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BLENDING TIME AND VELOCITY VARIATIONS DURING BLENDING IN A TANK USING DUAL OPPOSING JETS

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ABSTRACT

Blending times are required for many process industries, and statistical analysis of the measured blending times was used to determine a relationship between CFD (computational fluid dynamics) predictions and experiments. A 95% blending time occurs when tank contents are sufficiently blended to ensure that concentration throughout the tank is within ± 5% of the total change in concentration. To determine 95% blending times, acid and base tracers were added to an eight foot diameter tank, and the *pH* data were recorded to monitor blending. The data for six *pH* probes located throughout the tank were normalized to a range of 0 to 1. Then the blending time was established when the *pH* converged between 0.95 and 1.05 on the normalized graphs. Evaluation of results from 79 different tests concluded that the maximum blending time occurred randomly at any one of the six *pH* probes. The research then considered the calculated 95% blending times, which had uncertainties up to more than 100% at a 95% confidence level. However, this uncertainty is considered to be an actual variation in blending time, rather than an experimental error. Not only were there significant variations in the blending times, but there were significant variations in the velocities measured at different points in the blending tank.

INTRODUCTION

Design specifications were required for a pump to blend the contents of a 1.3 million gallon, radioactive liquid waste, storage tank for the Salt Disposition Project (SDI) at SRS, where the blending pump was required to mix salt solutions in the tank for further processing. This paper is the third in a series of five Conference papers to document the determination of these pump specifications. The tank contains several miles of vertical, serpentine two inch diameter cooling coils and a central column to support the tank roof. Details of the tank and pilot scale modeling requirements are available (Leishear, et al. also 1 and 2]). The required design parameter was *UoD*, where *Uo* is the nozzle velocity for each of two opposing pump nozzles, and *D* is the nozzle diameter. Once *UoD* was determined, recommended blending times were also required. Both the required *UoD* and blending times are discussed separately (Leishear, et al. [1 and 2]). This paper focuses on the use of CFD models to predict blending performance and velocities throughout the tank.

To obtain data for modeling the SDI pump in a full scale tank, an eight foot diameter pilot scale tank and an SDI pump model was used for most testing, and an 85 foot diameter full scale tank with an Advanced Design Mixer Pump (ADMP) pump was used for comparative velocity measurements. Specifically, blending tests and velocity measurements were performed in the pilot scale tank, and only velocity tests were performed in a full scale tank for a different pump, referred to as the ADMP. Tests in the pilot scale tank were performed with and without models of the internal cooling coils installed.

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Once the experimental data were measured, statistical analyses were performed to establish the uncertainty of the data, which was then used to establish engineering correction factors to be applied to CFD model predictions of blending times. A further discussion of the application of these factors is provided in a companion paper (Leishear, et al. [3])

NOMENCLATURE

ADMP	Advanced Design Mixer Pump
C_f	CFD blending time correction factor
C_V	velocity correction factor
CFD	computational fluid dynamics
D	nozzle diameter, ft
SDI	Salt Disposition Integration Project
UoD	pump design parameter, ft^2/second
Uo	nozzle velocity, ft/second
UTL	upper tolerance limit
V	velocity probe designation
ε	dissipation rate
κ	kinetic energy
σ	standard deviation

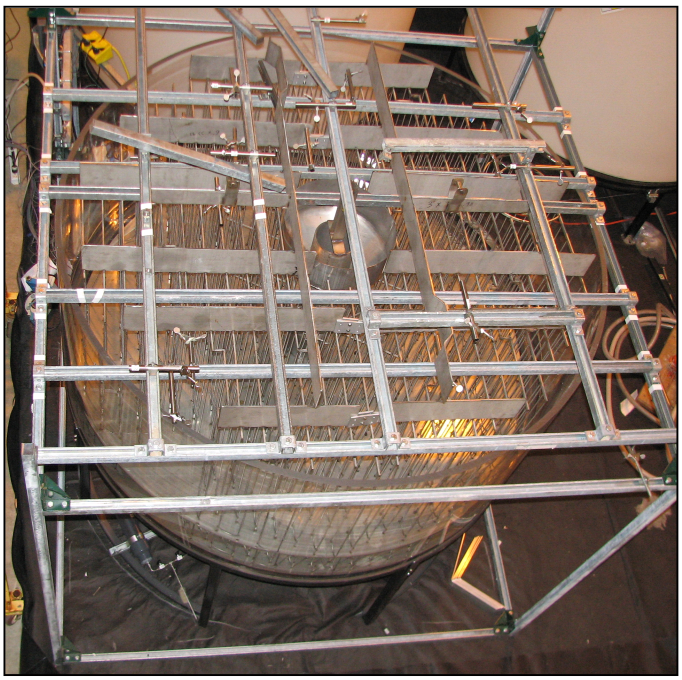

Figure 1: Pilot Scale Tank With Cooling Coil Models Installed

PILOT SCALE TEST EQUIPMENT DESCRIPTION

The eight foot diameter tank and pilot scale pump is shown in Fig. 1 and Fig. 2. In Fig. 3 a pump of much larger capacity is shown, where operational details are available (Leishear, et al. [4]). CFD models were performed for both pump systems, and comparisons of experiment to prediction were performed for each. Velocity measurements were taken with the same Marsh McBirney, Model 511 equipment, used to collect velocity data, as shown in Fig. 4. The probes were installed according to Fig. 5. In the pilot sale tank, probe locations were as shown in Fig. 6, and probe locations were as shown in Fig. 7 for the full scale tank.

