Cooling Coil Effects On Blending in a Pilot Scale Tank

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Abstract

Blending, or mixing, processes in 1.3 million gallon nuclear waste tanks are complicated by the fact that miles of serpentine, vertical, cooling coils are installed in the tanks. As a step toward investigating blending interference due to coils in this type of tank, a 1/10.85 scale tank and pump model were constructed for pilot scale testing. A series of tests were performed in this scaled tank by adding blue dye to visualize blending, and by adding acid or base tracers to solution to quantify the time required to effectively blend the tank contents. The acid and base tests were monitored with *pH* probes, which were located in the pilot scale tank to ensure that representative samples were obtained. Using the probes, the hydronium ion concentration [H^+] was measured to ensure that a uniform concentration was obtained throughout the tank. As a result of pilot scale testing, a significantly improved understanding of mixing, or blending, in nuclear waste tanks has been achieved. Evaluation of test data showed that cooling coils in the waste tank model increased pilot scale blending times by 200 % in the recommended operating range, compared to previous theoretical estimates of a 10 – 50% increase. Below the planned operating range, pilot scale blending times were increased by as much as 700 % in a tank with coils installed. One pump, rather than two or more, was shown to effectively blend the tank contents, and dual pump nozzles installed parallel to the tank wall were shown to provide optimal blending. In short, experimental results varied significantly from expectations.

Introduction

Project Overview

The Savannah River National Laboratory (SRNL) in conjunction with Savannah River Remediation (SRR) has completed some scaled blending tests using a pilot scale model of a nuclear waste tank to determine the flow rates and nozzle diameters for a fixed position, non-rotating, dual nozzle pump. The model was based on an 85 foot diameter SRS (Savannah River Site) waste tank (Tank 50H, Figures 1 and 2) and included tank internals such as pumps, 2 inch diameter cooling coils, and a central roof support column. The purpose of the testing was for SRNL to recommend design parameters to SRR for a blending pump as well as pump orientation and Tank 50H blending time. Presently, mixing pump motors are mounted at the top of waste tanks, and a 35 foot long drive shaft passes through the tank top to the mixing pump located below in the waste liquid. Further research is in progress for SRR, but this paper focuses on the initial pilot scale test results (Leishear, Fowley, and Poirier [1]).

Figure 1: Typical Mixing or Slurry Pumps Installed on the Top of an Underground Tank at Savannah River Site
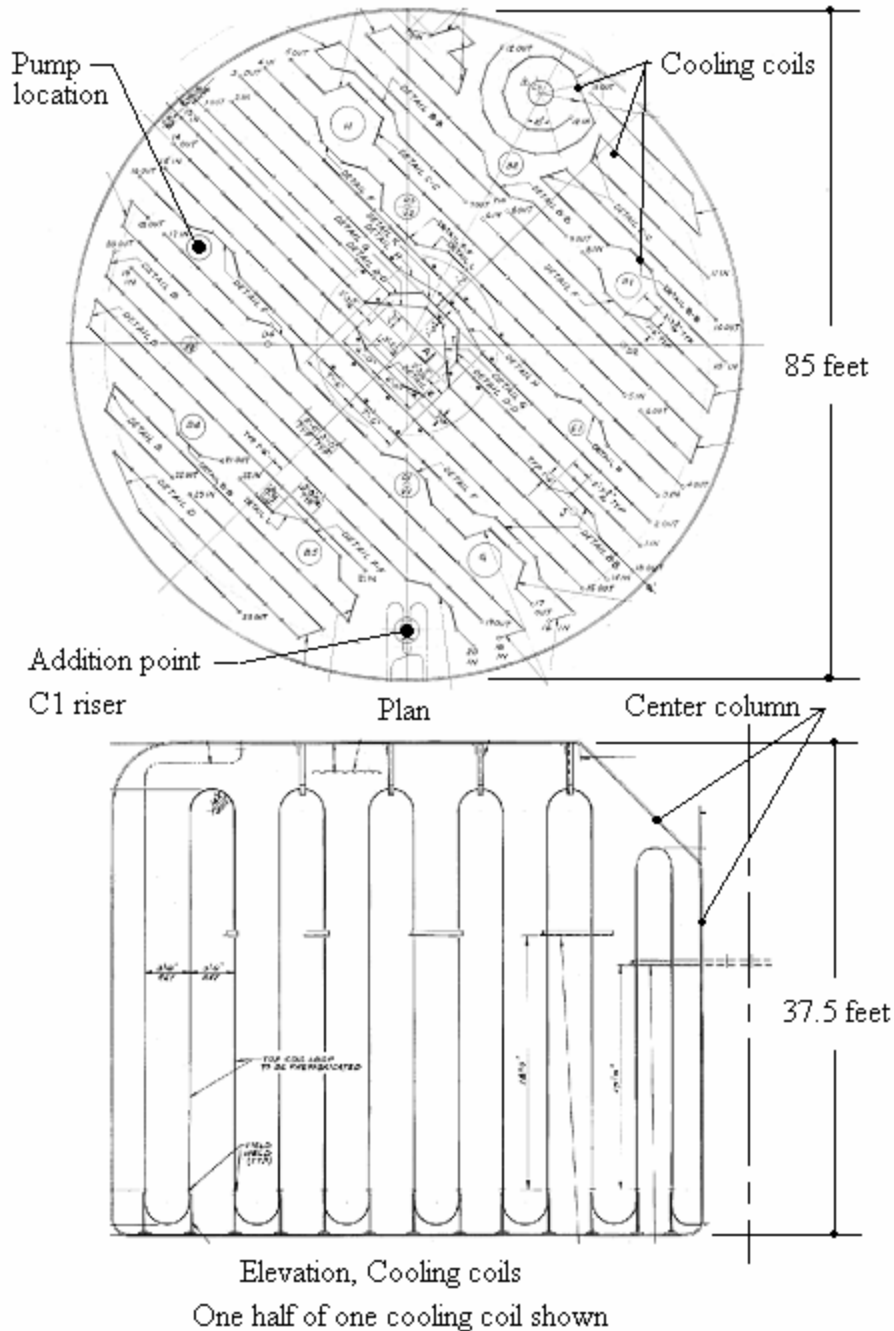
Figure 2: Tank 50H, Cooling Coil Arrangement

Pilot Scale Testing

        To model blending processes, a series of tests were performed using small quantities of acid and base chemical additions, which were blended using three different pilot scale pump models. These three pump models provided different length and diameter characteristics to investigate the effects of these characteristics on blending. The pilot scale pump locations and chemical addition point locations were scaled down from Tank 50H. Pilot scale tests were used to evaluate blending effectiveness by

blending nitric acid and sodium hydroxide solutions in a 40 inch deep by 94 inch inside diameter tank, which was scaled down from an 85 foot diameter nuclear waste tank (Figures 3 – 6). Dimensions were geometrically (linearly) scaled, and the pump discharge velocity remained constant at both scales to ensure that jet velocities were comparable at equivalent locations in both tanks. Concentrated solutions of acid and base (250 - 1000 milliliters) were added to 980 gallon batches of liquid (i.e., water and dilute sodium nitrate formed from acid-base reactions) at a location selected to match the addition point location in the waste tank (C1 riser). The tank contents were initially acidic or basic, and chemical additions changed the *pH* of the tank contents. That is, blending changed the contents from *pH* ≈ 4 to *pH* ≈ 10, or vice versa. The *pH* was monitored at several strategic locations and blending was considered complete when the *pH* readings converged to nearly constant values. Blending times were determined using these chemical changes.

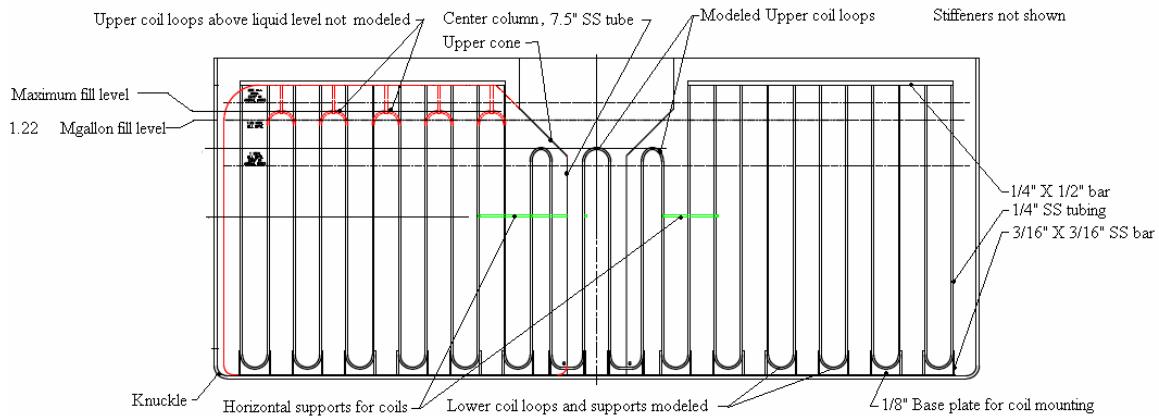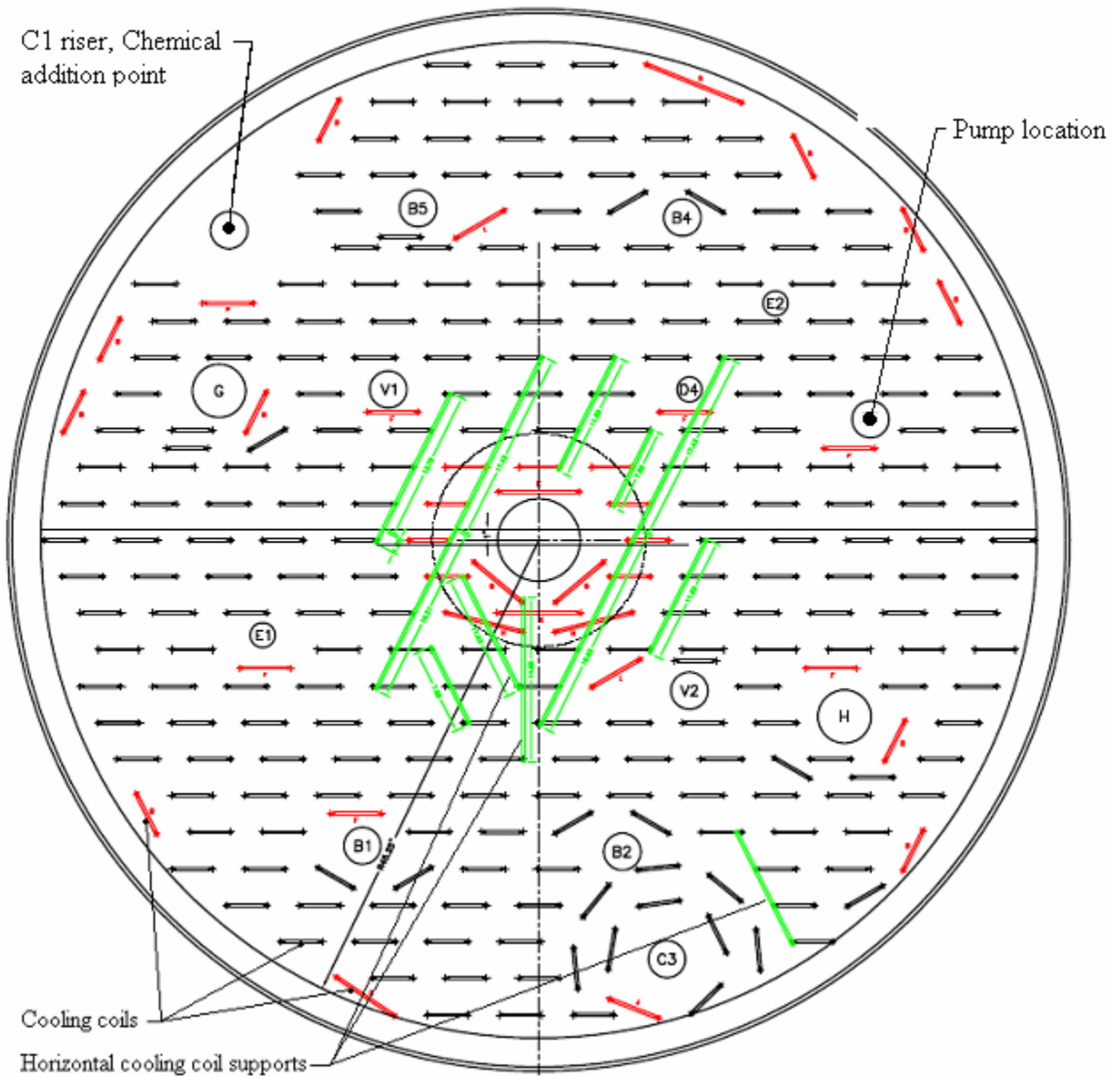**Figure 3: Pilot Scale Blending Tank, Elevation**

