretical

predictions, only one vertical system was considered. Figure 18 obtained from an experimental run at 33.19 gpm depicts the form of recorder strip-chart curves obtained from these experiments. With the exception of two sets of experimental data, a linear logarithmic relationship between the mixing time and the recirculation rate was observed. As discussed in an earlier report,⁽³⁾ this relationship (designated Equation 1) is intuitively acceptable. In the two limiting conditions of zero and infinite recirculation rate, the mixing time should approach values of infinity and zero, respectively. This is exhibited by the antilogarithmic form of the equation:

$$T = 10^A Q^{-B},$$

where:

$$T \rightarrow \infty \text{ for } Q \rightarrow 0 \text{ and}$$

$$T \rightarrow 0 \text{ for } Q \rightarrow \infty$$

when the limiting values of the recirculation rate are introduced.

For these reasons, mixing-time data for all experiments, as listed in Table A-1, were fitted to Equation 1 by least-squares methods. A plot of these data for each experimental series is given in Figures A-1 through A-18. Values of the constants for these data fits, their standard error, and the variance of estimate for the linear fits are reported in Table A-2.

For the two sets of data previously mentioned as exceptions to the linear logarithmic fit of Equation 1, three distinct relationships between the mixing time and the recirculation rate are apparent, as shown in Figures A-14 and A-15. These data were collected in a single tank system with the greatest length-to-diameter ratio studied ($L/d = 80$) and with two methods of tracer input. They exhibit linear logarithmic relationships in the laminar and turbulent regions. In the transition region for recirculation rates between about 10 and 30 gpm (Reynolds numbers between 5000 and 15,000) data appear more scattered than in the other regions. The existence of a three-region relationship between the mixing time and the recirculation rate for this system suggests that the scatter of data away from the linear data fit at the lowest recirculation rates for many of the other sets of data collected from systems with smaller length-to-diameter ratios is a characteristic of single tank system recirculation-mixing operations. As this multiregion characteristic was most apparent for the single tank system with greatest length-to-diameter ratio, and since published data⁽²⁹⁾ indicate that up to 50 diameters of straight pipe downstream of a flow disturbance is needed to attain the final fluid velocity distribution, tank end effects upon single safe tank mixing appears to be pronounced.

An alternate method of tracer input was used to demonstrate that pulse-type experiments are appropriate for safe-tank mixing studies. For data collected and plotted

in Figure A-15, tracer was added directly to the lower end of the safe tank by a special piping arrangement at the low-tank end reducer. Tracer placed in a horizontal tank in this manner will seek a level depending upon its specific gravity as do fuel process solutions in any storage facility. From a comparison of these data with those plotted in Figure A-14, the methods appear to give equivalent mixing-time data except at high recirculation rates. At the highest rates, measured mixing times were about 20% less for the tank-injection experimental series. Since in this case tracer is initially spread over a greater volume of the tank system than for the pulse-type experiments, it takes some number of circulations to get an equivalent tracer spread for a pulse experiment. At lower recirculation rates due to reduced radial mixing intensity during recirculation, this inequity in the initial conditions is less significant and becomes imperceptible. From these remarks and observations it has been shown that pulse-type mixing experiments are appropriate even though in some cases a shorter period of time is required to mix.

From a comparison of the mixing-time data collected for the vertical tank system with that collected for horizontal systems, it appears that mixing in vertical systems is less efficient. As shown in Figures A-8 and A-16, for comparable systems with six-inch-diameter by 20-foot-long tanks, the mixing-time requirement for the vertical system was from three to six times longer than that of the horizontal system within a range of recirculation rates between 4 and 80 gpm. Although no measurement of the dispersion intensity was made for the vertical system, it is clear that the dispersion intensity for the vertical system was much less than that for the horizontal systems. A possible explanation is that air which was entrained in the recirculating fluid of the vertical system caused the stream velocity distribution within the tank to be more plug like than normal for flow in the laminar and turbulent flow regimes and thus reduced the effective dispersion intensity which is greatly dependent upon velocity distribution, as reported by Tichacek, et al.⁽³⁰⁾ It should be pointed out that these data were collected from completely filled systems vented at the uppermost point, and that only in the vertical tank system was air induced into the flowing stream through the vent and retained in the stream.

In all cases studied, the mixing time for partially filled systems was less than that for the completely filled system. The mixing time for nearly full systems was observed to be roughly proportional to the degree of fullness.

Based on the dispersion model, mixing-time calculations have been made for all the completely filled single tank systems studied. It was found, by using the calculational procedure outlined previously, that published dispersion intensity data gave serious errors in the mixing-time predictions. Except at high recirculation rates, the logarithmic form of the predicted mixing-time curve was nonlinear; in the transition flow regime, a mixing time minimum was indicated. By using a linear extrapolation of Taylor's dispersion intensity prediction for the turbulent flow region⁽¹²⁾ into the laminar flow region, a much better comparison with experimental data was noted; however, when the dispersion intensity-Reynolds number correlation measured in this program was used, comparatively the best mixing-time prediction

Figure 18. TYPICAL STRIP CHART RECORDING FOR A RECIRCULATION-MIXED SINGLE TANK SYSTEM. (Series 26, Run 444)

Figure 19. TYPICAL STRIP CHART FOR A RECIRCULATION-MIXED, TWO-IN-PARALLEL TANK SYSTEM. (Series 38, Run 109)

was made. The comparison of mixing time calculated by using the measured (averaged) dispersion intensity correlation was made at several recirculation rates with mixing times based on the least-squares fit to experimentally observed mixing times.

From a comparison of the mixing times given in Table A-7, it should be noted that large relative errors exist in many cases. These errors result, at least in part, from the use of an averaged dispersion intensity-Reynolds number correlation in place of a correlation which was measured for that system, or one which in the future might be predictable for a given system.

In addition, an evaluation was made of the effect of disregarding the mixing that takes place outside the safe tank of a system. This effect was determined by using the measured dispersion intensity correlation and the outlined mixing-time calculational procedure. By disregarding this mixing, an error of about three percent was generated in the mixing-time prediction. This discrepancy results from the fact that the overall mixing number for these safe tank systems is only slightly different from the mixing number for the safe tank of each system. Therefore, in cases where the diameter and the aggregate volume of the loop piping is small compared with the safe tank itself, the loop-piping contribution to the system mixing number can be neglected as insignificant.

From an inspection of Equation 22 it is seen that the mixing number determines the mixing time for any system given the desired end condition of homogeneity.

For end conditions of 90, 95, 99, 99.5, 99.8, and 99.95% mixed, as defined by Equation 23 and for several values of the mixing number, the dimensionless mixing time, θ , has been found by digital computation. These values are given in Table A-4. For mixing numbers up to about 0.1, a linear logarithmic relationship exists between the mixing number and dimensionless mixing time for a given end-mixed condition. As essentially all single safe tank systems will have a mixing number in this linear range, the plot of these variables, as given in Figure A-20, which is the solution to Equation 22, gives single-tank mixing times.

To illustrate the utility of the mixing-time calculational method, the following steps are given:

A. Select values for the:

1. system recirculation rate (Q),
2. aggregate system volume (V),
3. safe tank length (L), and
4. safe tank inside diameter (d).

- B. Calculate in dimensionally consistent units the following quantities:
1. system mean residence time (V/Q),
 2. safe tank length-to-diameter ratio (L/d), and
 3. Reynolds number in the safe tank (Re).
- C. From Figure A-19, read off the safe-tank dispersion intensity, Di , using the calculated Reynolds number (B.3.).
- D. Calculate the approximate system mixing number, P , by Equation 9:

$$(P)_{\text{system}} = (Di)_{\text{safe tank}} \times \left(\frac{d}{L}\right)_{\text{safe tank}}$$

- E. For the desired end-mixed condition and with the system mixing number from Step D, read off the dimensionless mixing time, T , from Figure A-20.
- F. Calculate the system mixing time, t_m , by multiplying the dimensionless mixing time from Step E by the system mean residence time from Step B.2., or:

$$t_m = T \left(\frac{V}{Q}\right).$$

Recirculation-Mixed Parallel Tank System - A series of 142 experimental runs have been made in a horizontal, completely filled two-in-parallel tank system mixed by recirculation. These series were conducted at eleven levels of total recirculation rate between 10 and 100 gpm and at eleven levels of flow-split ratio (ratio of flow through one tank to the flow through the other tank) between 0.0 and 1.0. The system, as shown in Figure 15, had characteristic piping lengths and volumes listed in Table 1.