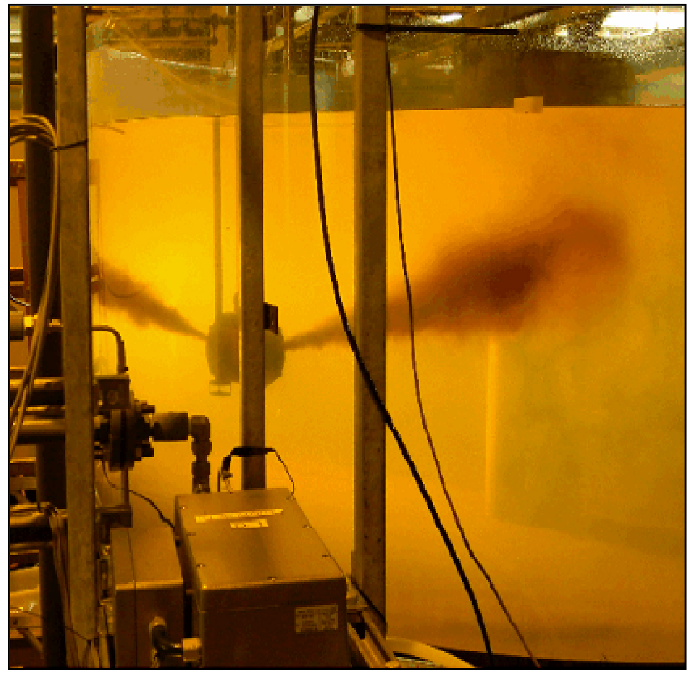

Figure 2: Pump Model installed in the Pilot Scale Tank

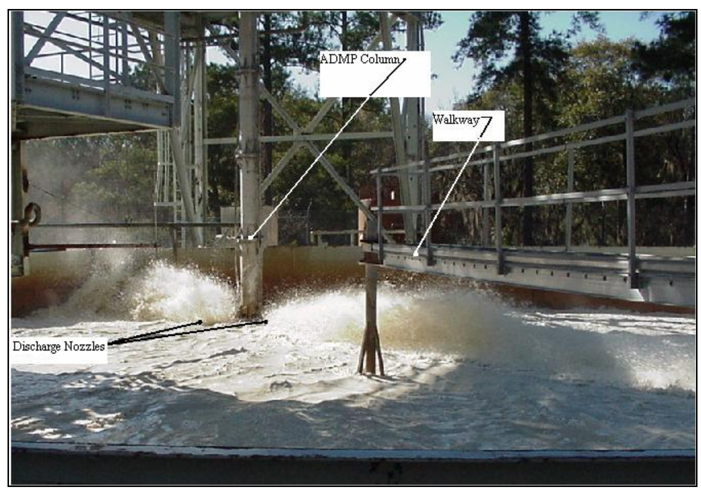

Figure 3: ADMP, Operating With the Water Level Near the Pump Discharge Centerline

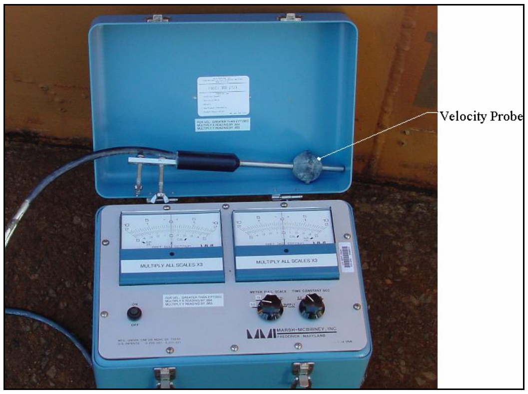

Figure 4: Velocity Probe

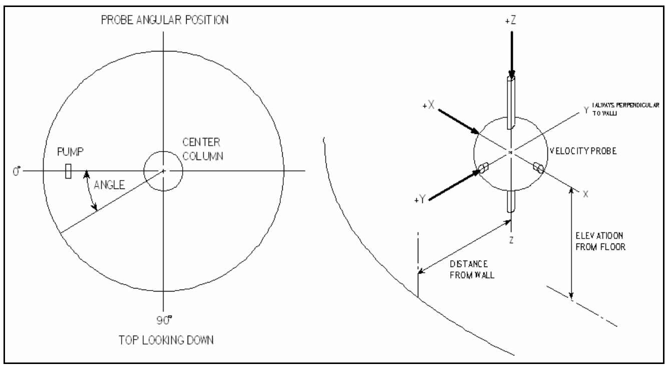

Figure 5: Velocity Probe Installation

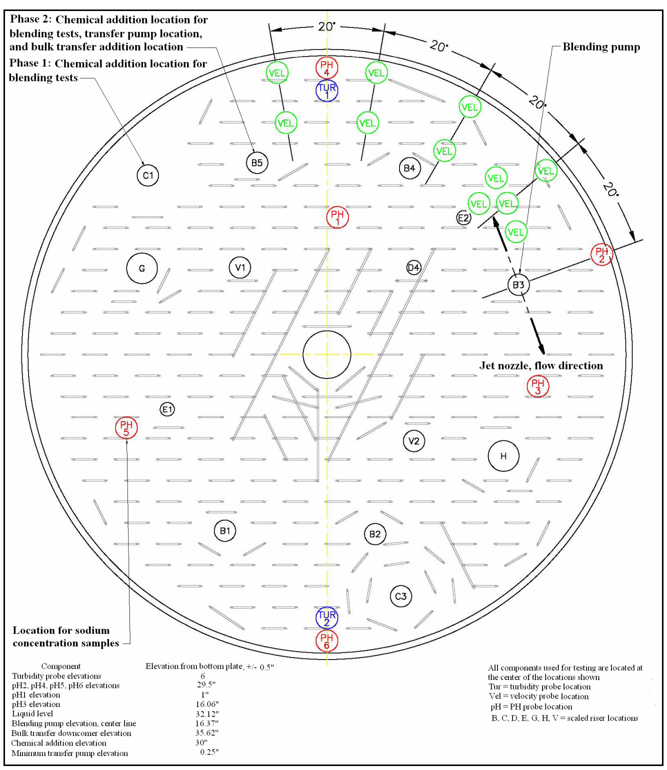

Figure 6: Phase 2, Locations of Velocity Probes (VEL)

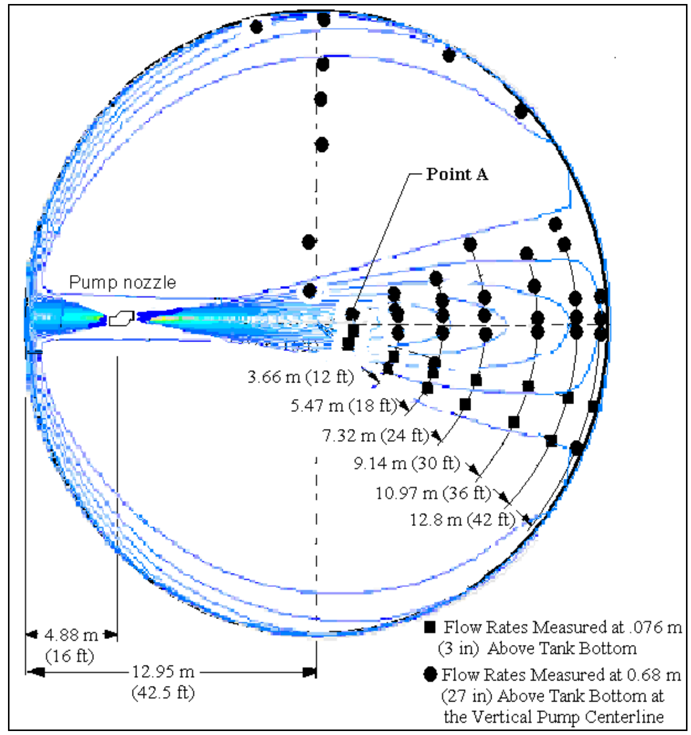

Figure 7: ADMP, Velocity Measurement Locations

CFD MODELS

Numerous SDI, CFD models were performed for both pilot and full scale tanks for different pump designs, where the blending pumps were installed at the mid-elevation, parallel to the tank wall as shown by typical results shown in Fig. 8 and Fig. 9. CFD predictions were within the range of experimental results, but variance of the predictions from experiment required investigation. Blending times were calculated using CFD (Lee and Armstrong [5]), and also required evaluation.