Figure 4: Cooling Coil Model, Cross Section

**Figure 5: Modeled Cooling Coils and Center Column Assembly
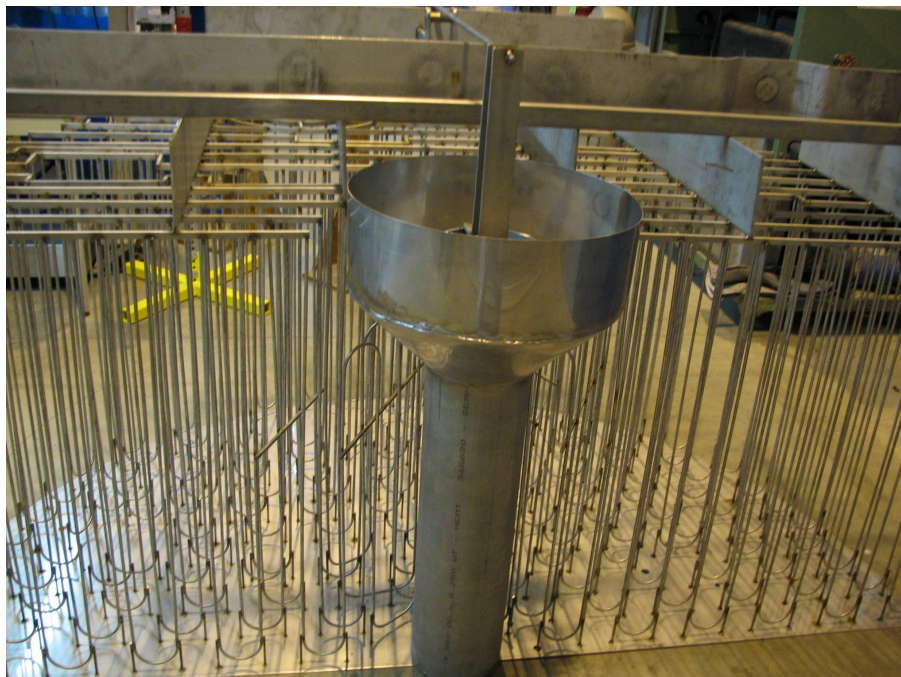with Stiffeners and Lifting Lugs**

Figure 6: Cooling Coil Assembly and Center Column

Analysis

Blending Theory

The controlling factor or design parameter for blending is expressed as $U_0 D$ (feet^2 / second), where U_0 is the discharge velocity of a blending pump nozzle, and D is the inside diameter of the pump nozzle. Nozzle diameters and flow rates were used to vary $U_0 D$. The diameters of the nozzles used in testing were scaled from 1-1/2", 2-1/4", and 3-5/8" full scale nozzles. Equations describing the blending time for miscible liquids in tanks mixed with single turbulent jets are typically of the general form

$$t = (C \cdot T^2) / (U_0 \cdot D) \qquad \text{Equation 1}$$

where *t* is the blending time, *C* is a constant, and *T* is the tank diameter.

This equation shows that the blend time is a function of $U_0 D$, where *C* is typically in the range: $3.0 < C < 4.5$. The most recently predicted value for *C* was 3.0 (Grenville and Tilton [Refs. 2 and 3]). Grenville noted that this value for *C* was valid for tank volumes up to 3 million gallons. Experimentally, the constant was required for the pilot scale models, since this value is based on experimental data presented in the literature for tanks blended without a center column or coils, and a single jet nozzle with a centerline coincident to the tank radius. Accordingly, the 3.0 value for *C* provided only an estimate to find flow rates and pilot scale blending times. The value for this constant was investigated as this study extended this simplified blending equation to a tank with dual nozzles in a tank with or without cooling coils. In short, Equation 1 was assumed to be valid for blending in pilot scale testing whether or not cooling coils and a center column were installed, even though previous testing had not been performed using cooling coils. This study showed that this simple equation was consistent with test results, even though the value of *C* varied for tanks with and without coils, and *C* is also affected by the number and location of nozzles.

Blending Performance and Blending Times

To quantify blending performance, blending times were determined using commercial 95% blending criteria. The Hydronium ion concentrations [H$^+$] were calculated from *pH* measurements and normalized to establish mixing times for 95% mixing (Paul, et.al [Ref. 4]). The 95% mixing criteria is a generally accepted criterion which defines the time following the addition of a tracer at which the concentrations throughout the tank are within ± 5 % of the bulk concentration. Normalization is a common practice for empirically quantifying mixing using concentration measurements. The 95% mixing time provided blending acceptance criteria, but lacked accuracy to quantify chemical concentrations throughout blended liquids.

From Paul, et. al. [Ref. 4], *pH* probes are commonly used to establish 95% blending times, which are determined from concentrations after adding a reactive tracer. To do so, a normalized concentration is calculated, where

$$C_i' = \frac{C_i - C_0}{C_\infty - C_0}$$

Equation 2

where C_i' equals the normalized concentration, C_i equals the measured variable concentration, C_0 equals the initial concentration, and C_∞ equals the final equilibrium concentration. The 95% blending time equals the time required for the normalized probe output to reach and remain within 95 to 105%. Equations 3 to 8 provide relationships between concentration and *pH*. For the *pH* probe response, Equation 2 is rewritten as

$$\text{Normalized } \left[H^+\right] = \frac{\left[H^+\right]_i - \left[H^+\right]_0}{\left[H^+\right]_\infty - \left[H^+\right]_0}$$

Equation 3

and

$$pH = -\log\left[H^+\right]$$

Equation 4

$$\left[H^+\right] = 10^{-pH}$$

Equation 5

$$pOH = -\log\left[OH^-\right]$$

Equation 6

$$\left[OH^-\right] = 10^{-pOH} = 10^{pH-14}$$

Equation 7

$$pH + pOH = 14$$

Equation 8

Typical acceptance criteria for good blending in process industries are defined by 95% blending (normalized [H⁺]), where a typical process is paint mixing. For pharmaceutical industries, where blending is more critical, 99% blending is sometimes used, where the normalized [H⁺] = 0.99 →1.01. Appendix C shows that 99% blending is not recommended with the commercially used instrumentation, even though high quality instruments were used for this research (Hach, Inc.) to measure 95% blending as the recommended acceptance criteria for this research. Additional discussion of probe uncertainty and solution buffering effects follow, since they are related to the determination of 95% blending.

In a few cases, tests were prematurely stopped before reaching the 95% mixing time. In those cases, the blending time was estimated using

$$t = t_{95} = t_n \cdot \frac{\ln\left(1 - \dfrac{95}{100}\right)}{\ln\left(1 - \dfrac{n}{100}\right)}$$

Equation 9

where t_{95} is the 95 % blending time, n is the percent blended, and t_n is a measured experimental blending time (Paul, et.al. [Ref.4]). This approximation assumes that the normalized concentration converges to the value of 1 in a smooth logarithmic fashion. In short, some tests were terminated prematurely, and Equation 9 was used to predict the estimated blending time if the test had been run to completion. Blending times obtained from this equation are approximate only, but provide insight into blending. A more detailed test equipment description is prerequisite to a discussion of test results.

Pilot Scale Equipment Description

Test Setup

The overall test setup is shown in Figure 7. The flow rate through the blending pump, Pump 1, was controlled by a variable frequency drive (VFD, Figure 8). The VFD provided the volumetric flow for blending through the pilot scale nozzles in the tank. . F1 and F2 are the flow meters used to measure and control flow rates through the nozzles, and probes 1 – 6 are *pH* probes. Data from the probes, the thermocouple (T1), the pump, and the flow meters were recorded by the data acquisition system (DAS, Figure 9).

Valves, V6 and V7, were used to add dye, acids, or bases to the tank for blending in a controlled, repeatable method. The miscible fluid to be blended was added to a funneled container, or hopper, above these valves, one of the valves was opened, and the acid or base was introduced below the surface of the tank contents by a ¼ inch diameter tube between the hoppers and tank contents. To eliminate transient blending concerns with respect to modeling and minimize testing, acids and bases were added to the tank after fluid flow in the tank reached steady state conditions. That is, all experimental blending times were provided from a steady state mixing condition. Proportional integral control (PI) was used to ramp up to steady state and maintain a constant flow rate through the pumps for pilot scale testing.
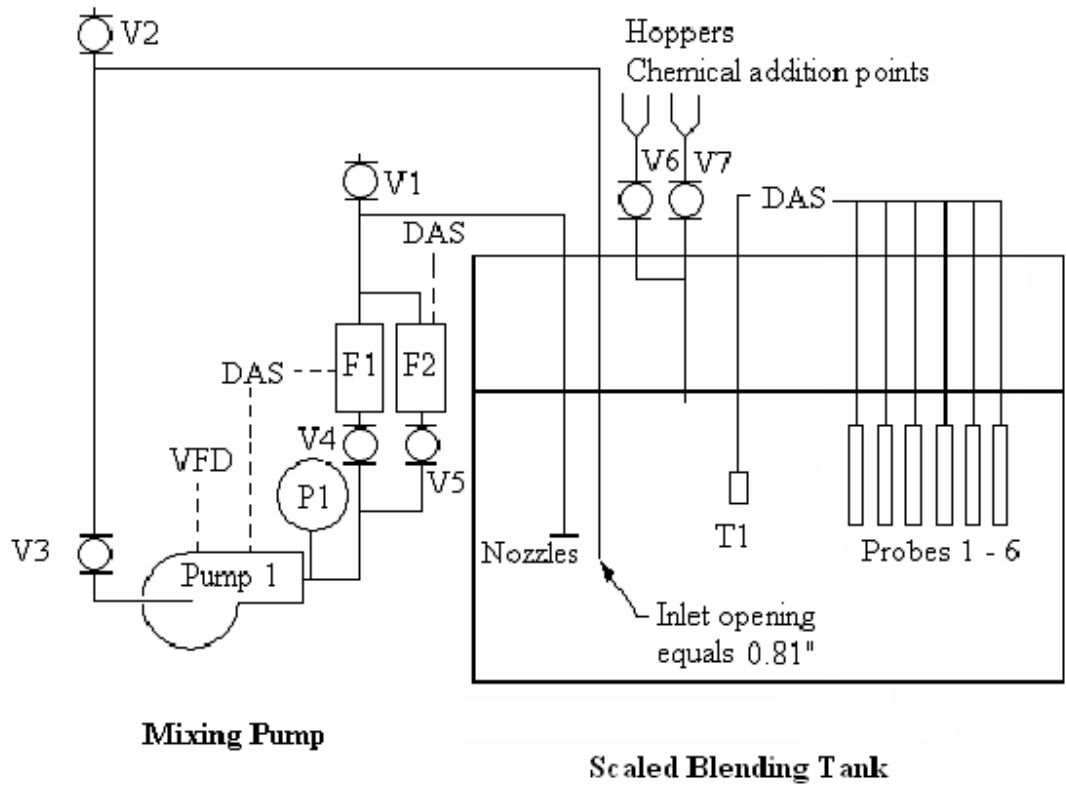
Figure 7: Test Schematic