As in the case of single tank systems mixed by recirculation, mixing-time strip charts were observed to have distinctive tracer conductivity curves. As expected, the shape of the curves for a parallel tank system was found to be greatly dependent upon the flow-split ratio, although for ratios of 0.0 and 1.0 the curves were similar to those for the single tank experiments. The form of the tracer curves with flow-split ratios between these limits is indicated in Figure 19 (Page 49) which is a strip chart obtained at a flow-split ratio of 0.667 and a total recirculation rate of 40.0 gpm.

For a given flow-split ratio and the range of recirculation rates considered, a linear logarithmic relationship between mixing-time and recirculation-rate data was observed to fit the form of Equation 1.

These mixing-time data, given in Table B-1, were treated to a least-squares fit of this form and plotted in Figures B-1 through B-11. Values of the constants for each fit, their standard errors, and the variance of estimate for the fit are given in Table B-2.

To expose the effect of the flow-split ratio upon the mixing time, a cross plot has been made of the data treated in Figures B-1 through B-11 to linear logarithmic equations. This semilogarithmic plot of mixing time as a function of the flow-split ratio is given in Figure B-12 and demonstrates the effectiveness of parallel-tank mixing. Within the flow-split ratio range of 0.6 to 0.8, a minimum in the mixing time relationship was found to exist. By mixing the two-in-parallel tank system within the range of flow-split ratios for mixing-time minimization, the mixing-time requirement was reduced at some recirculation rates to about 1/8 of the requirement when equal tank flows (flow-split ratio of 1.0) were used.

As a consequence of the mixing time minimization for the two-parallel tank system studied, it is apparent that an optimum flow-split ratio exists for every parallel tank system. Although it is not possible at this time to predict the optimum flow-split ratio for more than two tanks in parallel, it is clear that extreme ratios comparable to the two-tank system ratios of 0.0 and 1.0 would be least efficient. It appears that the best guide to optimize the mixing efficiency would be to use a different ratio for each tank where each is selected in the range of 0.6 to 0.8 when compared to the two tank system. To illustrate, the following flow-split ratio might be suggested for a three-in-parallel tank facility:

Allow Q_1/Q_2 to equal 3/4

and Q_2/Q_3 to equal 3/4.

Since $Q_T = Q_1 + Q_2 + Q_3$,

solving for Q_1 , Q_2 , and Q_3 gives:

$$Q_T = Q_1 + \frac{4}{3} Q_1 + \left(\frac{4}{3}\right)\left(\frac{4}{3} Q_1\right).$$

or: $Q_1 = 0.2433 Q_T$,

$Q_2 = 0.3243 Q_T$, and

$Q_3 = 0.4324 Q_T$.

For a four-in-parallel tank system, the following would be relatively efficient:

Allow Q_1/Q_2 to equal $3/4$,

Q_3/Q_4 to equal $3/4$, and

Q_1/Q_3 to equal $4/5$.

Since $Q_T = Q_1 + Q_2 + Q_3 + Q_4$,

$$Q_T = Q_1 + \frac{4}{3} Q_1 + \frac{5}{4} Q_1 + \left(\frac{4}{3}\right)\left(\frac{5}{4} Q_1\right),$$

or:

$$Q_1 = 0.1905 Q_T,$$

$$Q_2 = 0.2540 Q_T,$$

$$Q_3 = 0.2381 Q_T, \text{ and}$$

$$Q_4 = 0.3174 Q_T.$$

It should be emphasized that these flow-split ratios have been selected from those in the range where two-in-parallel tank mixing efficiencies were found to be the highest and for a case where no two tanks in parallel would have an equal recirculation rate. These ratios are then not optimum ratios but are such as should give a better mixing efficiency than might be achieved by selecting flow-split ratios in some random manner. Further, the necessity of having a sufficiently high recirculation rate through all tanks, at least in the low turbulent flow region (Reynolds number greater than about 10,000), cannot be neglected. The more dense liquid components contained in a horizontal tank system must be picked up by the recirculation flow for mixing. At low recirculation rates this is not achieved.

Recirculation-Mixed Mixing Tube Systems - Experimental pulse-type injection tracer studies have been conducted on four mixing-tube systems for mixing-time measurement. A total of 64 runs were made using the mixing tubes shown in Figure 20 and at recirculation rates between 1.87 and 79.78 gpm. The system, as shown in Figure 14, had characteristic piping lengths and volumes as shown in Table 1. At selected axial positions, as indicated in Figure 20, four equally spaced holes (9/32 inch in diameter) drilled and reamed provided approximately equal flow out into the annular safe tank region at each position.

Figure 20. REPRESENTATIVE ARRANGEMENT FOR ONE, TWO, THREE, AND FIVE-HOLE SET MIXING TUBES.

Mixing-time data for these mixing-tube systems were found to fit a linear logarithmic relationship of the form of Equation 1. These data, as listed in Table C-1, were fit to the equation by a least-squares method and plotted (Figures C-1 through C-4). Values of the constants of these fits, their standard error, and the variance of estimate of each fit is given in Table C-2.

It is apparent from a comparison of the data collected from the experiments using a single-axial-hole set location tube and using a two-axial-hole set location tube that mixing time is significantly reduced by utilizing series-parallel flows to mix. With the single-hole set tube, a simple flow pattern analogous to the dispersion mixing previously discussed for open single tanks exists, while with the addition of the second-hole set a complex series-parallel flow pattern is generated. For the two-hole set tube (second-hole set located six feet downstream from the first set), mixing time is reduced up to $1/5$ of that required by the single-hole set tube. From a comparison of Figure 21 obtained from the two-hole set mixing tube at a recirculation rate of 32.96 gpm with Figure 18 obtained from a single tank system at a recirculation rate of 33.19 gpm, the utility of a series-parallel flow pattern is readily noted.

The ineffectiveness of an indiscriminate addition of other axial hole sets is apparent from a comparison of the data plotted in Figure C-3. These data were obtained

Figure 21. STRIP CHART OBTAINED FOR A TWO-HOLE SET, RECIRCULATION-MIXED, MIXING TUBE SYSTEM. (Series 25, Run 390)

Figure 22. STRIP CHART OBTAINED FROM A FIVE-HOLE SET, RECIRCULATION-MIXED MIXING TUBE DESIGNED WITH AN ADJACENT-REGIONS RESIDENCE RATIO OF 2:3. (Series 31, Run 510)

Figure 23. A TYPICAL STRIP CHART FOR AN AIR-SPARGE-MIXED VERTICAL TANK SYSTEM. (Series 46, Run 4A)

after a third hole set was placed in the two-hole set tube at a position twelve feet downstream from the first hole set. In this case essentially no change in mixing time was measured when compared with the two-hole set tube at the same recirculation rate. This result agrees with the qualitative theoretical considerations mentioned previously.

To illustrate the effect of a more optimum pattern of series-parallel flows for safe tank mixing, a mixing tube designed to reduce the residence time of the fluid in upstream annular regions between hole sets was tested. The tube was designed to provide a residence-time ratio for adjacent annular regions of 2:3. The design accounted for the residence time of fluid moving through the tube from the position of the first hole set and also accounted for the loop piping residence time around the loop to the first hole set position in the last annular tank region residence time. Based on these considerations, a trial-and-error digital computer solution was used to determine the axial hole separations for five-hole sets, as indicated in Figure 20. The uniqueness of using this tube is shown by the strip chart of Figure 22 obtained at a recirculation rate of 23.96 gpm.

Although this mixing tube is more efficient at high recirculation rates than the two and three-hole set tubes, it appears slightly less efficient at the low rates, as is shown by comparing Figures C-2, C-3, and C-4. No explanation can be given at this time for the failure of the designed tube to more efficiently mix over the full range recirculation rate than these two and three-hole set tubes. It is suspected that additional experiments now in progress, where tubes with equal numbers of hole locations and where the tracer is injected directly into the annular region at the first hole set, will shift these mixing-time curves and show the designed tube to be more efficient.