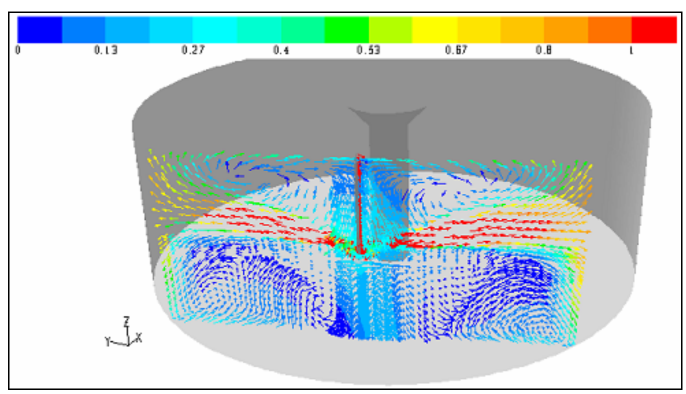

Figure 8: Velocity in a Pilot Scale Tank Without Coils at a Vertical Plane Through Upward Pointing Nozzles

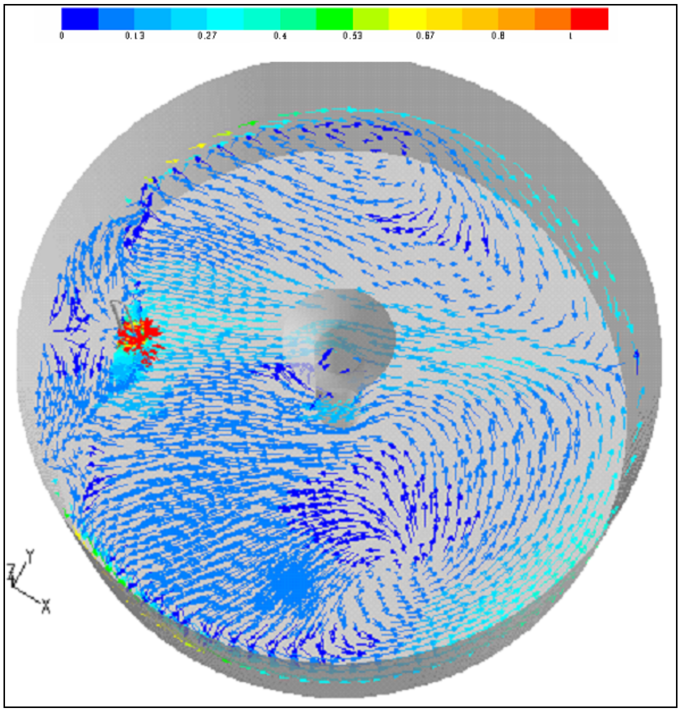

Figure 9: Velocity in a Pilot Scale Tank Without Coils at a Horizontal Plane Through the Horizontal Centerline of the Pump Model

A three-dimensional computational fluid dynamics (CFD) approach was used to calculate flow velocity distributions, and to estimate blending times for two miscible liquids. The results are benchmarked against both pilot scale test data and literature data. The commercial finite volume code, FLUENT®, was used to create a full scale geometry file in a non-orthogonal mesh environment.

The domain was meshed by a hybrid meshing technique. The number of meshes for the domain with no cooling coils was 1 x 10^6 nodes, as shown in Fig. 10. The number of mesh nodes for the model with 560 cooling coils was 4 x 10^6. Figures 11 and 12 show three-dimensional computational volume meshes and representative two-dimensional meshes near the pump and cooling coils for the tank model with cooling coils.

For modeling calculations, the transient governing equations consisted of one mass balance, three momentum equations, two turbulence transport equations for kinetic energy (k) and dissipation rate (ε), and one species transport equation. These equations were solved using an iterative technique until the species concentrations at all points in the tank met the 95% blending criteria, where the steady-state flow conditions for the tank were supplied as initial conditions. The governing equations were solved over the entire tank domain for the cases of a tank with or without coils, where further details of those CFD calculations are available (Lee and Armstrong [5]).

However, that work may be briefly summarized here. In earlier research, different turbulence models were investigated to assess measured velocities in the ADMP tank, and this model provided the most accurate results (Lee, et al. [6 and 7]). Consequently, the κ-ε turbulence model was used in this research as well. Fixed wall boundary conditions were assumed at the tank wall, coil s urfaces, and floor of the tank. The free liquid surface was assumed to act as a flat, slip plane. A more detailed discussion of CFD modeling will also be provided in a subsequent conference publication in this series of papers to describe this research (in process).