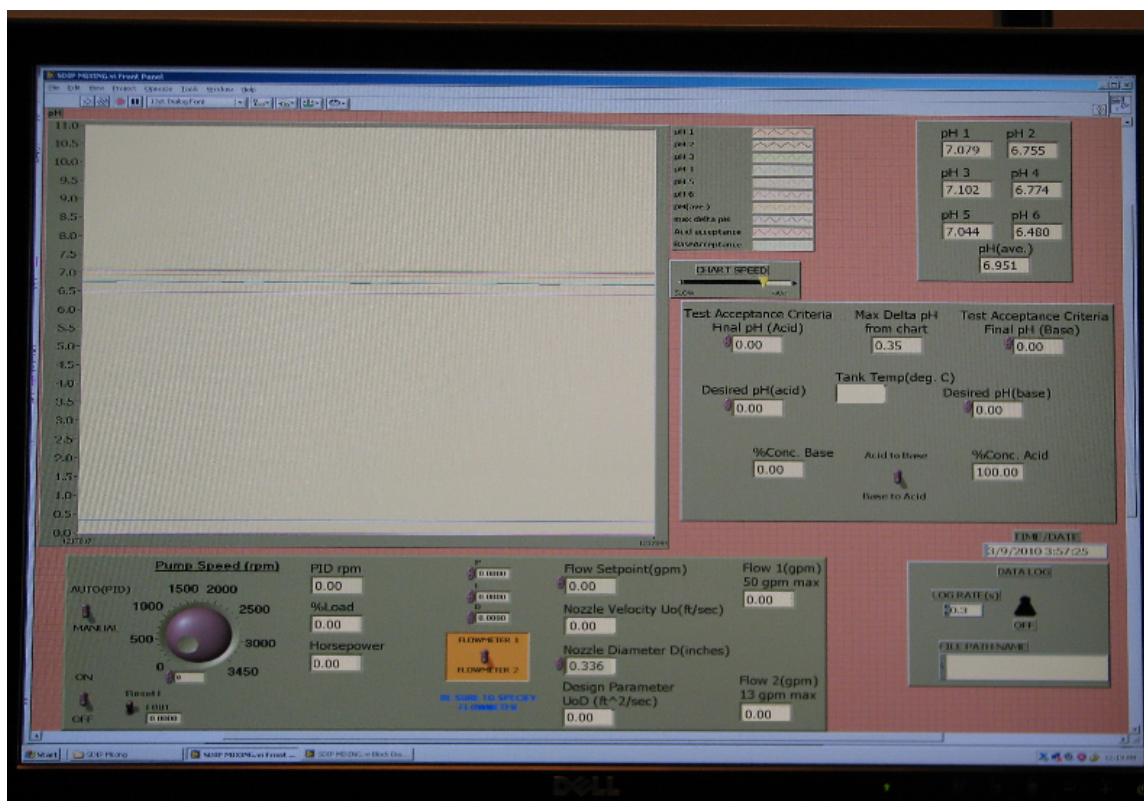**Figure 8: Mixing Pump for Pilot Scale Blending Tank**

Figure 9: DAS Display

Pilot Scale Modeling

For some testing, simulated cooling coils were installed, but for other testing, coils were removed to quantify the effects of cooling coils on blending (Figures 10 and 11). The center column in the pilot scale tank was installed during all tests.

Before acid and base testing, a blue dye was added to the pilot scale test tank to qualitatively visualize blending and provide an indication of the slowest and fastest blended areas to determine optimal locations for *pH* probes (Figure 12). For acid and base testing, pump parameters were varied to investigate blending effects.

Parameters considered were nozzle length, nozzle diameter, nozzle velocity, and pump orientation. Pump orientations included nozzle positions parallel to the tank wall (referred to as the 0° position), perpendicular to the tank wall (90°), and at an angle of 45° to the tank wall (Figure 12). Pump nozzle designs are referred to as Standard, long Quad, and short Quad, which are facility specific references not explained herein. All tests were performed with the pump nozzles located at the mid-height of the test fluid in the pilot scale tank to investigate pump nozzle performance, and the pump suction was modeled by a drilled hole in the bottom of a pipe cap (Figures 13 and 14).

Once the test equipment was assembled, blending times were determined. In addition to calculating blending times, various effects on blending tests were considered, such as chemical buffering within the test fluids and diffusion.
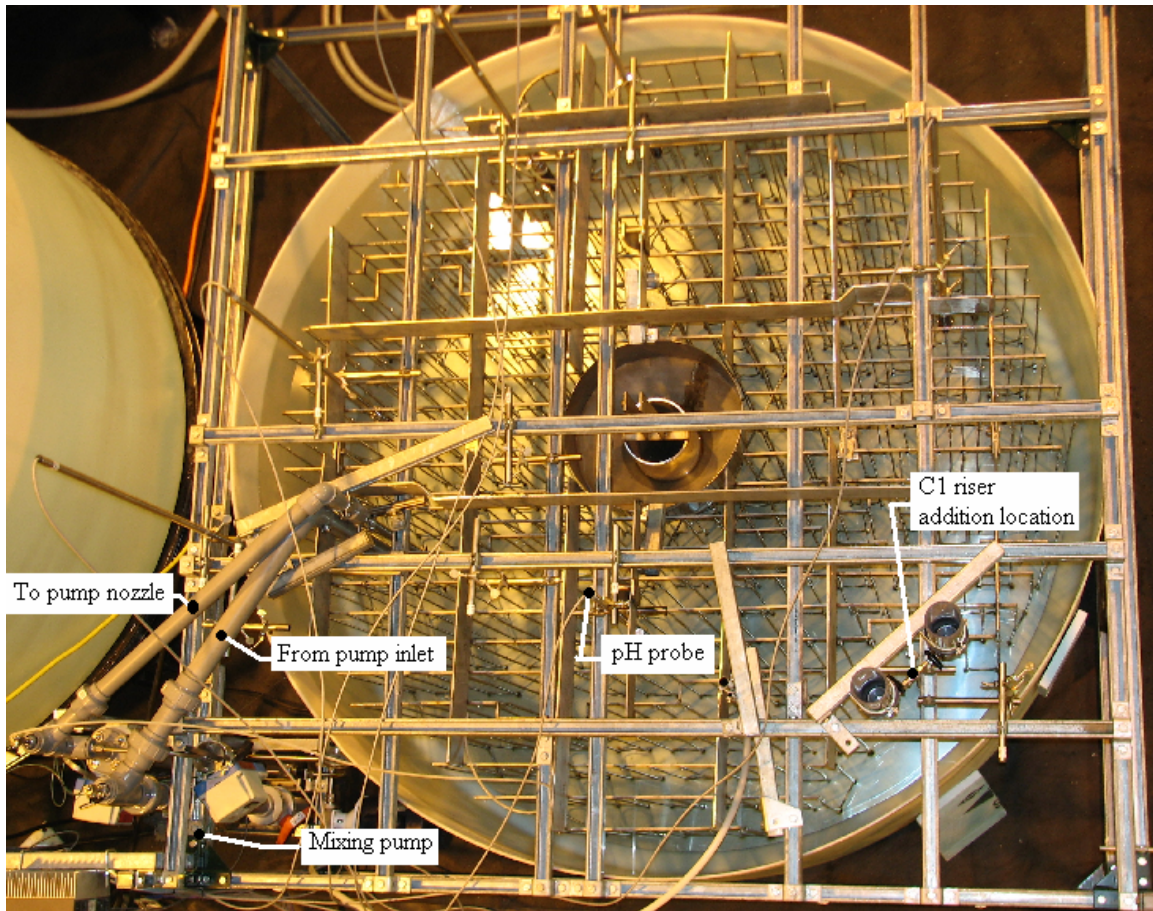
Figure 10: Assembled Tank, With Cooling Coil Models
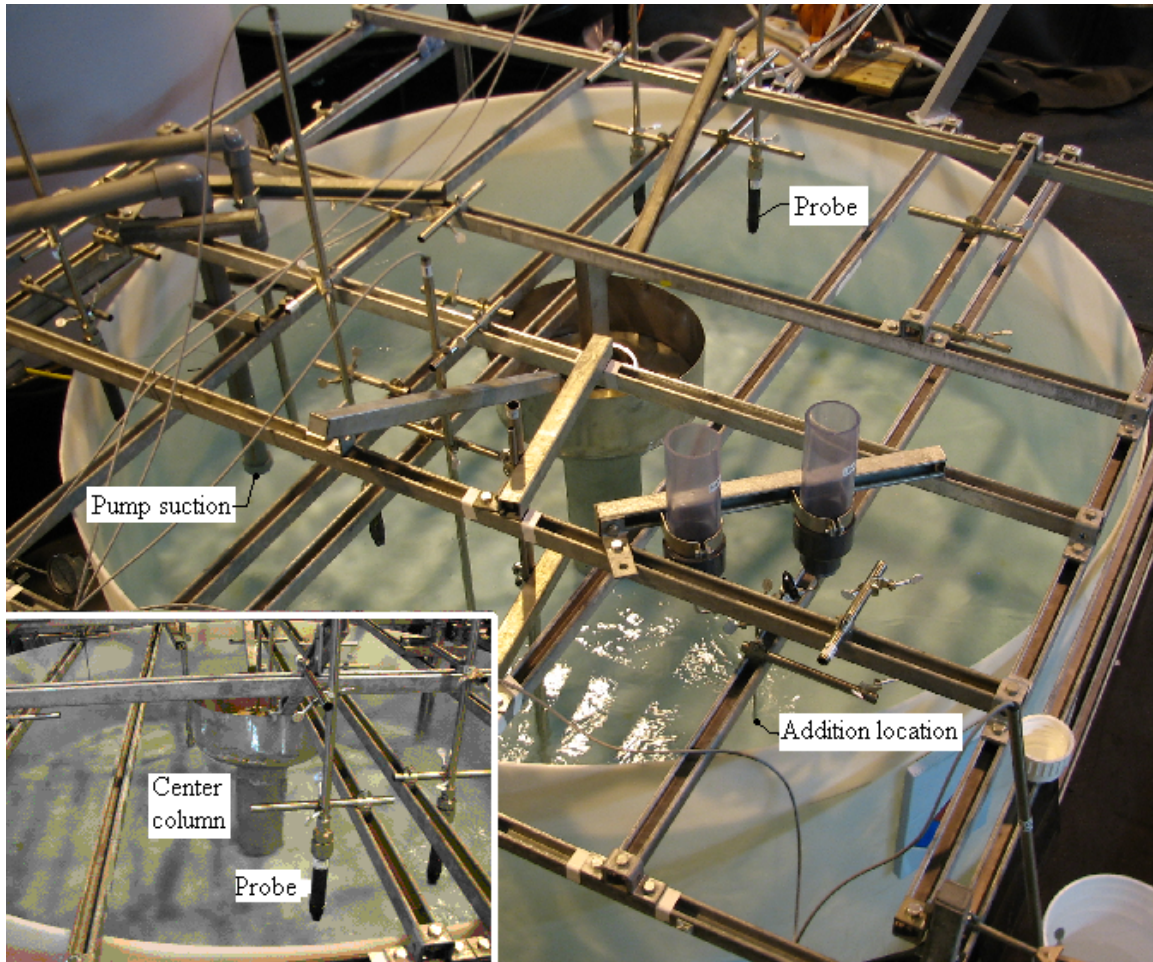
Figure 11: Assembled Tank, With Cooling Coil Models Removed

Probe locations	
Probe	Elevation from cooling coil plate
1	Bottom (fixed position)
2	31-1/2" (variable position)
3	16-1/16" (variable position)
4	29-7/8" (variable position)
5	29-7/8" (fixed position)
6	29-7/8" (not used for calculations)

