PNWD-3273
WTP-RPT-077 Rev. 0

Demonstration of Ability to Mix in a Small-Scale Pulsed-Jet Mixer Test Facility

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April 2003

WTP
Project
Report

Battelle – Pacific Northwest Division
Richland, Washington, 99352

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under Contract 24590-101-TSA-W000-0004

Test Specification: 24590-WTP-TSP-RT-01-022 Rev. 0
Test Plan: TP-RPP-WTP-160 Rev. 0
Test Exceptions: 24590-WTP-TEF-RT-02-058
R&T Focus Area: Pretreatment
Test Scoping Statement(s): B56

Battelle – Pacific Northwest Division
Richland, Washington 99352

Completeness of Testing

This report describes the results of work and testing specified by Test Specification 24590-WTP-TSP-RT-01-022 Rev. 0 and Test Plan TP-RPP-WTP-160 Rev. 0. The work and any associated testing followed the quality assurance requirements outlined in the Test Specification/Plan. The descriptions provided in this test report are an accurate account of both the conduct of the work and the data collected. Test plan results are reported. Also reported are any unusual or anomalous occurrences that are different from expected results. The test results and this report have been reviewed and verified.

Approved:

Gordon Beeman, Manager WTP R&T Support Project	Date
Research and Technology Manager	Date

Summary of Testing

This report documents the results of small-scale pulsed-jet mixer (SS-PJM) testing focused on addressing several issues associated with the effectiveness of the PJMs in the baseline design of strontium/transuranic (Sr/TRU) precipitation and sludge-washing processes in the U.S. Department of Energy (DOE) River Protection Project (RPP) Waste Treatment Plant (WTP). Section 5 of the Research and Technology Plan (BNI 2002) identifies the research needs for pulsed jet mixers. The tests (demonstrate ability to mix) are also addressed in Scoping statement B-56, which is included in Appendix C of the Research and Technology Plan.

Objectives

The objectives of the tests were to determine the following:

1. Influence of a density gradient on the mixer performance
2. Mixing time of liquids of dissimilar densities
3. Optimum mode of addition of reactants
4. Cycle frequency to achieve best mixing performance
5. Operating volume, pressure and vacuum optimum range to minimize air entrainment
6. Validation of the TEMPEST CFD model of the PJMs using the data generated in the small tank
7. Recommendations on what follow-on tests should be performed, if any, to assess the impact of chemical reactions on the fluid properties.

Conduct of Testing

The design of the test matrix for the SS-PJM experiments was grounded in applying the specific energy (energy/volume) of proposed full-scale PJM designs to solutions that closely simulate the density of the waste in the full-scale PJM tanks (~1.3 specific gravity [SG]) and the density of the reagent to be added (~1.0 SG). Tank and pulse-tube dimensions from the full-scale evaporator concentrate buffer-vessel PJM were used in conjunction with compressor-performance projections for cycle times to derive the specific energy targets for the SS-PJM test series[1]. Preliminary mixing tests indicated that specific energy ratios less than 1.0 would not produce acceptable mixing in the requisite one-hour time interval (at small scale). This resulted in a modification of the original Test Matrix, which had specific energy ratios ranging from 24 to 0.2 (Test Exception 24590-WTP-TEF-RT-02-058). Experiments were performed at specific energy targets at the plant design target specific energy and at ratios of 3, 5, and 14 times the design-target specific energy. Simulations were performed using the TEMPEST CFD model to validate model performance and the ability to predict mixing performance in full-scale PJMs. (As of the issue date of this report, TEMPEST is not a currently-approved software package for project use).

[1] Note: The design information regarding the PJMs dimensions in the evaporator concentrate buffer vessel provided by BNI at the time of planning of the small tank experiments are no longer valid since the current design calls for a 4 in nozzle as opposed to the 5 in nozzle diameter used in the energy/volume calculations.