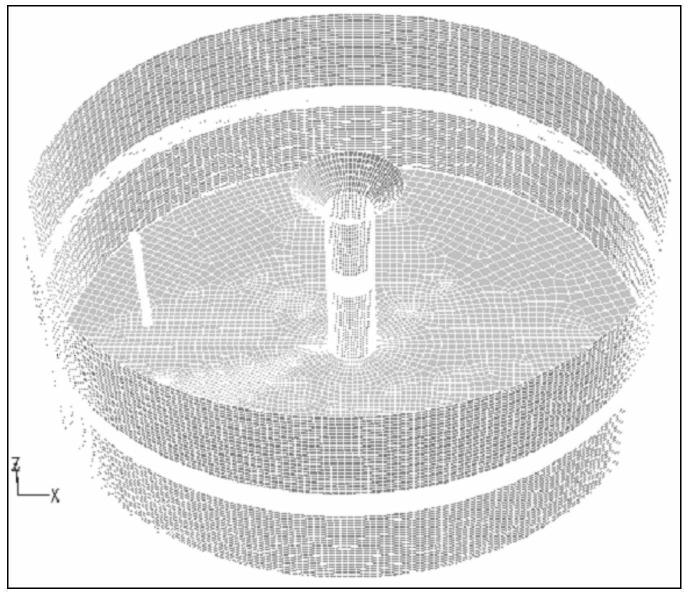

Figure 10: Model Geometry for a Tank Without Coils

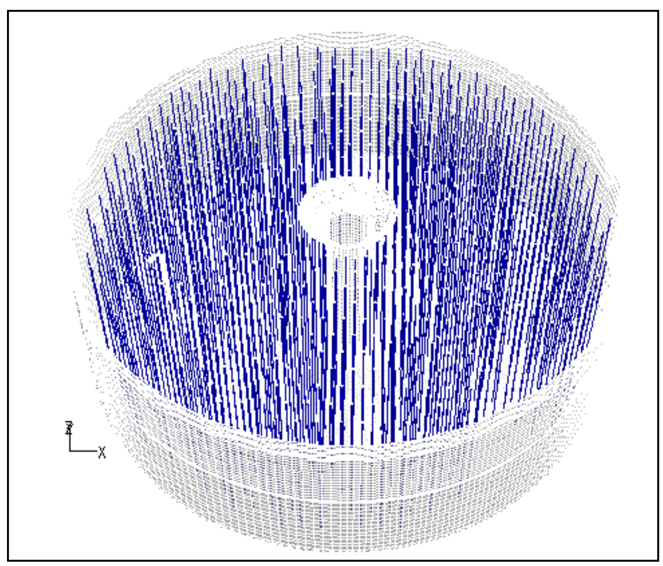

Figure 11: Model Geometry for a Tank With Coils

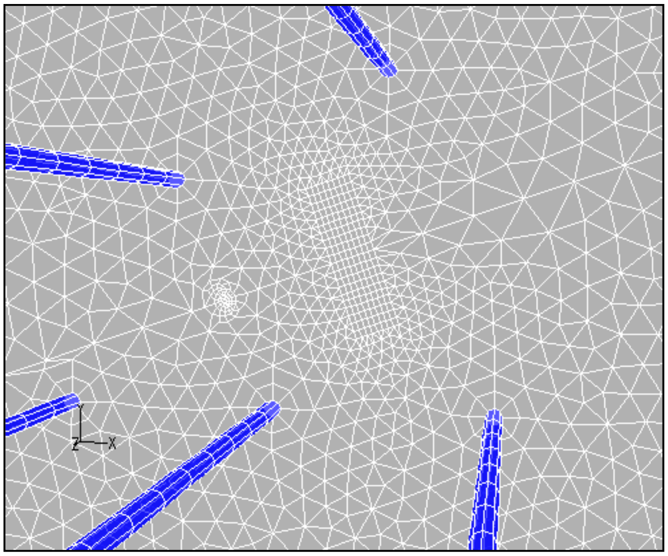

Figure 12: Model Geometry for a Tank With Coils Near the Pump Nozzles

VELOCITY DATA ANALYSIS

Using mean velocities, a velocity correction factor was established during this research, which can be applied to CFD model predictions for blending. Velocity data was used in calculations to establish a relationship between CFD and experiment.

Velocity Data

Velocity data were available from the pilot scale tests performed during this research, and additional data were available from other previous full scale testing (Leishear, et.al. [4]). Typical data from pilot scale testing are shown in Fig. 13 (Annex A), and typical data from full scale testing are shown in Fig. 14. Although the full scale testing was performed with a pump of much higher flow rates, the concern here is not the flow rate, but the accuracy of CFD to model those flow rates at any point in a tank. Tests were performed at much higher velocities for the ADMP testing than the velocities in the pilot scale tank. To ensure that data could be compared throughout the range of interest, additional tests were performed in the pilot scale tank to ensure that there was an overlap of velocity measurements at both scales as shown in Fig. 15.

All pilot scale velocity data is shown in Fig. 16 (Annex A). For blending analysis, velocities below 0.026 ft/second were discarded since they were below the range of interest, and velocities were also distinctly non-linear below 0.026. Presumably, instrumentation accuracy does not permit accurate measurements at these low velocity levels, but instrument accuracy was not further investigated.

Essentially, full scale test results at 10,500 gpm in an 85 foot diameter tank and pilot scale test results at 9-16 gpm in an eight foot diameter tank were shown to be comparable. For this comparison, the mean variation warranted consideration.

Approximation for Velocity Comparison of CFD to Experiment

Experimentally measured velocities were compared to CFD models, and velocities were shown to be comparable throughout the range of test data. As a first approximation to compare CFD to experiment, both CFD predictions and experimental test results are shown in Fig. 15 and Fig. 17 (Annex A). Each of the data points in the figures depicts the mean experimental velocity at a point for a discrete test. The solid lines in the figures indicate expected velocities predicted from CFD calculations. Figure 15 shows the variation of all blending times with respect to CFD predictions, and Figure A5 shows the variation of the mean blending time compared to CFD predictions.

The dotted lines in Fig. 15 provide a relationship between experimentally measured velocities and CFD results. For a 95% confidence level for 95% blending times, the variation between CFD predictions and the full range of experimental velocities varied by a factor of 1.56, where this large velocity variance is consistent with observations.

From this data, a single velocity correction factor, C_V, was determined to be applicable to CFD models of tanks with or without coils at either pilot scale or full scale, where

$$C_V = 1.56 \qquad (1)$$

Instrumentation uncertainties and the velocity oscillations at discrete points in the tank were also considered, and those effects changed the velocity correction factor from 1.554 to 1.556, which indicated a negligible effect of instrumentation uncertainty on velocity measurements.

ANALYSIS AND CFD RESULTS FOR BLENDING OF SIMILAR SOLUTIONS

A typical set of blending time data is shown in Fig. 18, and a summary of test results is shown in Fig. 20 (Annex A), where additional data are available (Leishear et al. [2]). To estimate a scaling factor for blending, the statistical discussion provided in Appendix A (Leishear, et al. [2]) needs to be related to experimental data. To do so, Fig. 19 provides two different variabilties for consideration, and one must be selected based on the nature of the tests performed. The typically larger variability (square symbol, UTL, upper tolerance limit for individual probes) provides a bound of values that would be predicted with 95% confidence if a single probe were installed in the tank to measure the blending time. This higher variability would only be used for evaluation of a single probe installed in a tank to measure a blending time. The typically lower variability (diamond symbol, UTL on mean blend time) provides the bound at 95% confidence for predicted blending times for a set of tests. This latter variability is appropriately applied to test groups. In short, predicted CFD values are within 20 – 80% of the average experimental values (cross symbol, grand average of blend times), but the predicted variation in blending times is even larger due to experimental variations in blending times.