Air-Sparged Vertical Tank System - Preliminary mixing-time measurements have been made for a vertical, air-sparged safe tank system. Mixing time measured for this six-inch-diameter by 20-foot-tall tank system filled to about 15 feet was made at air flow rates between 0.12 and 5.0 scfm of air. Data from these experiments, as listed in Table D-1, have been fitted to a linear logarithmic equation of the form:

$$\log T = A - B \log G, \quad (41)$$

where:

T represents the mixing time, and

G the volumetric gas sparge rate, by least-squares methods.

A and B are constants of the least-squares data fit.

The value of A, B, the standard error of A, the standard error of B, and the variance of the estimate of fit are, respectively, 1.227, 0.3182, 0.0225, 0.0416, and 0.00449. A plot of these data is presented in Figure D-1.

Because the analytical measurements required to determine the mixing time for this type of system have been difficult to interpret, as indicated by Figure 23 which is a strip chart for a 0.63 scfm experiment, and because of the scatter of these preliminary data, modifications to the experimental techniques are in progress.

FUTURE OBJECTIVES

A continuation of safe tank mixing and sampling studies is planned into the areas of: (1) parallel tank and mixing tube systems mixed by recirculation, (2) air-sparge mixed systems, and (3) systems mixed by recirculation or by air sparging when liquid-solid mixtures are handled. These studies will treat both horizontal and vertical tankage systems and will require experimental and theoretical methods.

By the use of accumulated mixing-time and dispersion-intensity data of mixing models presented herein, and of either digital or analog computers, it may be possible to generalize results of these systems in a manner similar to that given for single tank systems. This work includes the completion of mixing-time generalizations currently in progress for parallel tank facilities and will provide reliable methods for mixing-time predictions for most cylindrical storage tankage currently in use.

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APPENDIX A

DETAILED DATA FROM THE INVESTIGATION
OF SINGLE TANK SYSTEMS

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Table A-1
EXPERIMENTAL DATA FOR SINGLE TANK SYSTEMS

Run Number	Recirculation Rate (gpm)	Mixing Time (min)	Upstream Variance (min^2)	Downstream Variance (min^2)
<u>Series 1</u>				
161	2.82	104.3		0.51471
160	5.38	91.8		0.12524
159	7.90	92.5		0.02536
158	10.03	87.7		0.01386
168	31.31	44.2		0.00174
167	48.53	38.0		0.00070
166	83.66	24.4		0.00027
<u>Series 2</u>				
165	2.82	79.6		
164	5.38	83.9		
163	7.90	78.1		
162	10.03	79.2		
171	31.31	47.1		
170	48.53	29.6		
169	72.55	28.4		
<u>Series 3</u>				
154	2.82	119.3		
145	5.38	103.5		0.37667
144	7.81	113.4		0.12708
155	10.03	116.1		0.06805
137	31.31	57.2		0.00361
136	48.53	38.5		0.00170
135	89.26	29.3		0.00041
<u>Series 4</u>				
149	2.78	99.4		
148	5.29	100.3		
147	7.98	101.8		
156	10.03	104.3		
140	31.31	38.0		
139	48.53	35.2		
138	89.26	25.9		
<u>Series 5</u>				
152	2.78	117.3		
151	5.38	106.2		
150	7.90	110.6		
157	10.03	82.5		
143	31.31	44.5		
142	48.53	33.2		
<u>Series 6</u>				
103	2.05	84.9		3.20427
102	4.02	76.9		0.70689
101	6.00	73.5		0.39658
100	8.04	59.2		0.18936
99	9.84	48.8		0.09185
114	27.87	29.2		0.00755

Table A-1 (Contd)

Run Number	Recirculation Rate (gpm)	Mixing Time (min)	Upstream Variance (min ²)	Downstream Variance (min ²)
<u>Series 6 (Contd)</u>				
113	41.95	22.0		0.00353
112	52.02	19.2		0.00261
111	68.15	15.5		0.00153
110	79.58	13.0		0.00129
109	92.77	13.4		0.00057
115	92.77	14.2		0.00081
<u>Series 7</u>				
108	3.01	59.8		
107	4.18	58.3		
106	6.12	58.9		
105	7.83	53.6		
104	9.67	54.1		
121	27.87	28.2		
120	41.95	25.0		
119	52.02	22.2		
118	68.15	14.5		
117	79.58	12.7		
116	92.77	10.5		
<u>Series 8</u>				
132	1.14	401.4		
12	1.14	280.0		79.81937
6	1.14	216.0		
5	2.06	99.0		
11	2.14	216.0		
58	2.54	104.0		3.81365
59	2.77	107.1		1.79662
57	3.09	99.0		2.37644
56	4.06	71.3		0.84275
4	4.10	102.5		1.81880
22	4.10	98.3		
21	4.10	94.2		
10	4.10	75.7		0.59013
54	5.07	69.3		0.72515
3	6.04	89.8		0.35935
17	6.04	84.7		0.33150
18	6.04	78.8		0.87215
16	6.04	75.5		0.67171
9	6.04	73.5		0.40647
15	6.08	85.8		0.44258
19	8.04	87.6		0.28183
2	8.04	77.4		0.16090
14	8.04	67.3		0.24677
8	8.04	64.0		0.12221
20	8.08	88.3		0.37071
13	8.12			0.20086
1	10.06	65.4		
7	10.32	68.8		0.09760
29	25.65	51.2		0.01616
28	32.43	43.9		0.00732
27	41.95	45.2		0.00434
31	52.02	39.5		0.00268
25	57.26	35.3		0.00240
26	57.26	32.6		0.00242
24	73.80	36.2		0.00154
30	79.58	27.5		0.00118
23	91.54	28.3		0.00082

Table A-1 (Contd)

Run Number	Recirculation Rate (gpm)	Mixing Time (min)	Upstream Variance (min ²)	Downstream Variance (min ²)
<u>Series 9</u>				
133	1.14	295.9		
126	2.89	111.1		
153	4.10	101.2		
125	4.14	88.3		
124	6.12	85.0		
123	8.04	83.4		
122	9.80	75.5		
39	19.19	55.1		0.04611
36	23.03	51.9		0.01362
53	29.23	40.7		0.00914
37	37.12	39.7		0.00391
52	48.94	33.9		0.00326
38	52.02	26.1		0.00211
35	62.64	30.4		0.00140
34	79.58	24.9		0.00097
32	95.24	23.3		0.00068
<u>Series 10</u>				
134	1.14	82.8		
131	3.01	81.4		
130	4.10	66.4		
60	4.87	66.7		0.07412
129	6.04	64.0		
128	8.04	69.0		
127	9.80	65.0		
48	15.05	49.7		0.02158
44	23.46	47.1		0.00712
49	29.23	35.5		0.00483
45	32.43	38.4		0.00614
50	37.12	29.6		0.00263
43	41.95	25.7		0.00214
42	52.02	23.4		0.00129
46	62.64	19.4		0.00112
47	68.15	15.8		0.00091
<u>Series 11</u>				
67	2.93	194.4		2.01271
66	4.10	97.6		0.87989
63	6.04	79.6		0.46540
64	6.08	85.3		0.38992
65	6.12	80.4		0.55720
62	8.04	80.2		0.39868
61	9.71	108.1		0.18612
83	27.87	64.2		0.01621
82	37.12	58.1		0.00814
81	52.02	46.5		0.00372
80	62.64	42.8		0.00276
79	79.58	32.1		0.00175
78	92.16	27.9		0.00125
<u>Series 12</u>				
72	2.93	153.3		2.05812
71	4.10	100.0		1.00362
70	6.04	74.8		0.29573
69	8.04	75.2		0.17050
68	9.80	89.4		0.17009
90	27.87	64.0		0.01551
89	41.95	46.5		0.00527

Table A-1 (Contd)