Results and Performance Against Objectives

A mixing time criterion of one hour or less (at SS-PJM scale) was derived from pilot-scale experiments at the Savannah River Site (SRS). Experiments in the SS-PJM that were performed at the plant design-target specific energy did not produce acceptable mixing even within 90 minutes. (At small scale, all reagent was added in a static layer prior to test commencement to preclude scaling issues related to reagent addition unduly influencing test outcomes). Mixing time was reduced to 40 minutes at three times the design-target specific energy; experiments at 5 and 14 times the design-target specific energy produced mixing times of 33 minutes and 15 minutes, respectively. ***Although the small tank experiments indicate acceptable to good mixing at three times or higher multiples of the design energy/volume conditions, extreme caution must be exercised in using this data to predict full scale performance due to complexities associated with scaling pulsed jet mixers.***

Objective 2 above was fully achieved, and Objectives 1, 4, and 7 were partially achieved. Objective 3 was addressed insofar as the static bulk addition was a conservative condition for the top-addition (reagent) configuration. No parametric study was performed of air entrainment (Objective 5) because during the review of the Test Plan (TP-RPP-WTP-160 Rev. 0) this objective was considered to be out-of-scope for the SS-PJM test series. Validation of the TEMPEST CFD model (Objective 6) was attempted, but results were inconclusive. Significant modifications to the code would be necessary to produce satisfactory results. Because the SS-PJM is not geometrically and kinematically similar to the prototype PJM, it was concluded that the level of effort required to modify the code was not justified.

QA Requirements

Battelle – Pacific Northwest Division (PNWD) implemented the RPP-WTP quality requirements by performing work in accordance with the quality assurance project plan (QAPjP) approved by the RPP-WTP Quality Assurance (QA) organization. This work was conducted to the quality requirements of NQA-1-1989 and NQA-2a-1990, Part 2.7 as instituted through PNWD's Waste Treatment Plant Support Project Quality Assurance Requirements and Description (WTPSP) Manual.

PNWD addressed verification activities by conducting an independent technical review of the final data report in accordance with procedure QA-RPP-WTP-604. This review verified that the reported results were traceable, that inferences and conclusions were soundly based, and the reported work satisfied the Test Plan objectives.

Issues

The design-target specific energy of 9.21 x 10-5 hp/gal did not produce an acceptable level of mixing within 90 minutes. The criterion developed by mixing experiments at SRS required mixing to be completely accomplished within 60 minutes at SS-PJM scale. Finally, it is strongly recommended that mixing tests with a prototypical or near prototypical mixing vessel/PJMs/reagent/simulant be conducted to assess the PJM performance.

Terms and Abbreviations

APEL	Advanced Process Engineering Laboratory
BNI	Bechtel National Inc.
CFD	Computational Fluid Dynamics
DACS	Data Acquisition and Control Software
DOE	U. S. Department of Energy
JPP	Jet Pump Pair
PJM	Pulse Jet Mixer
PNWD	Battelle – Pacific Northwest Division
PVC	Polyvinyl chloride
RPP	River Protection Project
SRS	Savannah River Site
SS-PJM	Small-Scale Pulse-Jet Mixer
TEMPEST	Transient Energy Momentum and Pressure Equations Solutions in Three Dimensions (computational fluid dynamics code)
WTP	Waste Treatment Plant

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1.0 Introduction

1.1 Background

The current design of the River Protection Project Waste Treatment Plant (RPP-WTP) process system includes several hundred pulsed jet mixers (PJMs) in various unit operations throughout the plant. PJMs consist of several pulse tubes (large cylindrical tubes with one end tapered to a nozzle) that are connected to an air/vacuum line. These pulse tubes project vertically into the mixing vessel and are operated either in series or in parallel to accomplish the desired mixing.

Figure 1.1 illustrates PJM operation in a single pulse-tube system. The PJM cycle consists of a fill phase (where slurry is withdrawn from the mixing vessel into the pulse tube by application of a vacuum) and a drive phase (where slurry is ejected back into the mixing vessel under pressure). This cycle is repeated until the tank contents are adequately mixed. The fill (vacuum) and drive (pressure) phases of the PJMs are regulated by jet pump pairs (JPPs) driven by compressed air.