To establish an experimental correction factor for CFD models, Fig. 19 bears further scrutiny. Test sets {20, 21} and {32, 37} are discounted, since insufficient data points yielded questionable blending time predictions with very high resultant uncertainties. The rest of the data sets are pertinent to a correction factor.

Reviewing Fig. 19 (Annex A), the largest UTL data variance is shown to occur for test set {41-44}, which was the upper limiting case from available CFD modeling. For this data set, a preliminary pilot scale blending correction factor equals

$$\text{UTL/CFD blend time} = 28.33/10.73 = 2.64 \qquad (2)$$

which may seem large, but the 2.64 correction factor provides a reasonable estimate at a 95% confidence level to correct CFD models at pilot scale. This correction factor is based on experimental variation in pilot scale test data. The underlying physical explanation of this wide scatter in data was not fully investigated, since hundreds of additional experiments would have been required. Even so, experiments were carefully conducted to ensure that experimental results were consistent from test to test. Statistical analysis of experimental data was used to describe the complexities of chaotic blending processes and obtain a correction factor to be applied to CFD models.

Blending data are unavailable at full scale for all cases of concern, and Equation 2 is reconsidered, along with the velocity correction factor of 1.56 (Equation 1). Since the blend time is inversely proportional with respect to velocity, the velocity correction should also be inversely proportional with respect to blend time. Then the variability of blending times can be determined by multiplying to obtain a CFD blending time correction factor, C_f, where C_f = 1 plus the uncertainty equals

$$C_f = 1 + \sqrt{0.56^2 + 1.64^2} = 2.73 \qquad (3)$$

The terms in the radical are the variabilities, or mathematical uncertainties, of the velocities and blending times. The total uncertainty is calculated as the square root of the sum of the squares of the individual uncertainties, as discussed by Coleman and Steele [8].The velocity term, C_V, may, or may not be applicable to scale-up, but it conservatively increases the correction factor by only a few percent, and is therefore included in the CFD correction factor, C_f. Blending times are proportional to velocity in the tank, and a variability associated with the velocity is assumed to scale-up linearly as well. In that case, a CFD correction factor of 2.73 seems justified for scale-up of CFD blending calculations. That is, when a CFD model predicts a blending time for a tank with coils installed, that blending time needs to be multiplied by 2.73 to predict the probable maximum blending time that may occur.

Similarly, for a tank without coils, an optional correction factor equals 2.10 for a 94% maximum variation in blending times observed during tests without coils. The CFD blending time correction factor for a tank without coils equals

$$C_f = 1 + \sqrt{0.56^2 + 0.94^2} = 2.10 \qquad (4)$$

CONCLUSIONS

Correction factors were determined for CFD blending models for blending of tanks using dual opposing nozzles with or without coil obstructions installed. CFD blending time correction factors are not due to experimental error, but are a factor required to account for expected variations in blending times. Further research may improve the prediction of this value for a correction factor, but the need for a correction factor has been clearly demonstrated. In fact, the correction factors developed from this research are a significant advance to blending theory. CFD correction factors may be multiplied times blending times predicted by CFD models to predict a estimate of the upper limit for the time required to homogeneously blend miscible liquids in a tank. The factors provided in this research are considered to be applicable throughout typical operating ranges of interest, but at low pump flow rates (low values of *UoD*), these factors may be larger. Specifically, applications of the correction factors are limited as follows:

1. For a tank with coils installed and dual nozzles, the CFD correction factor equals 2.66 = C_f for *UoD* > 0.47 feet^2/second.
2. For a tank without coils installed and dual nozzles, the CFD correction factor equals 2.10= C_f for *UoD* > 0.33 feet^2/second.

ACKNOWLEDGMENTS

This research was performed per SRR direction of Keith Harp, Program Manager, Bill Van Pelt, Project Engineering Manager, Ken Parkinson, Lead Engineer, and Bob Ervin, Engineer, who each provided technical requirements and project leadership for this research.

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ANNEX A: TEST RESULTS

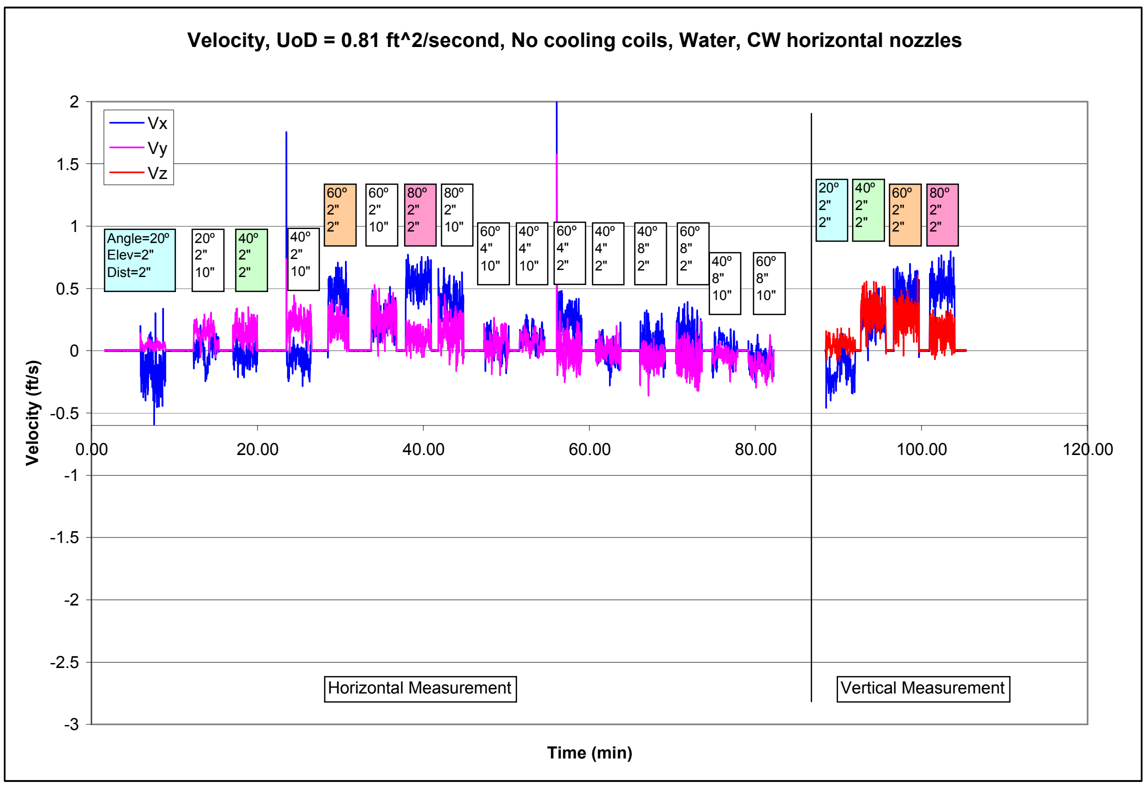


Figure 13: Typical Measured Pilot Scale Velocities (x and y directions)