Run Number	Recirculation Rate (gpm)	Mixing Time (min)	Upstream Variance (min ²)	Downstream Variance (min ²)
<u>Series 12 (Contd)</u>				
88	52.02	46.6		0.00359
87	68.15	32.8		0.00212
86	79.58	26.1		0.00124
85	92.16	26.7		0.00098
<u>Series 13</u>				
98	2.93	80.6		
76	4.10	78.8		0.18393
75	6.04	77.3		0.32887
74	8.04	76.5		0.19516
73	9.71	88.0		0.10273
96	27.87	53.7		
95	41.95	37.8		
94	52.02	31.2		0.00191
93	68.15	25.7		0.00168
92	79.58	21.9		0.00100
91	92.16	19.5		0.00080
<u>Series 16</u>				
236	11.45			0.12436
209	11.45			0.11159
235	19.61			0.03372
208	19.61			0.02485
234	28.32			0.01546
207	28.32			0.01363
233	37.60			0.00808
206	37.60			0.00660
232	47.42			0.00536
205	47.42			0.00428
231	57.79			0.00295
204	57.79			0.00280
230	68.71			0.00219
203	68.71			0.00168
229	80.17			0.00141
202	80.17			0.00121
228	97.73			0.00099
<u>Series 17</u>				
227	11.45			0.14603
218	11.45			0.11180
226	19.61			0.03828
217	19.61			0.03516
225	28.32			0.01515
216	28.32			0.01819
224	37.60			0.00770
215	37.60			0.00650
223	47.42			0.00465
214	47.42			0.00490
222	57.79			0.00277
213	57.79			0.00276
221	68.71			0.00186
212	68.71			0.00174
220	80.17			0.00149
211	80.17			0.00156
219	97.73			0.00087
210	97.73			0.00071

Table A-1 (Contd)

Run Number	Recirculation Rate (gpm)	Mixing Time (min)	Upstream Variance (min ²)	Downstream Variance (min ²)
<u>Series 18</u>				
255	11.45		0.03784	0.13095
246	11.45		0.03544	0.11310
254	19.61		0.01009	0.02648
247	19.62		0.01185	0.03147
253	28.32		0.00476	0.01775
244	28.32		0.00338	0.01275
252	37.60		0.00249	0.00943
243	37.60		0.00263	0.00626
251	47.42		0.00192	0.00489
242	47.42		0.00162	0.00403
250	57.79		0.00124	0.00282
241	57.79		0.00115	0.00242
249	68.71		0.00075	0.00177
240	68.71		0.00084	0.00193
248	80.17		0.00067	0.00107
239	80.17		0.00049	0.00146
248	96.47		0.00042	0.00106
238	96.47		0.00039	0.00100
237	96.47		0.00031	0.00084
<u>Series 19</u>				
267	6.04		0.17961	0.16680
266	7.90		0.10238	0.31269
265	10.03		0.05936	0.13343
264	11.45		0.02339	0.12014
263	19.61		0.00822	0.04116
262	28.32		0.00313	0.01141
261	37.60		0.00283	0.00797
260	47.42		0.00118	0.00433
259	57.79		0.00086	0.00234
258	68.71		0.00080	0.00161
257	80.17		0.00055	0.00161
256	96.47		0.00043	0.00102
<u>Series 24</u>				
375	3.62	321.3		
376	3.62	342.9		
374	5.45	238.4		
377	5.45	234.7		
373	6.80	166.0		
378	6.80	172.9		
372	7.75	150.6		
379	7.75	166.7		
371	8.95	141.0		
380	8.95	167.7		
361	11.60	166.4		
362	11.60	169.3		
360	19.90	157.9		
363	19.90	153.1		
359	28.80	129.1		
364	28.80	134.4		
358	37.90	123.2		
365	37.90	132.4		
357	47.40	111.8		
366	47.40	110.5		
356	57.50	94.9		
367	57.50	89.5		

Table A-1 (Contd)

Run Number	Recirculation Rate (gpm)	Mixing Time (min)	Upstream Variance (min ²)	Downstream Variance (min ²)
<u>Series 24 (Contd)</u>				
355	67.80	74.7		
368	67.80	76.7		
354	78.80	70.8		
369	78.80	63.1		
353	95.10	50.7		
370	95.10	59.7		
<u>Series 26</u>				
429	1.87	572.7		
430	1.87	511.0		
530	1.87	457.9		
428	3.62	354.3		
431	3.62	388.3		
427	5.45	224.7		
432	5.45	205.8		
426	7.35	148.7		
433	7.35	191.0		
425	8.95	126.0		
434	8.95	149.3		
441	11.60	163.7		
442	11.60	169.2		
440	19.90	132.3		
443	19.90	133.4		
439	33.19	110.5		
444	33.19	106.8		
438	47.40	77.7		
445	47.40	80.9		
437	62.80	63.2		
446	62.80	61.7		
436	78.80	58.6		
447	78.80	48.5		
435	95.10	47.7		
448	95.10	47.3		
449	101.00	45.4		
<u>Series 28</u>				
454	3.76	622.0		
458	3.76	591.3		
452	5.79	412.3		
455	5.79	461.0		
459	5.79	454.1		
475	6.70	317.4		
488	6.70	301.4		
451	7.90	282.7		
456	7.90	286.2		
450	10.00	176.4		
457	10.00	209.6		
476	18.20	87.7		
487	18.20	104.8		
477	31.78	66.9		
486	31.78	70.0		
478	46.30	66.2		
485	46.30	66.4		
479	62.20	56.9		
484	62.20	43.5		
480	78.70	40.8		
483	78.70	54.0		
481	92.00	41.1		
482	92.00	41.9		

Table A-1 (Contd)

Run Number	Recirculation Rate (gpm)	Mixing Time (min)	Upstream Variance (min ²)	Downstream Variance (min ²)
<u>Series 29</u>				
453	3.76	359.2		
464	5.79	299.6		
489	6.70	210.2		
460	7.90	226.8		
462	10.00	140.0		
490	18.20	93.3		
491	31.78	61.0		
492	46.30	44.4		
493	62.20	19.5		
494	78.70	13.9		
<u>Series 30</u>				
466	3.76	215.2		
467	5.79	189.5		
495	6.70	165.0		
468	7.90	143.8		
469	10.00	112.2		
496	18.20	84.5		
497	31.78	52.8		
498	46.30	36.8		
499	62.20	10.5		
500	78.70	9.6		

Table A-2

STATISTICAL QUANTITIES OBTAINED FROM THE RECIRCULATION-
MIXED, SINGLE TANK SYSTEM MIXING-TIME DATA FITS

Series Number	Parameter A		Parameter B		Variance of Estimate of Fit
	Value	Standard Error	Value	Standard Error	
1	2.302	0.065	0.441	0.051	0.005
2	2.180	0.080	0.375	0.063	0.007
3	2.378	0.085	0.442	0.067	0.008
4	2.333	0.096	0.459	0.075	0.010
5	2.365	0.078	0.474	0.069	0.005
6	2.251	0.030	0.568	0.020	0.001
7	2.138	0.068	0.510	0.049	0.007
8	2.284	0.034	0.437	0.032	0.011
9	2.359	0.036	0.505	0.027	0.004
10	2.102	0.057	0.401	0.045	0.008
11	2.305	0.066	0.394	0.050	0.009
12	2.312	0.063	0.424	0.045	0.006
13	2.225	0.072	0.429	0.051	0.008
24	2.764	0.042	0.476	0.030	0.007
26	2.813	0.033	0.567	0.025	0.005
28	3.206	0.051	0.845	0.037	0.007
29	3.070	0.053	0.860	0.047	0.002
30	2.792	0.038	0.717	0.034	0.001

Table A-3

STATISTICAL QUANTITIES OBTAINED FROM MIXING
NUMBER-DIMENSIONLESS MIXING TIME FITS

Mixed Condition	Parameter A		Parameter B		Variance of Estimate of Fit
	Value	Standard Error	Value	Standard Error	
90.0	1.0808	0.0110	0.9865	0.0049	0.0001
95.0	0.9587	0.0094	0.9763	0.0040	0.0001
99.0	0.8292	0.0083	0.9863	0.0034	0.0001
99.5	0.7672	0.0098	0.9810	0.0044	0.0001
99.8	0.6829	0.0220	0.9713	0.0097	0.0002
99.9	0.6857	0.0052	0.9906	0.0023	0.0001
99.95	0.5982	0.0167	0.9714	0.0074	0.0001