Plan View

Probe Locations for 0 Degree Nozzle Orientation
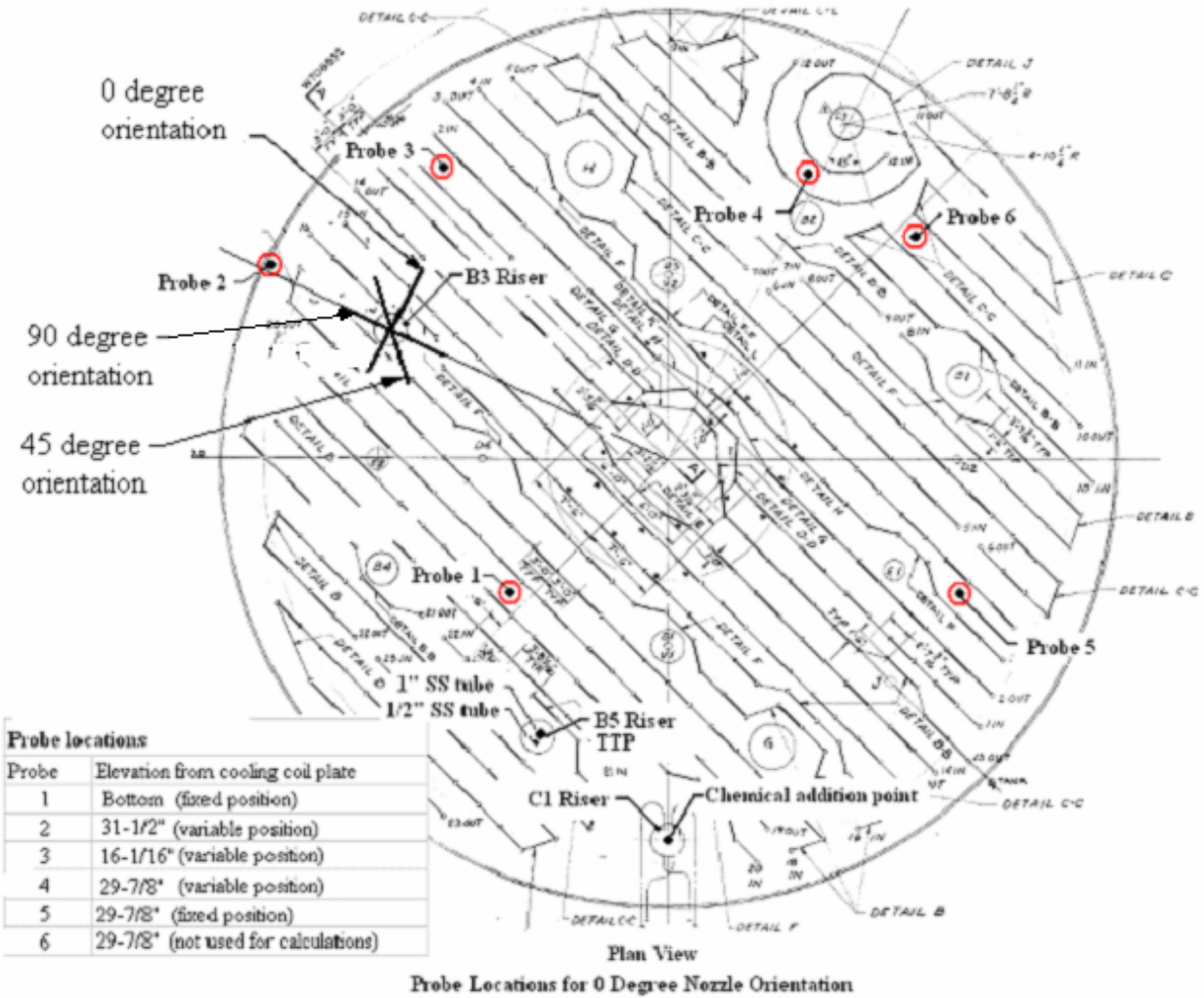
Figure 12: Nozzle Orientation and pH Probe Locations

Pump model	Part	ID	Length
Standard	1	0.136	3"
Long Quad	2	0.332	3"
Short Quad	3	0.332	1.36"
SDI model	4	0.209	3"

Figure 13: Pump Models for Discharge Nozzles / Jets

Figure 14: Pump Suction Inlet and Pump Nozzles

Results

Summary of Results

All test results are summarized in Table 1, where each of the parameters varied during testing is listed. A convenient testing term is introduced in the table, which is premature remixing. Between tests, the pump speed was increased to remix the tank contents. In those tests that were stopped before 95 % blending was achieved, the tank was said to be prematur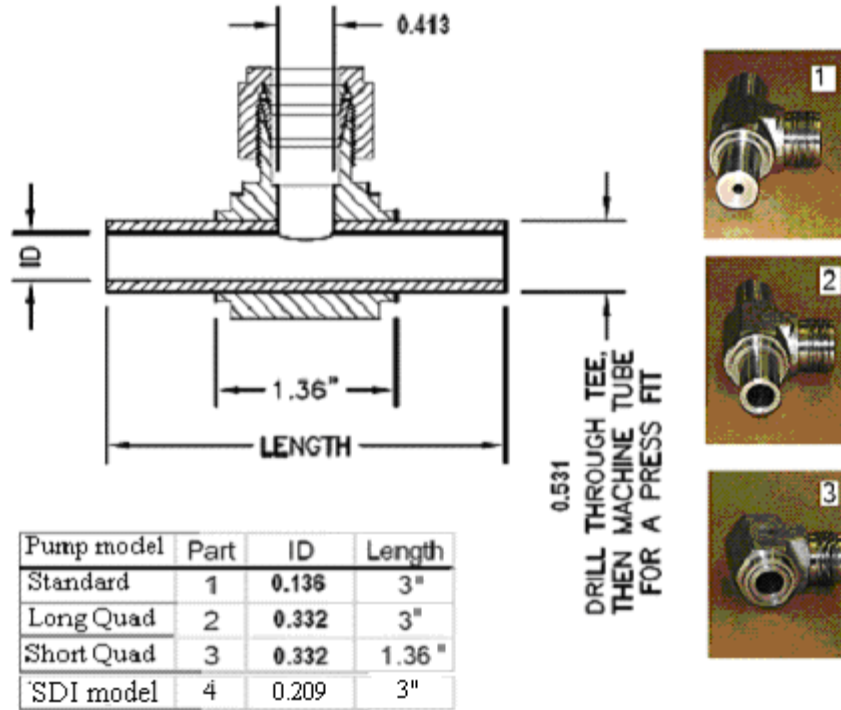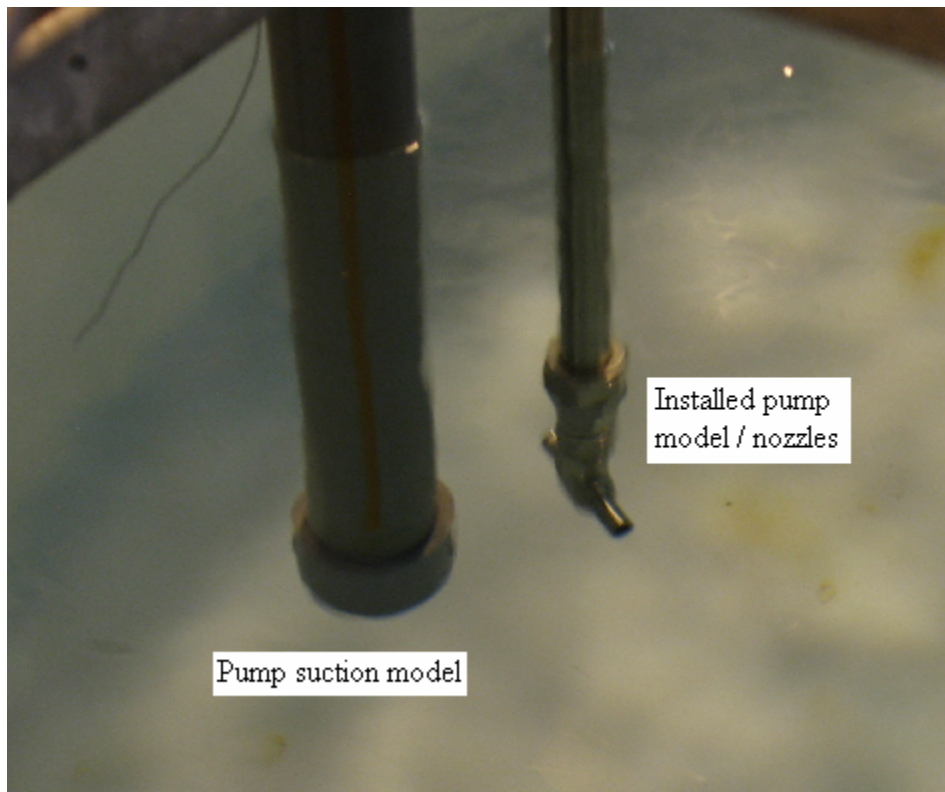ely remixed. All tests were performed at controlled room temperatures, which varied between 18 and 21° C. The first four tests used 250 milliliters of blue dye added to the hopper at the C1 riser location, and the remaining tests used 250 and 500 milliliters of either acid (nitric acid) or base (sodium hydroxide) for additions to the tank hoppers. The hoppers are shown at the addition points in Figures 10 and 11. Figures 15 and 16 provide the results from Table 1 in graphic formats. A summary of the test results determined from Table 1 is followed here by some discussion of supporting tests. Again, further detail is available (Leishear, Fowley, and Poirier [1]).

To summarize test results:

- Pilot scale blending times were significantly affected by cooling coil installation. Blending times in a tank with coils were twice the blending times for a tank without coils, within the recommended range of operation. Below the recommended range of operation the basic fluid mechanics of blending is not understood, and blending times for a tank with coils was as much as seven times the blending time for a tank without coils.
- A minimum pilot scale U_0D = 0.47 ft^2 /second is recommended for effective blending (Equation 1). Below this recommended lower limit, flow characteristics change significantly and the scaling relationships used in this work are inapplicable (Figure 16).
- Data affected by premature remixing is below the recommended design condition of U_0D = 0.47 ft^2 /second.
- Dye tests typically had apparent blending times less than a third of the blending times quantitatively found during *pH* testing for comparable conditions.
- Diffusion was very slow when compared to blending times, and consequently had a negligible effect on blending.
- Pilot scale blending times varied by more than 700% for apparently comparable conditions.
- For *pH* tests, pilot scale blending times were independent of initial and final concentrations of acid or base, the concentration range during an acid or base test, or the initial acidic or basic condition in the tank when testing started.
- The effects of nozzle lengths on blending were inadequately quantified. Only two nozzle lengths were investigated for the Quad Volute pump, and only one test was performed on the alternative nozzle length.