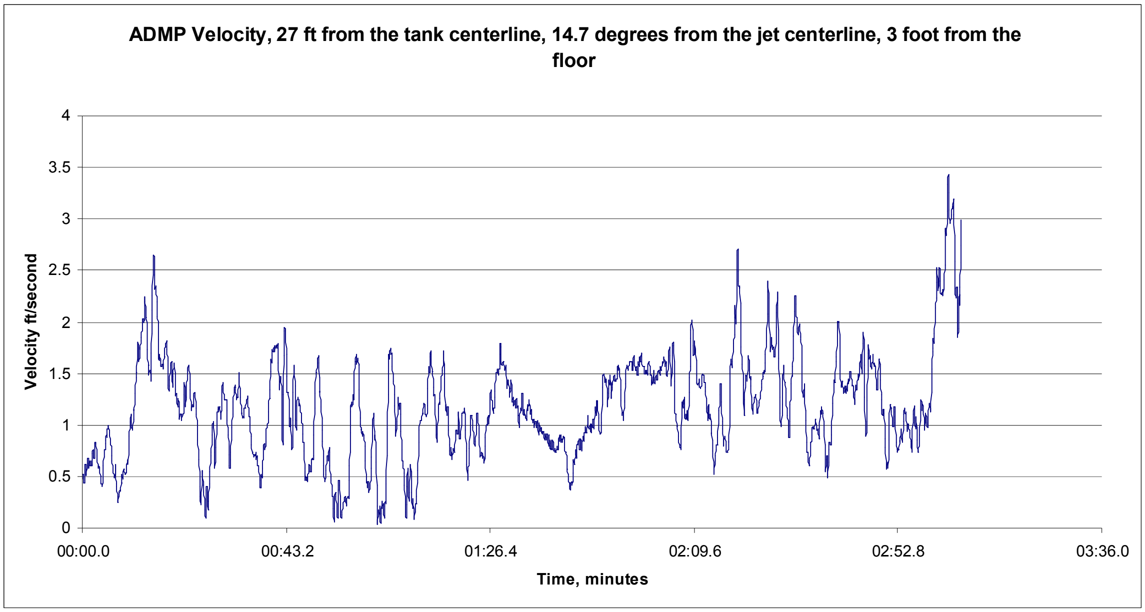
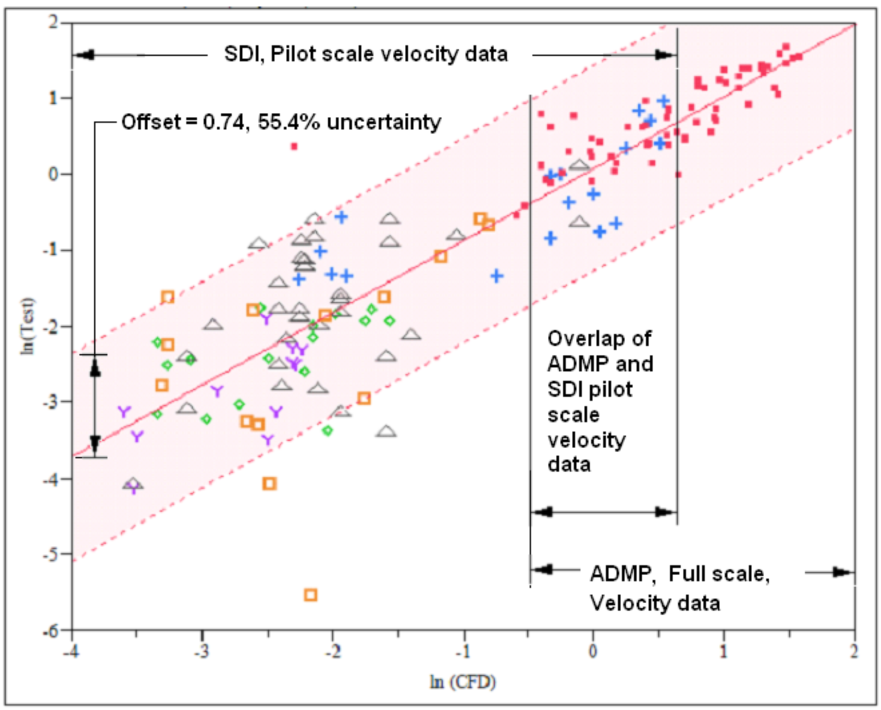


Figure 14: Typical ADMP, Resultant Velocity Measurement



	Test Description	Test Conditions	Scale	Type of Test
1	Full Scale, No Coils	UoD = 29.4 ft^2/sec; water; no coils	Full	ADMP
2	Pilot Scale, Coils	UoD= 0.70 ft^2/sec; salt solution; coils; 15 degree upward nozz	Pilot	Case 12a
3	Pilot Scale, No Coils	UoD = 0.58 ft^2/sec; salt solution; no coils; 15 degree upward	Pilot	Case 11a
4	Pilot Scale, No Coils	UoD = 0.58 ft^2/sec; salt solution; no coils; 15 degree upward	Pilot	Case 11b
5	Pilot Scale, No Coils	UoD = 0.81 ft^2/sec; salt solution, no coils, tee nozzle	Pilot	Case 2
6	Pilot Scale, No Coils	UoD = 0.81 ft^2/sec; water; no coils; tee nozzle	Pilot	Case 1

Figure 15: Mean Velocity for Full Scale and Pilot Scale Data (T. Edwards)