Table A-4
 PREDICTED DIMENSIONLESS MIXING TIME FOR A RECIRCULATION-
 MIXED, SINGLE TANK SYSTEM AS A FUNCTION OF THE SYSTEM
 MIXING NUMBER AT THE INDICATED MIXED CONDITIONS

Mixing Number	Dimensionless Mixing Time at Percentage Mixed Conditions of						
	90.0	95.0	99.0	99.5	99.8	99.9	99.95
0.001	75.9990	93.9990	134.9990	148.9756	172.9990	192.9990	210.9990
0.002	37.9980	46.9980	67.9980	75.9980	87.9980	96.9980	105.9980
0.004	18.9960	23.9960	33.9960	37.9960	43.9960	48.9960	52.9960
0.007	10.9930	13.9930	19.9930	21.9930	24.9930	27.9930	30.9930
0.01	7.9900	9.9900	13.9900	15.9900	17.9900	19.9900	21.9900
0.02	3.9801	4.9801	6.9801	7.9801	8.9801	9.9801	10.9801
0.04	1.9609	2.9609	3.9609	3.9609	4.9609	4.9609	5.9609
0.07	1.9419	1.9419	1.9419	2.9371	2.9371	2.9371	3.9354
0.10	1.0417	1.0417	2.2791	2.2791	3.7258	3.7258	3.7258
0.20	3.4339	3.4339	3.4339	3.4339	4.8592	4.8592	5.9904
0.40	11.0557	11.0557	11.0557	11.0557	11.0557	11.0557	11.0557
0.70	26.7117	26.7117	26.7117	26.7117	26.7117	26.7117	26.7117
1.0	45.7156	45.7156	45.7156	45.7156	45.7156	45.7156	45.7156
2.0	73.9147	73.9147	73.9147	73.9147	73.9147	120.5495	120.5495
4.0	78.3575	78.3575	78.3575	78.3575	78.3575	153.8380	153.8380

Table A-5
 STATISTICAL QUANTITIES OBTAINED FROM RECIRCULATION-
 MIXED, SINGLE TANK SYSTEMS VARIANCE DATA FITS

Series Number	Parameter A		Parameter B		Variance of Estimate of Fit
	Value	Standard Error	Value	Standard Error	
6	1.356	0.086	2.302	0.059	0.012
8	1.583	0.088	2.207	0.077	0.037
9	1.550	0.302	2.213	0.182	0.015
10	0.219	0.184	1.751	0.122	0.015
11	1.361	0.063	2.156	0.048	0.008
12	1.300	0.055	2.189	0.039	0.005
13	0.917	0.208	2.041	0.144	0.047
16	1.415	0.075	2.246	0.046	0.003
17	1.571	0.062	2.338	0.038	0.002
18 ⁽¹⁾	0.793	0.061	2.124	0.037	0.002
18 ⁽¹⁾	1.457	0.085	2.274	0.051	0.004
19 ⁽¹⁾	0.876	0.133	2.204	0.089	0.015
19 ⁽¹⁾	1.222	0.155	2.133	0.104	0.021

(1) The first and second entries for Series 18 and 19 are for the upstream and downstream variance measurements respectively (See Table A-1).

Table A-6
 TABULATED ANALYSIS OF VARIANCE RESULTS FOR THE HYPOTHESIS
 THAT ALL VARIANCE DATA ARE REPRESENTED BY A SINGLE
 REYNOLDS NUMBER-DISPERSION NUMBER FIT.

Estimates of Intercepts, Slopes, and Standard Errors⁽¹⁾

Series Number	Number of Runs Used	Parameter A		Parameter B	
		Value	Standard Error	Value	Standard Error
6	12	0.6444	0.2436	0.3024	0.0593
8	28	0.6480	0.2050	0.3148	0.0538
16	17	0.4389	0.1997	0.2455	0.0462
17	18	0.8374	0.1630	0.3380	0.0375
18	18	0.7595	0.3223	0.3314	0.0741
19	11	0.8821	0.3989	0.3573	0.0943
Combined Data	104	0.5540	0.0913	0.2805	0.0219

Analysis of Variance Test for Data Representation

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Test
<u>For Slope (B)</u>				
Total	104	218.207		
Mean	1	203.494		
Combined Regression	1	9.068		
Difference of Regressions	5	0.057	0.0115	0.21
Combined Residual	92	5.054	0.0549	
Difference of Positions	5	0.534		
<u>For Intercept (A)</u>				
Total	104	218.207		
Mean	1	203.494		
Combined Regression	1	9.068		
Difference of Positions	5	0.534	0.1068	2.03
Combined Residual	97	5.111	0.0527	

(1) At a 95.0 percent confidence level both hypotheses of equal slope and of equal intercept are accepted.

Table A-7
COMPARISON OF EXPERIMENTAL AND PREDICTED MIXING TIMES
FOR SINGLE TANK SYSTEMS AT FIVE RECIRCULATION RATES

Series Number	Source of Mixing Time Data Given in Minutes	Recirculation Rate (gpm)				
		2.82	7.0	15.0	35.0	83.7
1	Experimental Data ⁽¹⁾	126.8	84.9	60.7	41.8	28.4
	Predicted for System ⁽²⁾	241.6	122.2	68.7	35.8	18.0
		2.82	6.0	14.0	32.0	72.6
2	Experimental Data ⁽³⁾	102.6	77.3	56.3	41.3	30.3
	Predicted for System	241.6	137.3	72.4	38.1	20.1
		2.82	7.00	15.0	37.0	89.3
3	Experimental Data	151.1	101.1	72.2	48.4	32.8
	Predicted for System	448.1	225.6	127.9	65.3	33.4
		2.78	7.00	15.0	37.0	89.3
4	Experimental Data ⁽³⁾	134.6	80.1	62.1	41.0	27.4
	Predicted for System	454.5	225.6	127.9	65.3	33.4
		2.78	6.0	12.0	24.0	48.3
5	Experimental Data ⁽³⁾	142.7	99.1	71.4	51.4	36.8
	Predicted for System	454.5	255.7	152.3	90.3	53.0
		2.85	7.0	18.0	40.0	92.8
6	Experimental Data	98.3	59.0	34.5	21.9	13.6
	Predicted for System	163.8	86.3	41.2	22.7	12.1
		3.01	7.0	18.0	40.0	92.8
7	Experimental Data ⁽³⁾	78.4	51.0	31.5	21.0	13.7
	Predicted for System	155.1	86.3	41.2	22.7	12.1
		1.14	3.0	10.0	30.0	91.5
8	Experimental Data	181.7	119.1	70.4	43.6	26.8
	Predicted for System	532.5	261.9	107.2	47.6	20.7
		1.14	3.0	10.0	30.0	95.2
9	Experimental Data ⁽³⁾	213.8	131.2	71.5	41.1	22.9
	Predicted for System	532.5	261.9	107.2	47.6	20.3
		1.14	3.0	9.0	30.0	68.2
10	Experimental Data ⁽³⁾	120.0	81.4	52.3	32.3	23.2
	Predicted for System	532.5	261.9	115.1	47.6	25.7

(1) Experimental Data were back calculated from least-squares fits as given in Table A-2.

(2) Predicted system data were calculated by the use of a computer program which took into account all factors such as loop piping and the pump. The final mixed conditions was 99.8%.

(3) Experimental data for Series 2, 4, 5, 7, 9, 10, 12, and 13 were obtained for partially filled systems as noted in Table 1. However, the predicted data were based on a completely filled system.