- The 0º nozzle position is recommended.
- Perhaps due to limited data, larger diameter Quad nozzle pilot scale blending times are slightly shorter than smaller diameter Standard nozzle blending times for a tank with coils and comparable U_0D.
- Nozzle diameter effects were not investigated outside the range of the Standard and Quad nozzle diameters (1-1/2" – 3-5/8" scaled down to 0.138 and 0.334" respectively). At smaller diameters, conclusions with respect to U_0D and blending times may be questionable.
- Blending times were significantly shortened when a dye was added to the pump suction, instead of at the addition point hopper. The addition point location in the tank may affect blending times.
- A 95% blending time criteria was validated for use in test results, but a 99% blending time could not be obtained with available equipment.
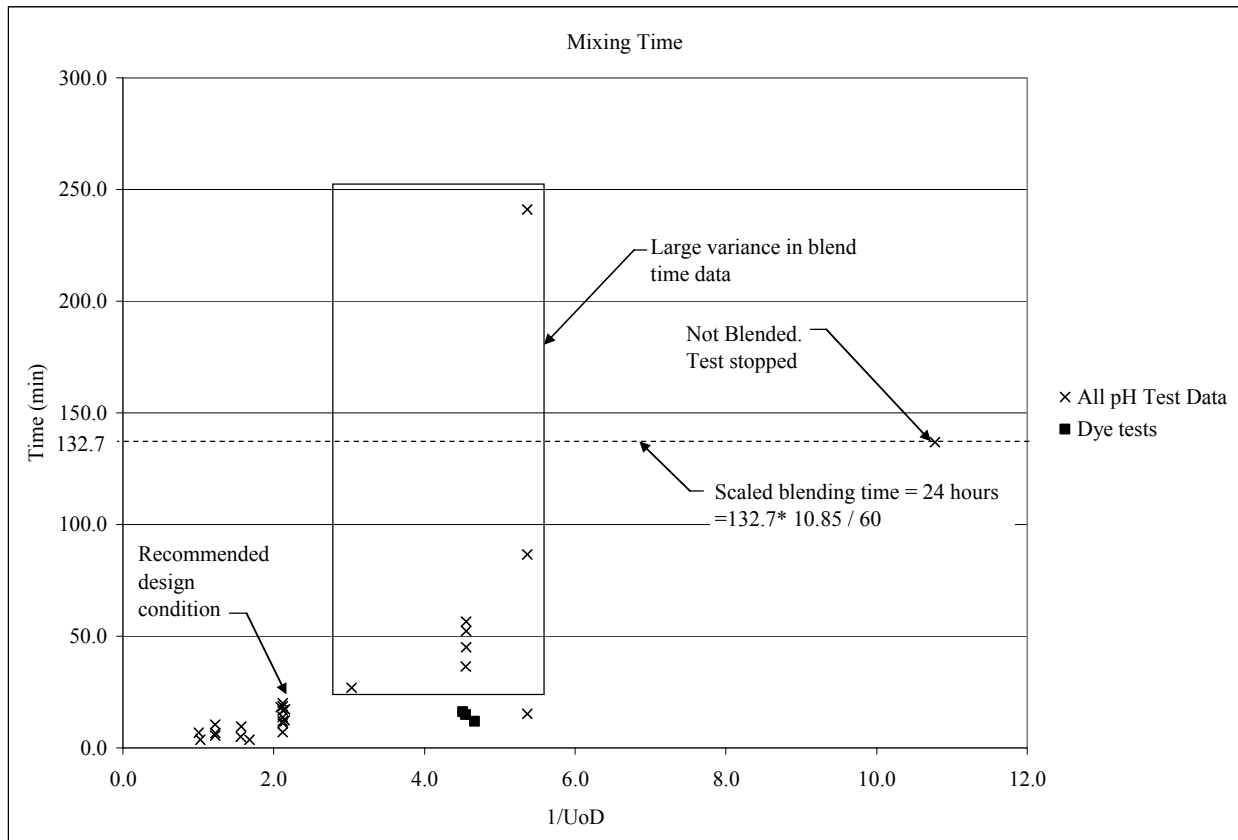

Figure 15: Measured Blending Times for All Tests

Table 1: Test Results

| Test	Test type, Nozzle design	Fluid additions / strikes	Coils	Blue Dye	Nozzle position (deg)	D (m)	Uo (ft/s)	UoD (ft2/s)	Q (gpm)	Nozzle Re	Start cond	Start pH	End pH	Theoretical Time, no coils (min) t(theoretical)	Blending Time (min) t(measured)	Time ratio	Pilot scale UoD, relative standard deviation, %	Notes
1	Blending, dye, Quad	Dye	Y	Y	0	0.334	7.90	0.22	4.31	20,428	DI water	N/A	N/A	17.3	15	0.87	0.023	
2	Blending, dye, Quad	Dye	Y	Y	90	0.334	7.97	0.22	4.35	20,596	DI water	N/A	N/A	17.2	16.3	0.95	0.025	
3	Blending, dye, Quad	Dye	Y	Y	45	0.334	7.70	0.21	4.20	19,908	DI water	N/A	N/A	17.7	12	0.68	0.023	
4	Diffusion, dye	Dye	Y	Y	N/A	N/A	0	0	0	0	DI water	N/A	N/A	N/A	3.5 hours	N/A	N/A	
5	Diffusion, base	Base	Y	N	N/A	N/A	0	0	0	0	DI water	N/A	N/A	N/A	> 13.3 hours	N/A	N/A	
6	Diffusion, acid	Acid	N	N	N/A	N/A	0	0	0	0	Acid	9.96	N/A	N/A	> 38.5 hours	N/A	N/A	
7	Blending, Quad	Base	Y	N	0	0.334	7.89	0.22	4.31	20,411	Acid	5.5	8.6	17.3	52.3	3.02	0.007	Premature remix
8	Blending, Quad	Acid	Y	N	0	0.334	7.89	0.22	4.31	20,402	Base	9.97	9.66	17.3	45.0	2.60	0.003	Premature remix
9	Blending, Quad	Acid	Y	N	0	0.334	7.90	0.22	4.31	20,428	Base	9.66	9.05	17.3	36.4	2.10	0.003	Premature remix
10	Blending, Quad	Base	Y	N	0	0.334	16.93	0.47	9.24	43,765	Acid	5.94	10	8.1	28.7	3.55	0.007	Premature remix
11	Blending, Quad	Acid	Y	N	0	0.334	16.94	0.47	9.24	43,791	Base	9.98	3.93	8.1	18.6	2.30	0.004	
12	Blending, Quad	Acid	Y	N	0	0.334	16.94	0.47	9.25	43,803	Base	10.22	8.7	8.1	11.0	1.36	0.005	
13	Blending, Quad	Base	Y	N	0	0.334	16.94	0.47	9.24	43,791	Acid	3.92	9.78	8.1	11.9	1.47	0.004	
14	Blending, Quad	Base	Y	N	0	0.334	29.29	0.82	15.99	75,738	Acid	4.27	10.21	4.7	6.6	1.41	0.054	
15	Blending, Quad	Base	Y	N	0	0.334	29.38	0.82	16.03	75,958	Acid	5.81	9.68	4.7	10.4	2.24	0.058	
16	Blending, Quad	Acid	Y	N	0	0.334	29.38	0.82	16.03	75,958	Base	9.97	4.23	4.7	5.5	1.18	0.073	
17	Blending, Short Quad	Base	Y	N	0	0.33	17.35	0.48	9.25	44,326	Acid	3.96	9.96	8.0	18.1	2.27	0.004	
18	Blending, Standard	Base	Y	N	0	0.134	20.93	0.23	1.84	21,713	Acid	4.06	10.07	16.3	116.9	7.19	0.007	Premature remix
19	Blending, Standard	Acid	Y	N	0	0.134	41.64	0.46	3.66	43,193	Base	9.96	4.05	8.2	17.3	2.11	0.009	
20	Blending, Quad	Acid, dye	Y	Y	90	0.334	16.94	0.47	9.24	43,791	Base	9.91	3.94	8.1	20.0	2.48	0.004	
21	Blending, Quad	Base	Y	N	90	0.334	16.94	0.47	9.24	43,791	Acid	3.95	9.92	8.1	13.7	1.70	0.004	
22	Blending, Quad	Acid	Y	N	45	0.334	3.34	0.09	1.82	8,624	Base	10.12	4.03	41.0	136.80	none	0.011	Not blended
23	Blending, Quad	Acid	Y	N	45	0.334	6.70	0.19	3.66	17,325	Base	9.87	4.14	20.4	149.9	7.35	0.003	Blending incomplete
24	Blending, Quad	Base	Y	N	45	0.334	7.89	0.22	4.31	20,402	Acid	3.89	9.83	17.3	56.5	3.26	0.003	Premature remix
25	Blending, Quad	Acid	Y	N	45	0.334	11.90	0.33	6.50	30,771	Base	9.98	3.86	11.5	317	2.76	0.003	
26	Blending, Quad	Acid	Y	N	45	0.334	16.94	0.47	9.24	43,791	Base	10.11	3.96	8.1	16.8	2.08	0.004	
27	Blending, Quad	Base	Y	N	45	0.334	22.89	0.64	12.49	59,176	Acid	4.06	9.95	6.0	9.5	1.59	0.024	
28	Blending, Quad	Base	Y	N	45	0.334	35.71	0.99	19.49	92,339	Acid	6.45	9.95	3.8	6.8	1.78	0.065	
29	Blending, Quad	Acid	N	N	45	0.334	6.70	0.19	3.66	17,325	DI water	9.97	5.63	20.4	15.2	0.74	0.003	
30	Blending, Quad	Base	N	N	45	0.334	6.70	0.19	3.66	17,325	Acid	4.02	10.13	20.4	23.2	1.14	0.003	Blending incomplete
31	Blending, Quad	Acid	N	N	45	0.334	11.85	0.33	6.47	30,629	Base	10	4.05	11.5	12.3	1.07	0.004	
32	Blending, Quad	Base	N	N	45	0.334	16.74	0.47	9.14	43,273	Acid	4.1	9.97	8.2	4.9	0.60	0.021	
33	Blending, Quad	Base	N	N	45	0.334	22.98	0.64	12.54	59,422	Acid	4.02	9.99	5.9	3.6	0.61	0.022	
34	Blending, Quad	Acid	N	N	45	0.334	34.99	0.97	19.10	90,477	Base	9.93	4	3.9	4.0	1.03	0.029	
35	Blending, Standard	Acid	N	N	45	0.134	9.22	0.105	0.81	9,560	Base	9.96	3.99	37.0	86.6	2.34	0.006	Premature remix
36	Blending, Standard	Base	N	N	45	0.134	20.93	0.23	1.84	21,713	Acid	3.98	9.95	16.3	15.6	0.96	0.007	
37	Blending, Standard	Acid	N	N	45	0.134	42.30	0.47	3.72	43,878	Base	10.11	3.96	8.1	7.0	0.87	0.051	
38	Blending, Standard	Base	N	N	45	0.134	52.84	0.60	4.64	54,817	Acid	3.9	9.91	6.4	3.6	0.56	0.052	
39	Blending, 0.209" nozzles	Dye	Y	Y	0	0.209	46.51	0.81	9.94	75,251	DI water	N/A	N/A	4.6	0.42	0.09	N/A	Dye added to suction pipe
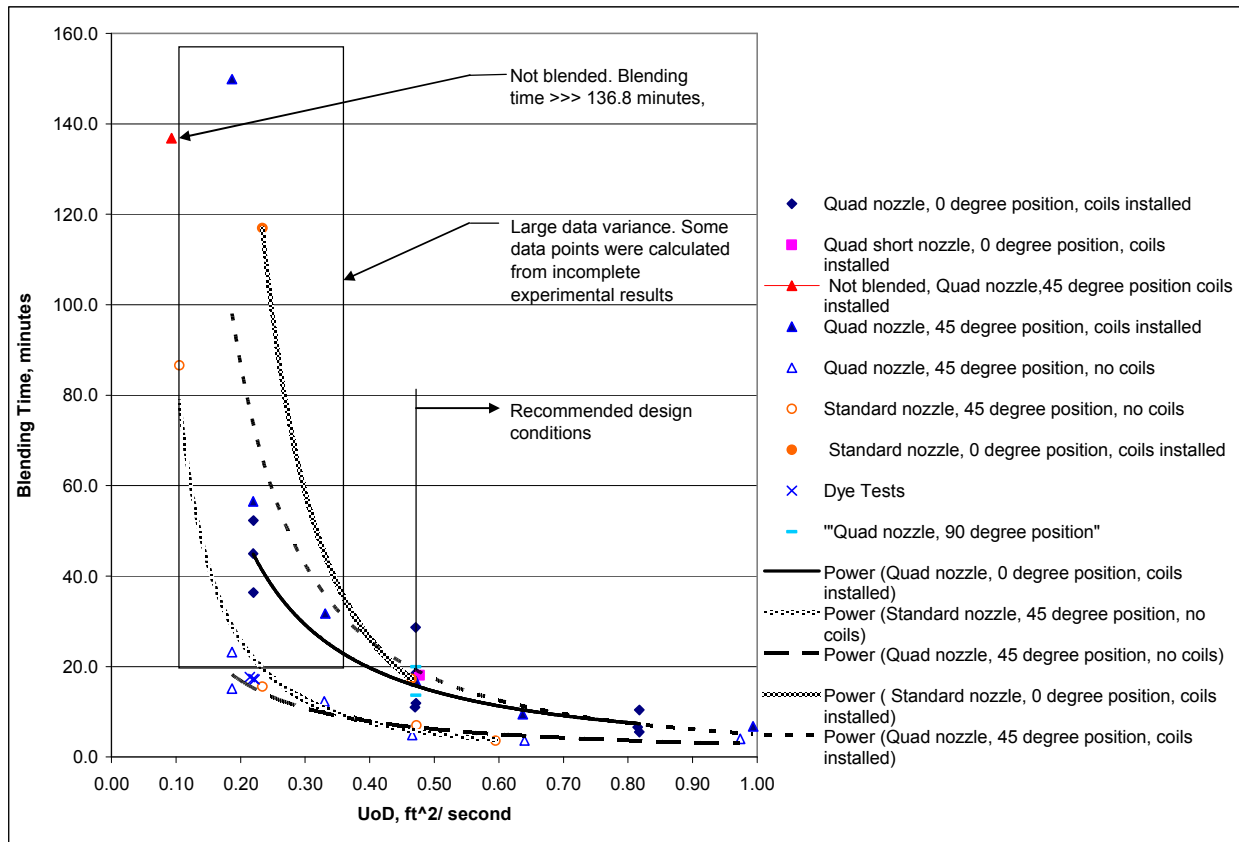
**Figure 16: U$_0$D vs. Pilot Scale Blending Times for Acid and Base Tests**

Dye Tests

The addition of dye to the hopper for one of the tests is shown in Figure 17, and the distribution of the dye across the tank floor is shown in Figure 18. Although the distribution varied somewhat for different nozzle orientations, this figure depicts the typical spread of dye in the pilot scale tank. For one test (Test 39), dye was added directly to the pump suction piping, and the tank blended in about 30 seconds, which was much faster than other tests with comparable U_0D. This result indicated that blending time may also be affected by the location of the chemical addition point.