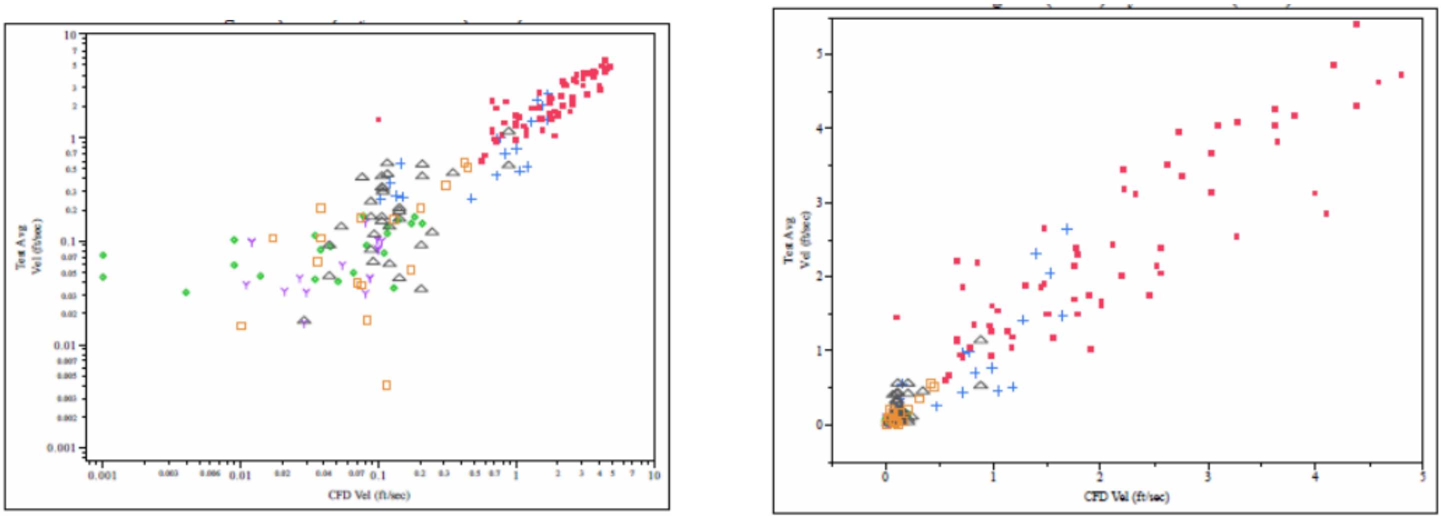


Figure 16: All Mean Velocity Data (T. Edwards)

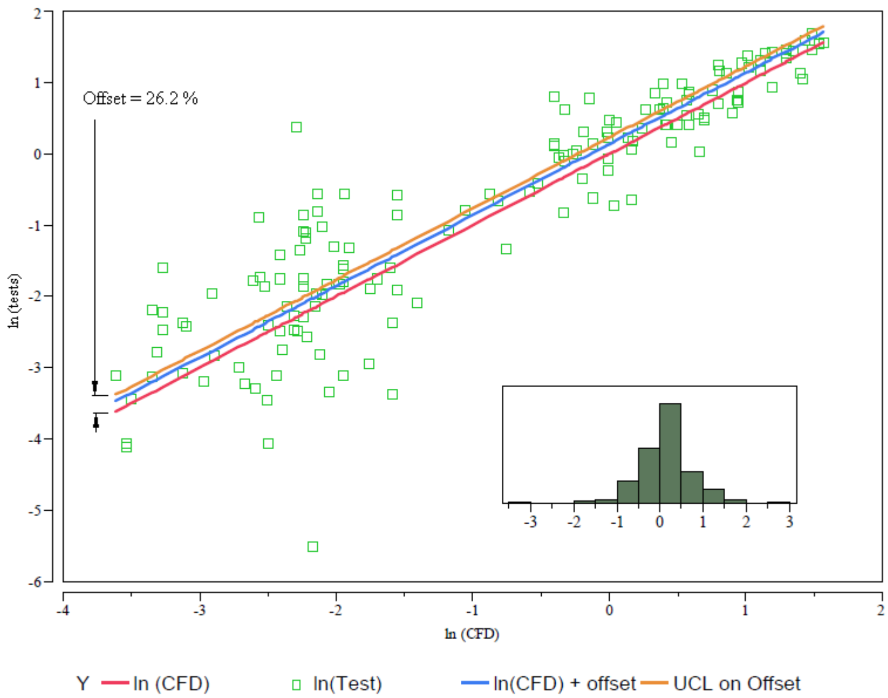


Figure 17: Variation of Experimental Mean Velocities Compared to CFD Velocities (T. Edwards)