Table A-7 (Contd)

Series Number	Source of Mixing Time Data Given in Minutes	Recirculation Rate (gpm)				
		2.93	7.0	20.0	42.0	92.2
11	Experimental Data	132.2	93.8	62.0	46.3	34.0
	Predicted for System	402.5	205.9	96.1	55.1	30.8
		2.93	7.0	20.0	42.0	92.2
12	Experimental Data ⁽³⁾	129.9	89.8	57.5	42.0	30.1
	Predicted for System	402.5	205.9	96.1	55.1	30.8
		2.93	7.0	20.0	42.0	92.2
13	Experimental Data ⁽³⁾	105.8	72.8	46.4	33.7	24.1
	Predicted for System	402.5	205.9	96.1	55.1	30.8
		3.62	6.0	15.0	40.0	95.1
24	Experimental Data	315.1	247.7	160.2	100.5	66.6
	Predicted for System	925.4	641.5	327.9	158.6	84.0
		3.62	6.0	15.0	40.0	95.1
26	Experimental Data	323.5	235.4	240.0	80.3	49.1
	Predicted for System	925.4	641.5	327.9	158.6	84.0

(3) Experimental data for Series 2, 4, 5, 7, 9, 10, 12, and 13 were obtained for partially filled systems as noted in Table 1. However, the predicted data were based on a completely filled system.

Figure A-1. MEASURED MIXING TIME AS A FUNCTION OF THE RECIRCULATION RATE FOR A COMPLETELY FILLED, FOUR-INCH-DIAMETER BY 15-FOOT-LONG SAFE TANK SYSTEM.

Figure A-2. MEASURED MIXING TIME AS A FUNCTION OF THE RECIRCULATION RATE FOR A 97.7 PERCENT-FILLED, FOUR-INCH DIAMETER BY 15-FOOT-LONG SAFE TANK SYSTEM.

Figure A-3. MEASURED MIXING TIME AS A FUNCTION OF THE RECIRCULATION RATE FOR A COMPLETELY FILLED, FOUR-INCH-DIAMETER BY 25-FOOT-LONG SAFE TANK SYSTEM.

Figure A-4. MEASURED MIXING TIME AS A FUNCTION OF THE RECIRCULATION RATE FOR A 98.5 PERCENT-FILLED, FOUR-INCH-DIAMETER BY 25-FOOT-LONG SAFE TANK SYSTEM.

Figure A-5. MEASURED MIXING TIME AS A FUNCTION OF THE RECIRCULATION RATE FOR A 79:6 PERCENT-FILLED, FOUR-INCH-DIAMETER BY 25-FOOT-LONG SAFE TANK SYSTEM.

Figure A-6. MEASURED MIXING TIME AS A FUNCTION OF THE RECIRCULATION RATE FOR A COMPLETELY FILLED, SIX-INCH-DIAMETER BY 15-FOOT LONG SAFE TANK SYSTEM.

Figure A-7. MEASURED MIXING TIME AS A FUNCTION OF THE RECIRCULATION RATE FOR A 98.5 PERCENT-FILLED, SIX-INCH-DIAMETER BY 15-FOOT-LONG SAFE TANK SYSTEM.

Figure A-8. MEASURED MIXING TIME AS A FUNCTION OF THE RECIRCULATION RATE FOR A COMPLETELY FILLED, SIX-INCH-DIAMETER BY 20-FOOT-LONG SAFE TANK SYSTEM.

Figure A-9. MEASURED MIXING TIME AS A FUNCTION OF THE RECIRCULATION RATE FOR A 98.9 PERCENT-FILLED, SIX-INCH-DIAMETER BY 20-FOOT-LONG SAFE TANK SYSTEM.

Figure A-10. MEASURED MIXING TIME AS A FUNCTION OF THE RECIRCULATION RATE FOR AN 85.2 PERCENT-FILLED, SIX-INCH-DIAMETER BY 20-FOOT-LONG SAFE TANK SYSTEM.

Figure A-11. MEASURED MIXING TIME AS A FUNCTION OF THE RECIRCULATION RATE FOR A COMPLETELY FILLED, SIX-INCH-DIAMETER BY 25-FOOT-LONG SAFE TANK SYSTEM.

Figure A-12. MEASURED MIXING TIME AS A FUNCTION OF THE RECIRCULATION RATE FOR A 99.1 PERCENT-FILLED, SIX-INCH-DIAMETER BY 25-FOOT-LONG SAFE TANK SYSTEM.

Figure A-13. MEASURED MIXING TIME AS A FUNCTION OF THE RECIRCULATION RATE FOR AN 88.2 PERCENT-FILLED, SIX-INCH-DIAMETER BY 25-FOOT-LONG SAFE TANK SYSTEM.

Figure A-14. MEASURED MIXING TIME AS A FUNCTION OF THE RECIRCULATION RATE FOR A COMPLETELY FILLED, SIX-INCH-DIAMETER BY 40-FOOT-LONG HORIZONTAL SAFE TANK SYSTEM.

Figure A-15. MEASURED MIXING TIME AS A FUNCTION OF THE RECIRCULATION RATE FOR A COMPLETELY FILLED, SIX-INCH-DIAMETER, BY 40-FOOT-LONG HORIZONTAL SAFE TANK WITH TRACER INJECTED AT THE DOWNSTREAM REDUCER.

Figure A-16. MEASURED MIXING TIME AS A FUNCTION OF THE RECIRCULATION RATE FOR A SIX-INCH-DIAMETER BY 40-FOOT-LONG HORIZONTAL SAFE TANK SYSTEM.

Figure A-17. MEASURED MIXING TIME AS A FUNCTION OF THE RECIRCULATION RATE FOR A 75.0 PERCENT-FILLED, SIX-INCH-DIAMETER BY 20-FOOT-LONG VERTICAL SAFE TANK SYSTEM.

Figure A-18. MEASURED MIXING TIME AS A FUNCTION OF THE RECIRCULATION RATE FOR A 50.0 PERCENT-FILLED, SIX-INCH-DIAMETER BY 20-FOOT-LONG VERTICAL SAFE TANK SYSTEM.

Figure A-19. EXPERIMENTAL CORRELATIONS FOR THE DISPERSION INTENSITY AS A FUNCTION OF THE REYNOLDS NUMBER WITH COMPARISON TO TAYLOR'S PREDICTION AND TO LEVENSPIEL'S COMPILED DATA.

Figure A-20. PREDICTED DIMENSIONLESS MIXING TIME FOR A RECIRCULATION-MIXED, SINGLE TANK SYSTEM AS A FUNCTION OF THE MIXING NUMBER FOR SEVEN FINALLY MIXED CONDITIONS.

Figure A-21. MEASURED TRACER VARIANCE AS A FUNCTION OF THE RECIRCULATION RATE FOR A COMPLETELY FILLED, SIX-INCH-DIAMETER BY 15-FOOT-LONG HORIZONTAL SAFE TANK SYSTEM.

Figure A-22. MEASURED TRACER VARIANCE AS A FUNCTION OF THE RECIRCULATION RATE FOR A COMPLETELY FILLED, SIX-INCH-DIAMETER BY 20-FOOT-LONG HORIZONTAL SAFE TANK SYSTEM.

Figure A-23. MEASURED TRACER VARIANCE AS A FUNCTION OF THE RECIRCULATION RATE MEASURED IMMEDIATELY INSIDE A COMPLETELY FILLED, SIX-INCH-DIAMETER BY 20-FOOT-LONG HORIZONTAL SAFE TANK SYSTEM.

Figure A-24. MEASURED TRACER VARIANCE AS A FUNCTION OF THE RECIRCULATION RATE MEASURED IMMEDIATELY OUTSIDE A COMPLETELY FILLED, SIX-INCH-DIAMETER BY 20-FOOT-LONG HORIZONTAL SAFE TANK SYSTEM.

Figure A-25. MEASURED TRACER VARIANCE AS A FUNCTION OF THE RECIRCULATION RATE FOR A 98.9 PERCENT-FILLED, SIX-INCH-DIAMETER BY 20-FOOT LONG HORIZONTAL SAFE TANK SYSTEM.

Figure A-26. MEASURED TRACER VARIANCE AS A FUNCTION OF THE RECIRCULATION RATE FOR A COMPLETELY FILLED, SIX-INCH-DIAMETER BY 25-FOOT-LONG HORIZONTAL SAFE TANK SYSTEM.

Figure A-27. MEASURED TRACER VARIANCE AS A FUNCTION OF THE RECIRCULATION RATE FOR A 99.1 PERCENT-FILLED, SIX-INCH-DIAMETER BY 25-FOOT-LONG HORIZONTAL SAFE TANK SYSTEM.