During later *pH* testing, the acids were lower viscosity than bases and spread across the entire floor faster, while the thicker, higher viscosity bases tended to flow directly toward the pump suction along the tank floor. The acid had a higher viscosity and density than water, while the base had an even higher viscosity and density. In later acid-base testing, the *pH* probes indicated that at higher flows, the acids and bases actually spread across the air / water surface, rather than dropping immediately to the tank floor, when a *pH* probe at the surface responded to *pH* changes before the probe on the tank floor responded. Regardless of acid or base addition, the results showed that the selection of an acid or base addition had a negligible effect on pilot scale blending times.
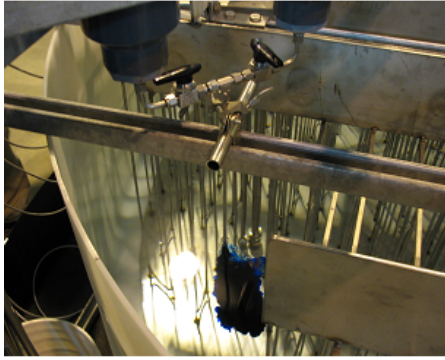
Dye Addition Started, C1 Riser
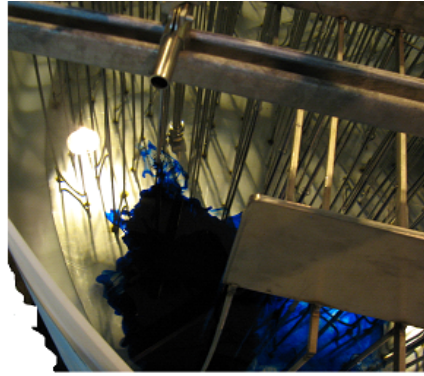
Dye Addition Complete, C1 Riser

Dye Addition Near Completion,
C1 Riser

Dye Spreading Across the Tank Floor,
B3 Riser, Near the Pump

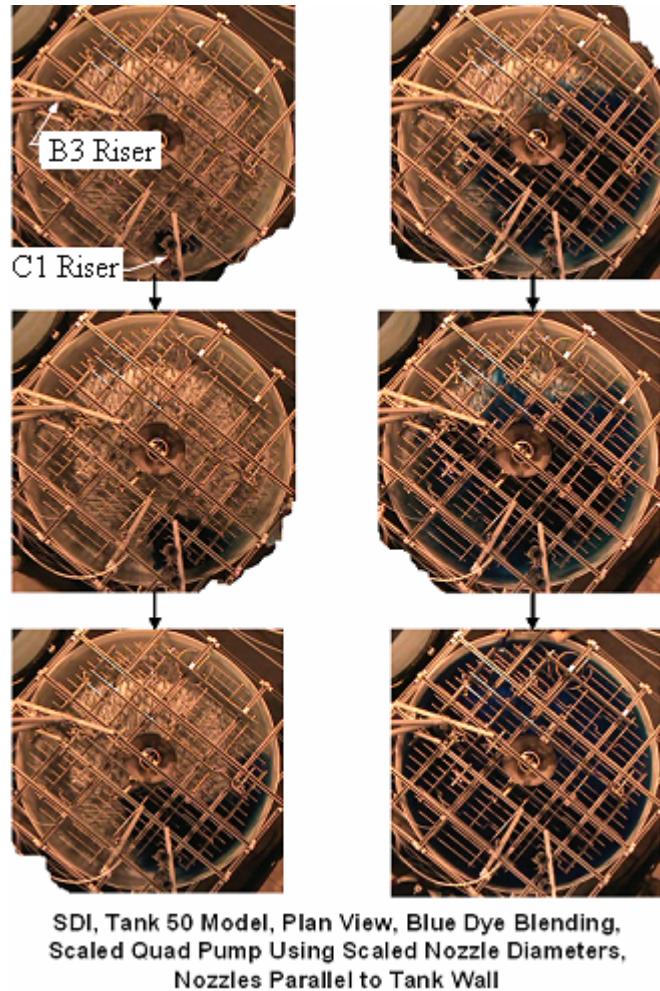**Figure 17: Dye Addition at C1 Riser (Test 1)**

SDI, Tank 50 Model, Plan View, Blue Dye Blending,
Scaled Quad Pump Using Scaled Nozzle Diameters,
Nozzles Parallel to Tank Wall

Figure 18: Typical Dye Distribution in the Pilot Scale Tank (Test 1)

Acid and Base Testing Using pH Measurements

Test 11 is provided as an example of test data used to establish the blending times listed in Table 1. The raw data was displayed on the DAS in the format shown in Figure 19 during testing. The zero time, $t = 0$, equaled the time at which the valve on the hopper at the C1 riser location was opened to release acid into the tank. The pump was already operating at the selected speed and flow rate. Probe 1 was located near the upper surface of the tank fluid, while the other probes were located near the tank bottom, as shown in Figure 12.

Several steps were taken to calculate bending times. First, *pH* data was converted to hydronium ion concentrations as shown in Figures 20 and 21. Then, a bias, or offset gain, was applied to the data to eliminate the offset between probes, and ensure that the data converged, or collapsed, to a common datum. Finally, the data was normalized to establish pilot scale blending times using Equation 2, as shown in Figure 22. Most test results are similar, except the limiting case where the tank contents did not

completely mix, which is shown in Figure 23. Numerous test details, and plots for all tests are available (Leishear, Fowley, and Poirier [1]), where blending times for all tests were similarly obtained. Details of diffusion, buffering, and instrument uncertainty also require some discussion.
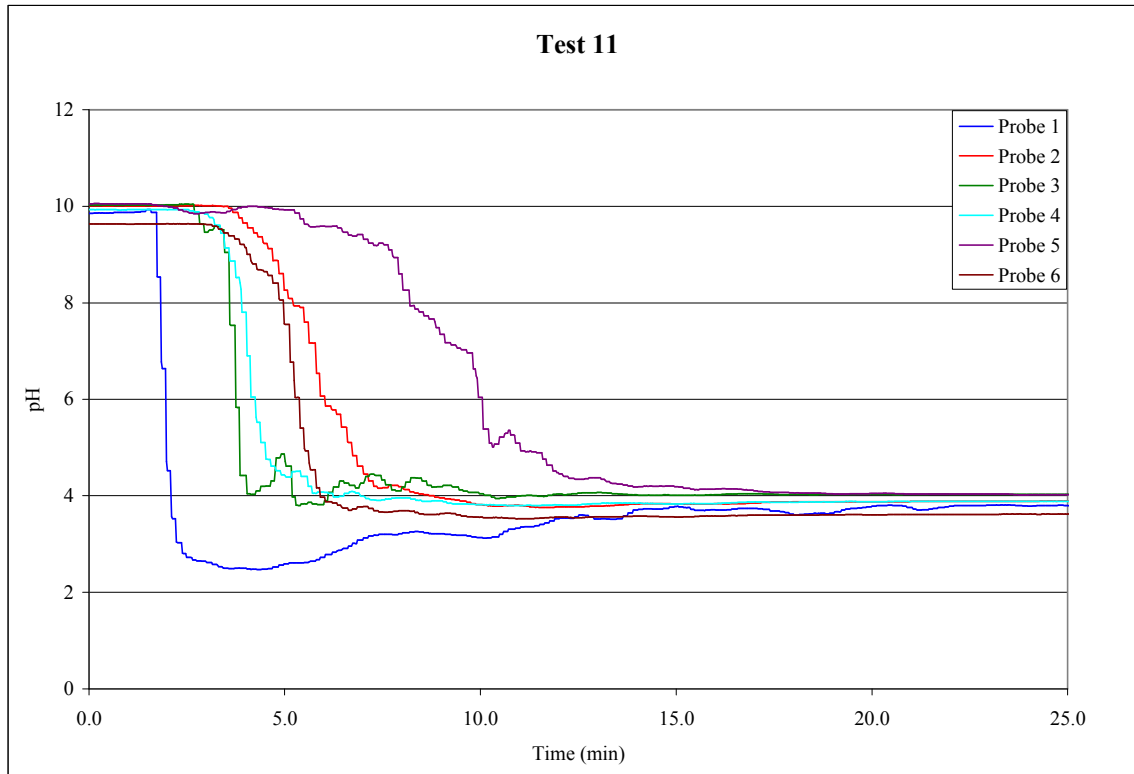