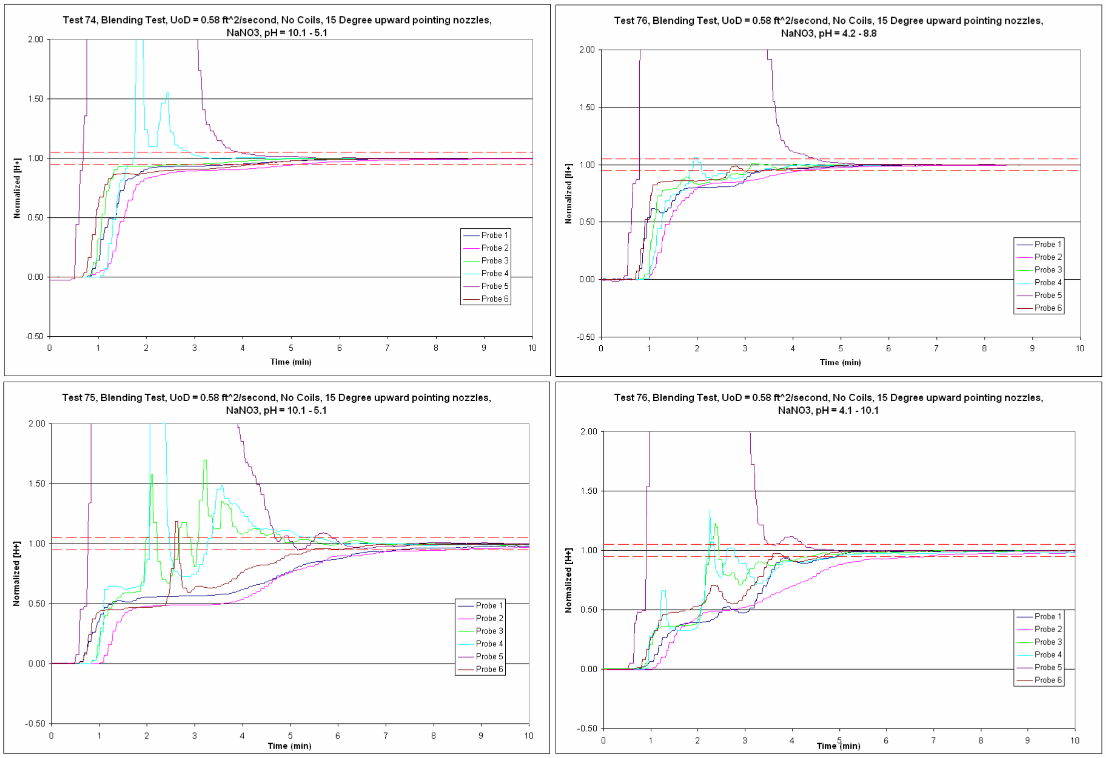


Figure 18: Typical Set of Blending Time Data

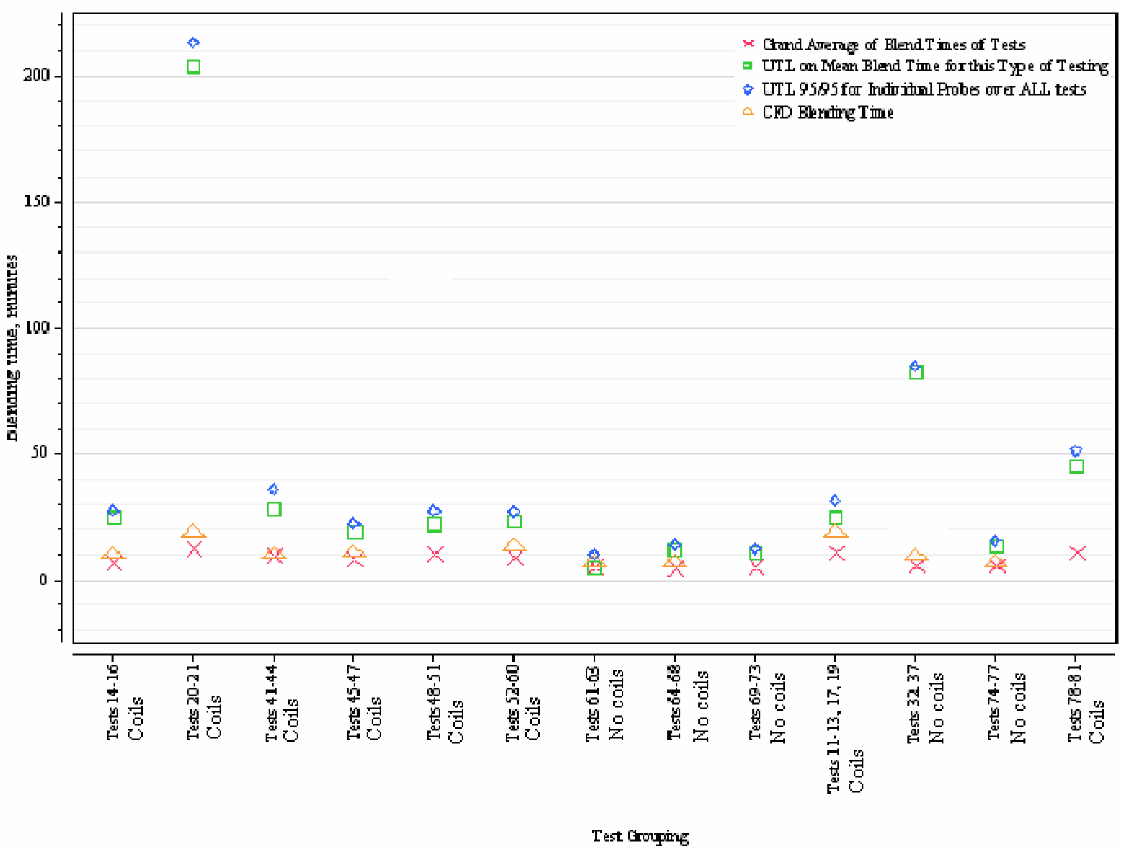


Figure 19: Data Analysis (T. Edwards)

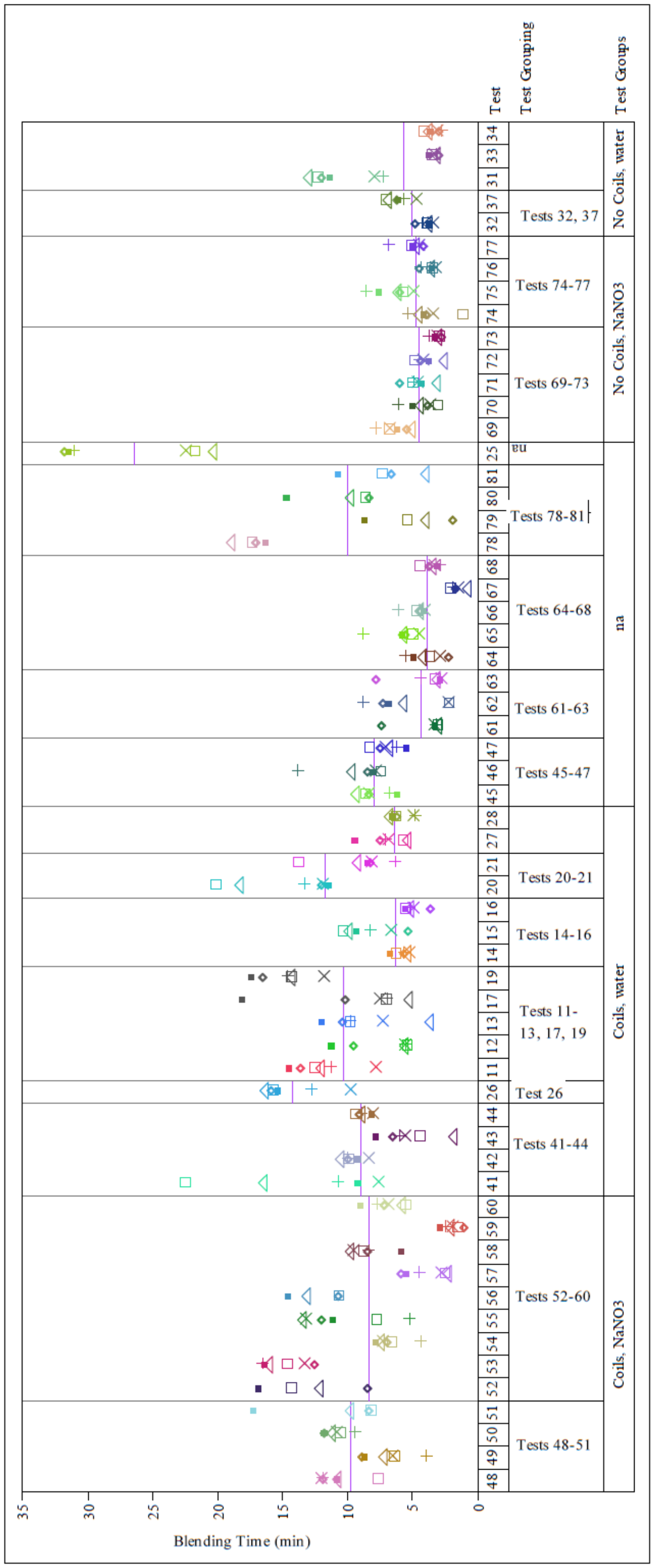


Figure 20: Summary of Blending Test Results (T. Edwards)