Figure A-28. MEASURED TRACER VARIANCE AS A FUNCTION OF THE RECIRCULATION RATE MEASURED UPSTREAM FROM THE TEST SECTION IN A COMPLETELY FILLED, SIX-INCH-DIAMETER BY 26-FOOT-LONG HORIZONTAL SAFE TANK SYSTEM.

Figure A-29. MEASURED TRACER VARIANCE AS A FUNCTION OF THE RECIRCULATION RATE MEASURED DOWNSTREAM FROM THE TEST SECTION IN A COMPLETELY FILLED, SIX-INCH-DIAMETER BY 26-FOOT-LONG HORIZONTAL SAFE TANK SYSTEM.

Figure A-30. MEASURED TRACER VARIANCE AS A FUNCTION OF THE RECIRCULATION RATE MEASURED UPSTREAM FROM THE TEST SECTION IN A COMPLETELY FILLED, SIX-INCH-DIAMETER BY 26-FOOT-LONG SAFE TANK SYSTEM WITH TURBULENCE PROMOTERS.

Figure A-31. MEASURED TRACER VARIANCE AS A FUNCTION OF THE RECIRCULATION RATE MEASURED DOWNSTREAM FROM THE TEST SECTION IN A COMPLETELY FILLED, SIX-INCH-DIAMETER BY 26-FOOT-LONG SAFE TANK SYSTEM WITH TURBULENCE PROMOTERS.

APPENDIX B

DETAILED DATA FROM THE INVESTIGATION
OF PARALLEL TANK SYSTEMS

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Table B-1
EXPERIMENTAL DATA FOR THE PARALLEL TANK SYSTEM

Run Number	Recirculation Rate (gpm)	Mixing Time (min)
<u>Series 32 (FSR⁽¹⁾ 0.0)</u>		
2-147	10.0	114.9
2-148	15.0	100.0
2-149	20.0	89.2
2-150	30.0	66.3
2-151	40.0	55.0
2-152	50.0	45.1
2-153	60.0	36.3
2-154	70.0	36.4
2-155	80.0	28.2
2-156	90.0	29.9
2-157	100.0	23.1
<u>Series 33 (FSR 0.1)</u>		
2-81	10.0	79.1
2-92	15.0	60.1
2-93	20.0	52.6
2-99	30.0	40.0
2-105	40.0	27.5
2-111	50.0	21.6
2-117	60.0	18.5
2-123	70.0	18.4
2-129	80.0	19.8
2-135	90.0	15.3
2-141	100.0	14.1
<u>Series 34 (FSR 0.2)</u>		
2-82	10.0	52.3
2-91	15.0	44.2
2-94	20.0	33.5
2-100	30.0	29.8
2-106	40.0	25.4
2-112	50.0	21.0
2-118	60.0	19.3
2-124	70.0	18.2
2-130	80.0	15.8
2-136	90.0	17.5
2-142	100.0	13.7
<u>Series 35 (FSR 0.4)</u>		
2-83	10.0	47.4
2-90	15.0	50.6
2-95	20.0	33.7
2-101	30.0	32.9
2-107	40.0	25.5
2-113	50.0	18.8
2-119	60.0	19.1
2-125	70.0	17.2
2-131	80.0	13.2
2-137	90.0	16.6
2-143	100.0	10.8

(1) FSR - Flow split ratio.

Table B-1 (Contd)

Run Number	Recirculation Rate (gpm)	Mixing Time (min)
<u>Series 36 (FSR 0.5)</u>		
2-84	10.0	44.1
2-89	15.0	48.4
2-96	20.0	51.6
2-102	30.0	28.6
2-108	40.0	19.0
2-114	50.0	26.6
2-121	60.0	23.1
2-126	70.0	19.5
2-132	80.0	22.2
2-138	90.0	15.9
2-144	100.0	12.5
<u>Series 37 (FSR 0.6)</u>		
2-174	10.0	26.1
2-175	15.0	23.4
2-176	20.0	22.6
2-177	30.0	17.1
2-178	40.0	13.6
2-179	50.0	12.5
2-180	60.0	11.6
2-181	70.0	6.8
2-182	80.0	8.3
2-183	90.0	6.6
2-184	100.0	7.1
<u>Series 38 (FSR 0.67)</u>		
2-85	10.0	32.9
2-88	15.0	24.4
2-97	20.0	25.0
2-103	30.0	16.2
2-109	40.0	13.0
2-115	50.0	10.3
2-120	60.0	10.3
2-127	70.0	9.2
2-133	80.0	10.8
2-139	90.0	7.6
2-145	100.0	5.8
<u>Series 39 (FSR 0.75)</u>		
2-86	10.0	49.0
2-87	15.0	32.0
2-98	20.0	19.7
2-104	30.0	20.7
2-110	40.0	15.9
2-116	50.0	13.5
2-122	60.0	11.2
2-128	70.0	8.3
2-134	80.0	8.5
2-140	90.0	7.4
2-146	100.0	6.1

Table B-1 (Conrd)

Run Number	Recirculation Rate (gpm)	Mixing Time (min)
<u>Series 40 (FSR 0.8)</u>		
2-185	10.0	79.0
2-186	15.0	48.8
2-187	20.0	41.4
2-188	30.0	30.1
2-189	40.0	25.8
2-190	50.0	18.1
2-191	60.0	18.4
2-192	70.0	14.6
2-193	80.0	11.8
2-194	90.0	11.4
2-195	100.0	9.0
<u>Series 41 (FSR 0.9)</u>		
2-196	10.0	89.7
2-212	10.0	98.4
2-213	15.0	92.3
2-198	20.0	87.3
2-214	20.0	82.8
2-199	30.0	74.7
2-215	30.0	87.7
2-200	40.0	57.8
2-216	40.0	53.4
2-201	50.0	36.3
2-217	50.0	41.8
2-202	60.0	41.3
2-218	60.0	41.1
2-203	70.0	27.5
2-219	70.0	33.0
2-204	80.0	34.3
2-220	80.0	35.0
2-205	90.0	26.1
2-221	90.0	25.1
2-206	100.0	28.5
2-222	100.0	28.4
<u>Series 42 (FSR 1.0)</u>		
2-158	10.0	94.4
2-159	15.0	95.1
2-160	20.0	86.4
2-161	30.0	84.8
2-162	40.0	72.8
2-163	50.0	65.8
2-164	60.0	69.5
2-165	70.0	53.3
2-166	80.0	48.7
2-167	90.0	47.6
2-168	100.0	49.6

Table B-2

STATISTICAL QUANTITIES OBTAINED FROM THE RECIRCULATION-MIXED,
PARALLEL TANK SYSTEM MIXING-TIME DATA FITS

Series Number	Parameter A		Parameter B		Variance of Estimate of Fit
	Value	Standard Error	Value	Standard Error	
32	2.824	0.064	0.700	0.039	0.002
33	2.682	0.063	0.765	0.038	0.002
34	2.280	0.040	0.556	0.025	0.001
35	2.385	0.097	0.634	0.059	0.004
36	2.283	0.140	0.542	0.086	0.008
37	2.173	0.104	0.652	0.064	0.008
38	2.220	0.088	0.684	0.054	0.003
39	2.487	0.084	0.827	0.051	0.003
40	2.766	0.059	0.877	0.036	0.001
41	2.697	0.084	0.624	0.051	0.005
42	2.360	0.066	0.329	0.040	0.002

Figure B-1. MEASURED MIXING TIME AS A FUNCTION OF THE RECIRCULATION RATE FOR A TWO-IN-PARALLEL, HORIZONTAL, FOUR-INCH-DIAMETER BY 25-FOOT-LONG SAFE TANK SYSTEM AT A FLOW-SPLIT RATIO OF 0.0.

Figure B-2. MEASURED MIXING TIME AS A FUNCTION OF THE RECIRCULATION RATE FOR A TWO-IN-PARALLEL, HORIZONTAL, FOUR-INCH-DIAMETER BY 25-FOOT-LONG SAFE TANK SYSTEM AT A FLOW-SPLIT RATIO OF 0.1.