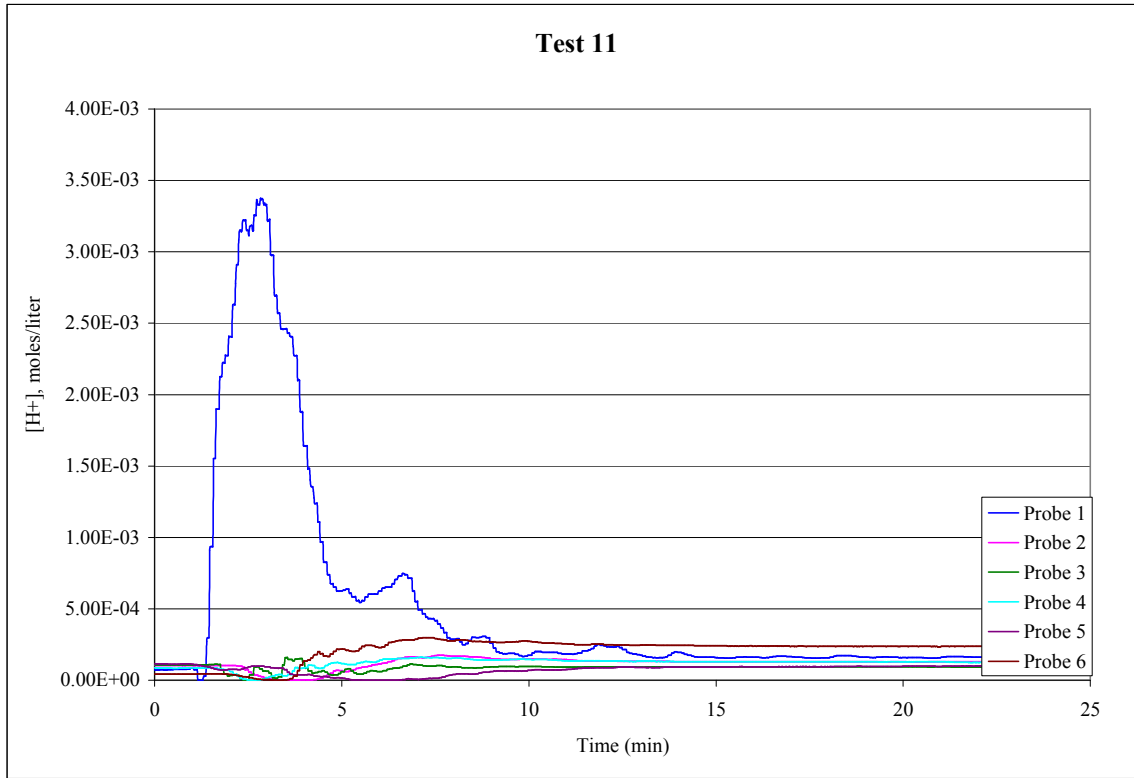**Figure 19: Raw pH Data for Analysis**
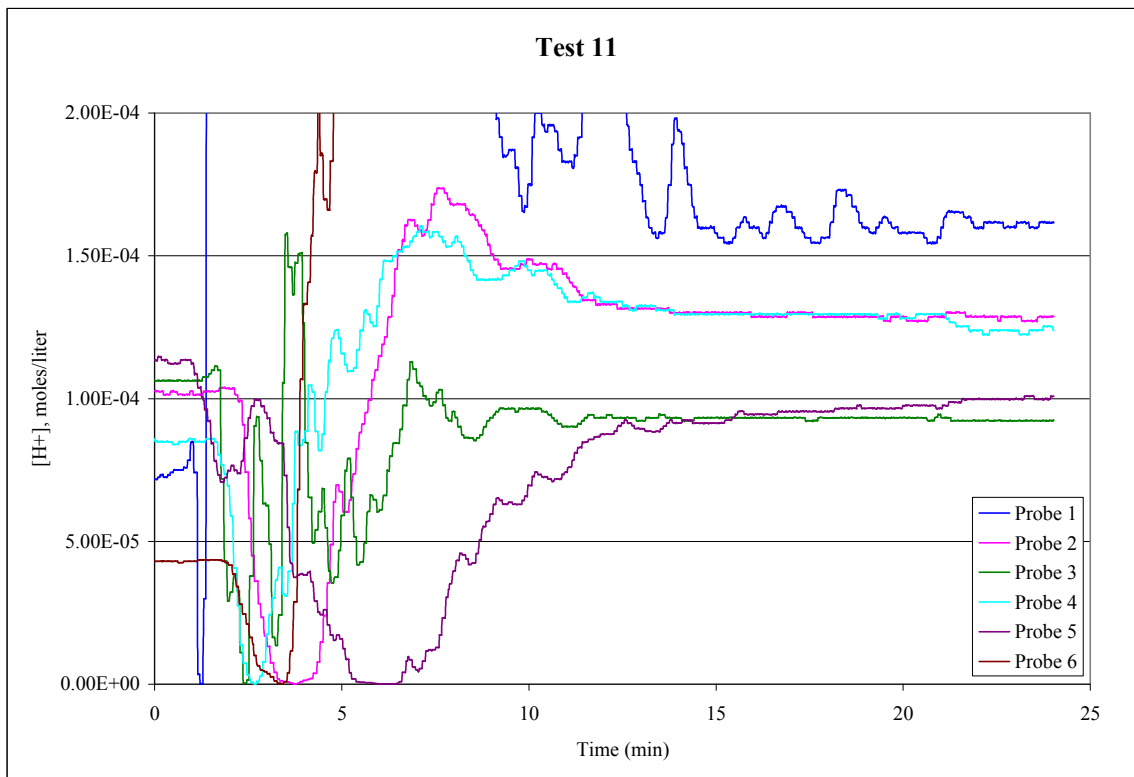
Figure 20: Concentration Data for Analysis

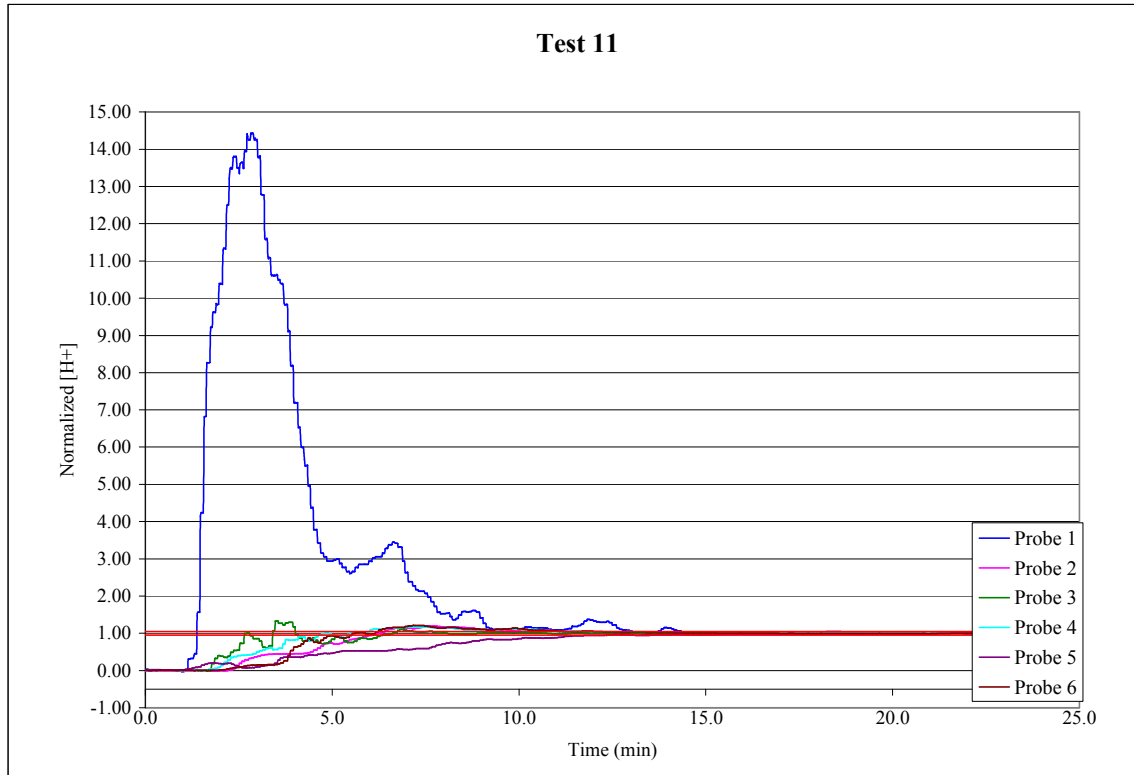**Figure 21: Concentration Data for Analysis Near Equilibrium**

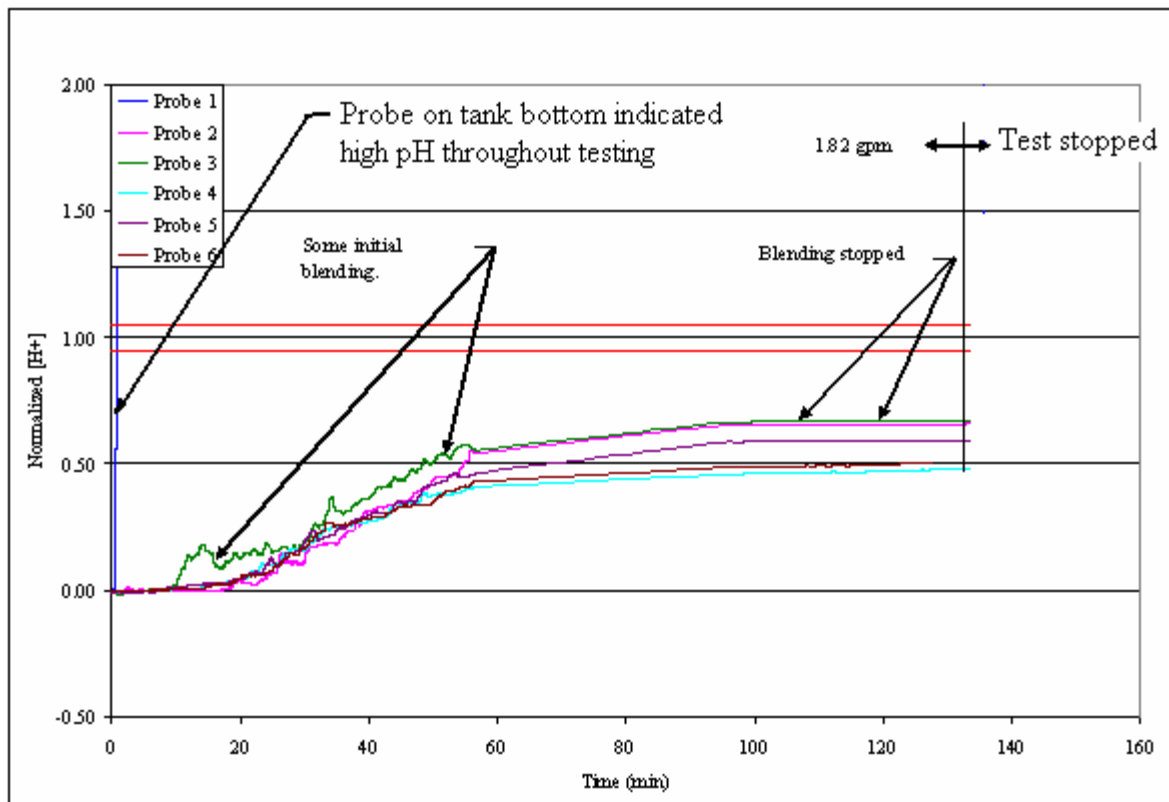**Figure 22: Normalized Concentration Data for Analysis**

Figure 23: Inadequate Blending (Test 22)

pH Uncertainty

Uncertainties of *pH* measurements are affected by instrument errors and buffering, but are little affected by diffusion. Tests were performed to evaluate diffusion, by adding acid or base to the hopper, and measuring the time for the tank to blend. The tank did not blend in 3-1/2 hours, which is considerably longer than any of the tests. Statistical analyses were performed for all test results and instrumentation.

To obtain a 95% confidence for 95% blending throughout the blending process, the instrument errors were shown to be as large as ± 50.6%. However, instrument errors were shown to be as low as +/- 0.5% near equilibrium. Essentially, data sets similar to Figure 24 had large instrument errors as the blending process proceeded, but the error significantly reduced as the tank contents approached equilibrium. That is, the normalization technique provided a valid estimate of blending effectiveness near 95% blending. Also observed in the figure, some data scatter continues to exceed the 99% blending criteria, which indicates that 99% blending cannot be accurately measured using *pH* probes currently available.

Similarly, buffering of the solution was shown to affect *pH* results. Carbon dioxide in solution contributed a buffering effect to chemical reactions as carbonates and bicarbonates were formed. The concentrations of each chemical were not determined. However, the hydronium ion concentration was the measured blending parameter, and chemical reactions in solution therefore did not affect blending times. In other words, when the reactions were complete, hydronium ions were evenly distributed, and blending was complete.
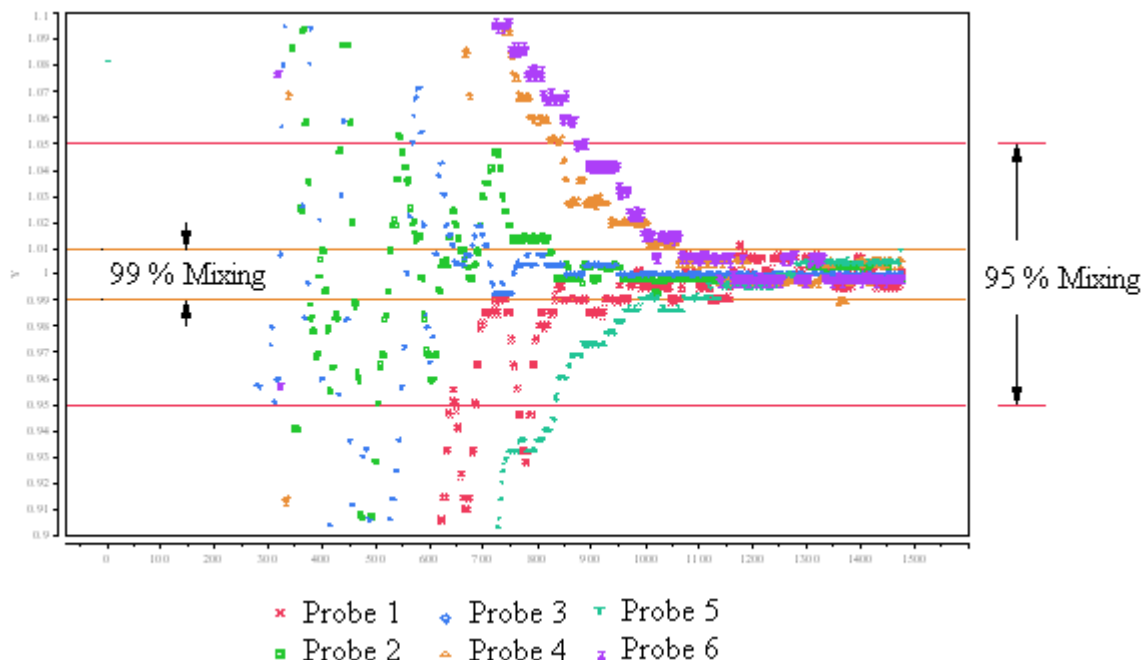

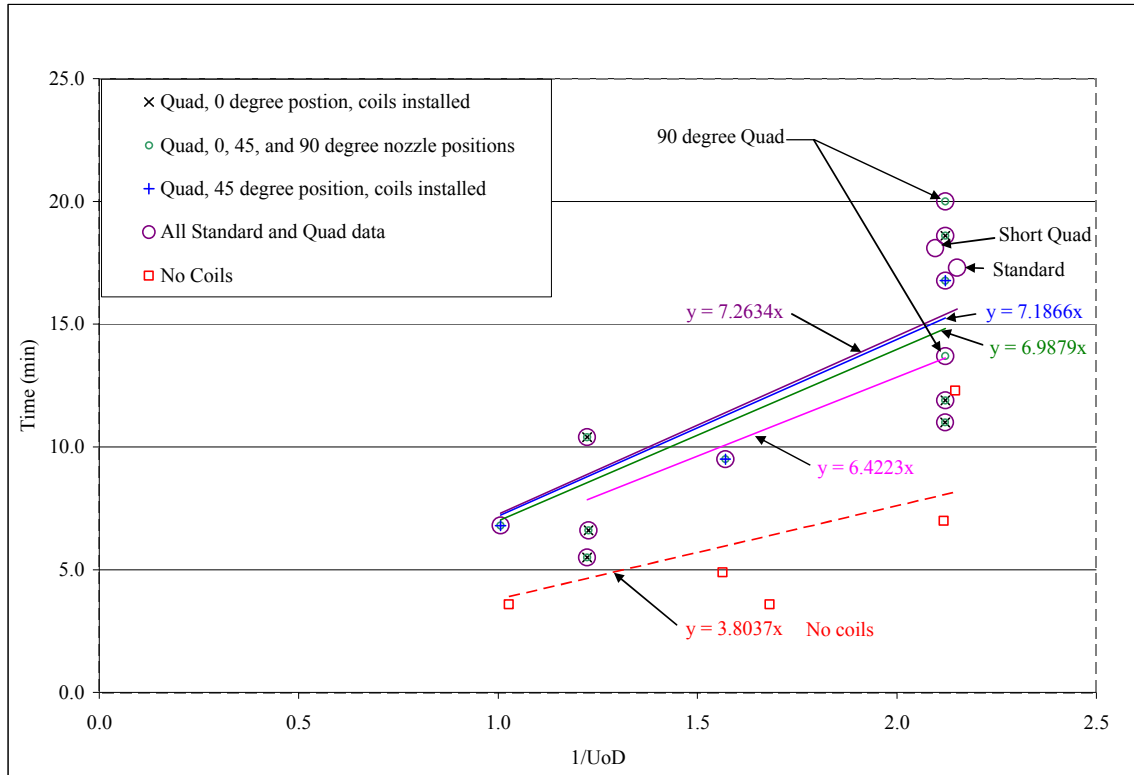**Figure 24: Comparison of 95% Blending to 99% Blending (Test 21)**

Figure 25: Blending Times for Different Design Parameters (Pilot scale $U_0D \geq 0.47$ feet^2/second)

Blending Time Equation for a Tank Without Coils

Once blending tests were completed, the blending time Equation 1 and Figure 25 were used to find the blending time constant, *C*, such that

$$t(\text{theoretical}) = \frac{3.8037}{U_0 \cdot D} \qquad \text{Equation 10}$$

To determine the constant, Equation 2-1 is rewritten as

$$t(\text{theoretical})(\text{min}) = \frac{C \cdot T^2}{U_0 \cdot D} = \frac{C \cdot \left(\dfrac{1\_\text{ft}}{12\_\text{in}} \cdot 94\_\text{in} \right)^2}{U_0 \left(\dfrac{\text{ft}}{\text{sec}} \right) \cdot D(\text{ft}) \cdot 60 \left(\dfrac{\text{sec}}{\text{min}} \right)} \qquad \text{Equation 11}$$

Solving Equations 10 and 11, *C* = 3.72. Note that the 3.72 value is close to the 3.0 value recommended by Grenville for a tank without a center column, which was blended by a single jet nozzle normal to the tank wall. This validation for *C* demonstrates the applicability of Equation 1 to the pilot scale tank without coils. Similarly, *C* may be found for any of the curves in Figure 25. Accordingly, the validity of Equation 1 with respect to a tank without coils was confirmed. Statistical analysis of the

data in Figure 25 provided a recommendation that the nozzles should be installed parallel to the pump wall, and that insufficient testing was performed to evaluate the effects of nozzle length.

Time Ratios for Tanks With and Without Coils

Test results were compared to the blending equation, using a normalized time ratio, such that

$$Time\_ratio = \frac{t(measured)}{\dfrac{3.72 \cdot T^2}{U_0 \cdot D}}$$
Equation 12

where the time ratios and measured blending times, *t(measured)* are listed in Table 1. Figure 26 summarizes test results in a normalized form. As U_0D decreases, non-linearity was observed for both tanks with and without coils as the time ratio increased. Data points at and above U_0D = 0.47 were within the recommended design range. In this range for tanks without coils, the time ratio was near one as expected. Also in this range, time ratios for tanks with coils significantly exceeded one for all data points, and coils therefore had a quantifiable effect on blending.
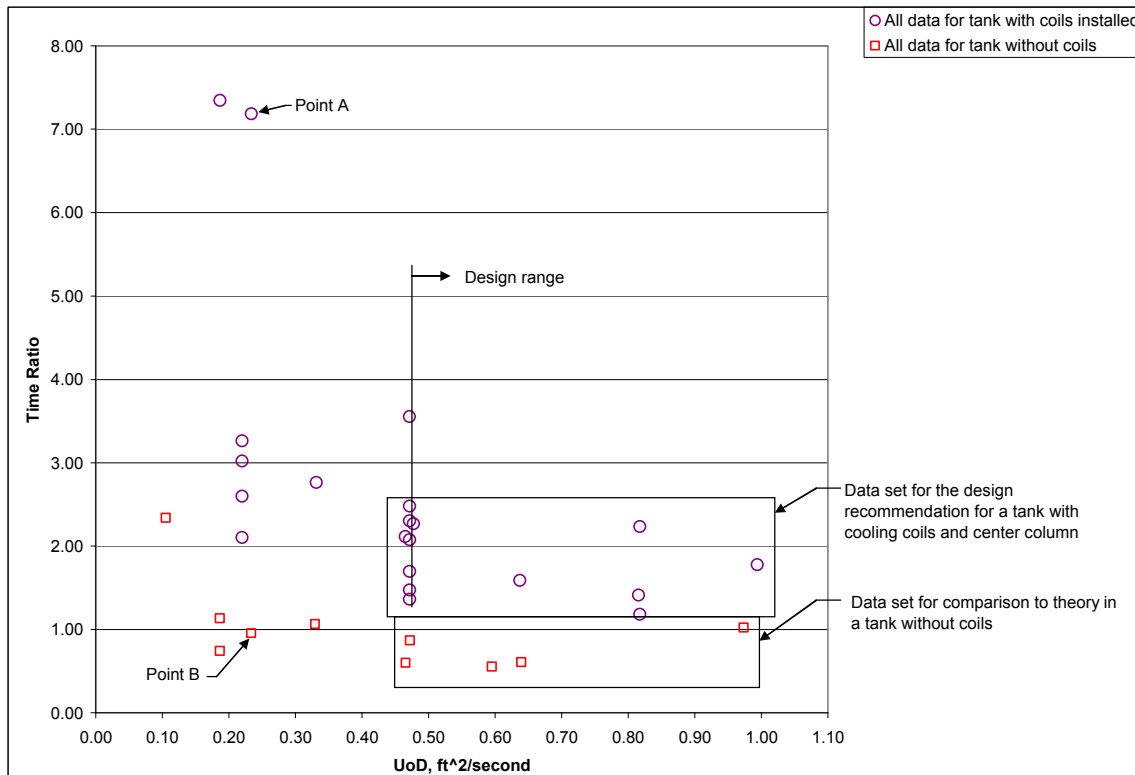

Figure 0-1: Ratio of Pilot Scale Measured Times to Theoretical Times

Conclusions and Recommendations

Pilot scale testing provided new insight into blending in a tank with cooling coils, such that:

- A single pump is adequate to blend the pilot scale tank contents.
- Pump nozzles should be installed parallel to the tank wall.
- The recommended minimum value for U_0D equals 0.47 ft^2 /second for a pilot scale tank filled with water.
- Pilot scale blending times were significantly affected by cooling coil installation, where blending times in a tank with coils were twice the blending times for a tank without coils, when $U_0D > 0.47$ ft^2 /second for the pilot scale tank.
- For a tank with coils when $U_0D < 0.47$ ft^2 /second, the basic fluid mechanics of blending were not understood, and blending times were as much as seven times the blending time for a tank without coils.
- Diffusion had a negligible effect on blending, since the time to blend a tank using diffusion only was considerably longer than the time to blend tank contents using a blending pump.
- Dye testing had apparent blending times at least 1/3 of measured blending times using pH probes.
- Nozzle diameters above 0.332 inch diameter and below 0.136 inch diameter were not evaluated.
- Data uncertainty analysis indicated that the 95% commercially used blending criterion provided a valid estimate of full scale blending effectiveness and blending time.

Recommendations for further research include:

- Further testing using a model of the final pump design is recommended.
- Further testing is recommended to quantify blending effects due to higher viscosities. The fluid mechanics and scaling with respect to viscosity and cooling coils in larger diameter tanks are not fully understood.
- Full scale and small scale computational fluid dynamics (CFD) models are recommended for the entire tank with and without coils to validate EDL pilot scale modeling.
- Validations of the CFD models are recommended, using pilot scale blending times and local velocity measurements obtained from small scale testing.

References

[1] Leishear, R. A., Fowley, M. D., Poirier, M. R., "Leishear, R. A., Poirier, M. R., Fowley, M. D., "SDI Blend and Feed Blending Study, Tank 50H Scale Model for Blending Pump Design, Phase 1", SRNL-STI-2010-00054.

[2] Grenville, R., Tilton, J., "Turbulence or Flow as a Predictor of Blend Time in Turbulent Jet Mixed Vessels", Proceedings of the North European Conference on Mixing, 1997.

[3] Grenville, R., Tilton, J., "A New Theory Improves the Correlation of Blend Time Data from Turbulent Jet Mixed Vessels", Transactions of the Institute of Chemical Engineers, Vol. 74, Part A, 1996.

[4] Paul, E. L., Atieno-Oberg, V. A., Kresta, S. M., Eds., "Handbook of Industrial Mixing", Brown, D. A. R., Jones, P. N., Middleton, J. C., "Experimental Methods", Hoboken, John Wiley and Sons, New Jersey, 2004.