Figure B-3. MEASURED MIXING TIME AS A FUNCTION OF THE RECIRCULATION RATE FOR A TWO-IN-PARALLEL, HORIZONTAL, FOUR-INCH-DIAMETER BY 25-FOOT-LONG SAFE TANK SYSTEM AT A FLOW-SPLIT RATIO OF 0.2.

Figure B-4. MEASURED MIXING TIME AS A FUNCTION OF THE RECIRCULATION RATE FOR A TWO-IN-PARALLEL, HORIZONTAL, FOUR-INCH-DIAMETER BY 25-FOOT-LONG SAFE TANK SYSTEM AT A FLOW-SPLIT RATIO OF 0.4.

Figure B-5. MEASURED MIXING TIME AS A FUNCTION OF THE RECIRCULATION RATE FOR A TWO-IN-PARALLEL, HORIZONTAL, FOUR-INCH-DIAMETER BY 25-FOOT-LONG SAFE TANK SYSTEM AT A FLOW-SPLIT RATIO OF 0.5.

Figure B-6. MEASURED MIXING TIME AS A FUNCTION OF THE RECIRCULATION RATE FOR A TWO-IN-PARALLEL, HORIZONTAL, FOUR-INCH-DIAMETER BY 25-FOOT-LONG SAFE TANK SYSTEM AT A FLOW-SPLIT RATIO OF 0.6.

Figure B-7. MEASURED MIXING TIME AS A FUNCTION OF THE RECIRCULATION RATE FOR A TWO-IN-PARALLEL, HORIZONTAL, FOUR-INCH-DIAMETER BY 25-FOOT-LONG SAFE TANK SYSTEM AT A FLOW-SPLIT RATIO OF 0.67.

Figure B-8. MEASURED MIXING TIME AS A FUNCTION OF THE RECIRCULATION RATE FOR A TWO-IN-PARALLEL, HORIZONTAL, FOUR-INCH-DIAMETER BY 25-FOOT-LONG SAFE TANK SYSTEM AT A FLOW-SPLIT RATIO OF 0.75.

Figure B-9. MEASURED MIXING TIME AS A FUNCTION OF THE RECIRCULATION RATE FOR A TWO-IN-PARALLEL, HORIZONTAL, FOUR-INCH-DIAMETER BY 25-FOOT-LONG SAFE TANK SYSTEM AT A FLOW-SPLIT RATIO OF 0.8.

Figure B-10. MEASURED MIXING TIME AS A FUNCTION OF THE RECIRCULATION RATE FOR A TWO-IN-PARALLEL, HORIZONTAL, FOUR-INCH-DIAMETER BY 25-FOOT-LONG SAFE TANK SYSTEM AT A FLOW-SPLIT RATIO OF 0.9.

Figure B-11. MEASURED MIXING TIME AS A FUNCTION OF THE RECIRCULATION RATE FOR A TWO-IN-PARALLEL, HORIZONTAL, FOUR-INCH-DIAMETER BY 25-FOOT-LONG SAFE TANK SYSTEM AT A FLOW-SPLIT RATIO OF 1.0.

Figure B-12. CROSS PLOT OF THE MIXING TIME AS A FUNCTION OF THE FLOW-SPLIT RATIO FOR A TWO-IN-PARALLEL, HORIZONTAL, SAFE TANK SYSTEM.

APPENDIX C

DETAILED DATA FROM THE INVESTIGATION
OF MIXING TUBE SYSTEMS

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Table C-1
EXPERIMENTAL DATA FOR THE MIXING TUBE SYSTEMS

Run Number	Recirculation Rate (gpm)	Mixing Time (min)
<u>Series 22</u>		
342	2.15	110.6
341	4.10	90.1
340	6.04	63.1
339	8.45	66.7
338	9.72	74.9
337	11.45	77.3
336	15.46	64.9
335	19.61	64.9
334	23.90	58.9
333	27.87	57.6
332	27.87	51.1
<u>Series 25</u>		
397	4.10	35.4
401	4.10	35.2
396	6.04	25.0
400	6.04	25.3
393	7.37	22.9
387	7.37	21.7
395	7.90	22.4
399	7.90	26.3
394	10.03	20.8
398	10.03	20.2
392	15.53	17.6
386	15.53	17.0
391	23.96	13.5
385	23.96	14.0
390	32.96	9.5
384	32.96	9.6
389	42.51	8.0
383	42.51	8.8
388	49.00	7.2
382	49.00	7.2
<u>Series 27</u>		
406	4.10	35.4
407	4.10	35.1
405	6.04	28.0
408	6.04	27.3
411	7.37	24.0
424	7.37	23.6
404	7.90	23.7
409	7.90	30.5
403	10.03	21.8
410	10.03	21.7
412	15.53	13.5
423	15.53	13.5
413	23.96	12.2
422	23.96	9.6
414	32.96	8.2
421	32.96	7.3
415	42.51	7.7
420	42.51	6.6
416	52.50	5.7
419	52.50	5.7
417	63.20	5.2
418	63.20	5.0

Table C-1 (Contd)

Run Number	Recirculation Rate (gpm)	Mixing Time (min)
<u>Series 31</u>		
501	2.15	65.4
502	4.10	43.9
503	6.04	33.8
504	7.90	23.8
505	10.03	18.8
511	15.46	12.0
510	23.96	7.7
509	32.96	6.2
508	47.42	4.7
507	63.20	3.5
506	79.78	2.8

Table C-2

STATISTICAL QUANTITIES OBTAINED FROM THE RECIRCULATION-MIXED,
SERIES-PARALLEL TANK SYSTEM MIXING-TIME DATA FITS

Series Number	Parameter A		Parameter B		Variance of Estimate of Fit
	Value	Standard Error	Value	Standard Error	
22	2.231	0.031	0.291	0.027	0.001
25	1.911	0.027	0.601	0.022	0.001
27	2.028	0.031	0.732	0.024	0.002
31	2.217	0.025	0.935	0.019	0.001

Figure C-1. MEASURED MIXING TIME AS A FUNCTION OF THE RECIRCULATION RATE FOR A ONE-HOLE SET MIXING TUBE IN A COMPLETELY FILLED, SIX-INCH-DIAMETER BY 20-FOOT-LONG HORIZONTAL SAFE TANK SYSTEM.

Figure C-2. MEASURED MIXING TIME AS A FUNCTION OF THE RECIRCULATION RATE FOR A TWO-HOLE SET MIXING TUBE IN A COMPLETELY FILLED, SIX-INCH-DIAMETER BY 20-FOOT-LONG HORIZONTAL SAFE TANK SYSTEM.

Figure C-3. MEASURED MIXING TIME AS A FUNCTION OF THE RECIRCULATION RATE FOR A THREE-HOLE SET MIXING TUBE IN A COMPLETELY FILLED, SIX-INCH-DIAMETER BY 20-FOOT-LONG HORIZONTAL SAFE TANK SYSTEM.

Figure C-4. MEASURED MIXING TIME AS A FUNCTION OF THE RECIRCULATION RATE FOR A FIVE-HOLE SET MIXING TUBE IN A COMPLETELY FILLED, SIX-INCH-DIAMETER BY 20-FOOT-LONG HORIZONTAL SAFE TANK SYSTEM.

APPENDIX D

DETAILED DATA FROM THE INVESTIGATION
OF AIR SPARGE SYSTEMS

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Table D-1
EXPERIMENTAL DATA FOR THE AIR-SPARGE SYSTEM

Run Number	Air Flow Rate (scfm)	Mixing Time (min)
<u>Series 46</u>		
1A	5.00	11.91
2A	3.55	12.16
3A	2.09	10.48
4A	0.63	15.88
5A	0.54	20.58
6A	0.46	23.05
7A	0.37	28.06
8A	0.29	23.26
9A	0.20	32.06
10A	0.12	30.74

Figure D-1. MEASURED MIXING TIME AS A FUNCTION OF THE AIR FLOW IN A SIX-INCH-DIAMETER BY 20-FOOT-LONG VERTICAL MIXING TANK FILLED TO 76.7 PERCENT OF CAPACITY.