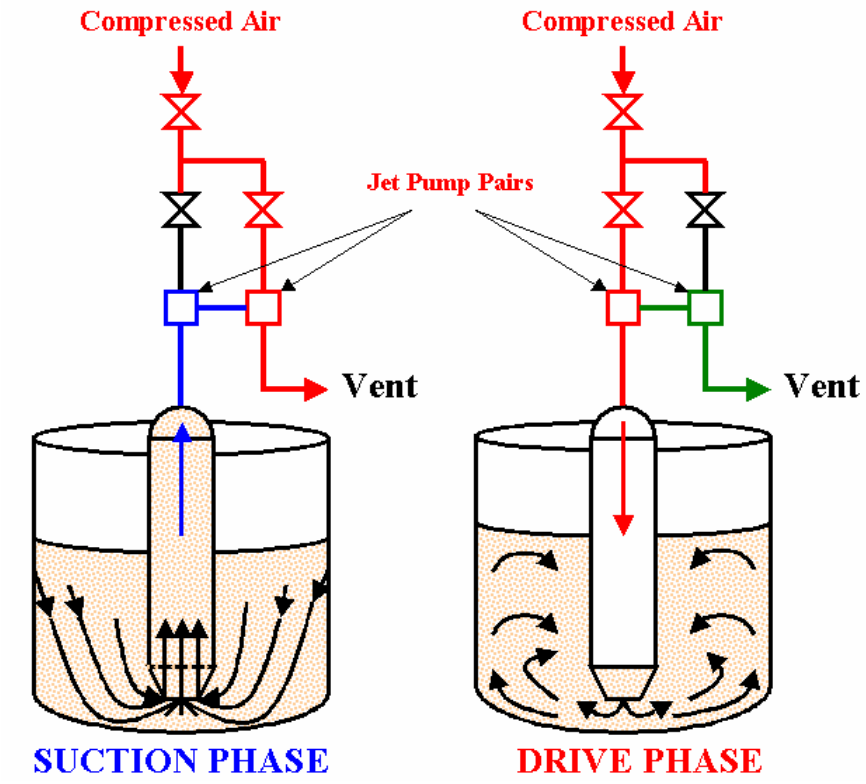

Figure 1.1. Schematic of a Typical PJM Operation

In FY 2001, Battelle – Pacific Northwest Division (PNWD) was tasked to develop and validate a model of the PJM system using the in-house TEMPEST (Transient Energy Momentum and Pressure Equation Solutions in Three Dimensions) computational fluid dynamics (CFD) code. TEMPEST was chosen over other commercially available CFD codes because of its demonstrated ability to model the complex multiphase fluid-flow behavior encountered with Hanford high-level tank waste.

During FY 2001/02, testing was done to generate small-tank hydrodynamic (water only) data for the TEMPEST model of the PJM system using the small-scale pulsed jet mixer (SS-PJM) test system in the Applied Process Engineering Laboratory (APEL) high-bay area. The results of these experiments are provided in the report, WTP-RPT-061 Rev 0, *Development and Validation of the TEMPEST CFD Model of the Pulsed Jet Mixing Systems*.

The current series of experiments was conducted using the same experimental systems to evaluate the applicability of PJMs to mix solutions of different densities and to generate density gradient data for computer model validation.

1.2 Goals and Objectives

Various unit operations of the RPP-WTP project require sufficient mixing to ensure that particulates are suspended in solution, mixed at a given target rate, or completely homogenized.

The objectives of the current work involve evaluating the applicability of PJMs to mix solutions of different densities and to generate density gradient data for CFD validation. In these experiments, a low-density reagent liquid (water at specific gravity (SG) ~0.99) was carefully introduced into the SS-PJM tank on top of an inventory of a high-density waste-simulant liquid (sodium thiosulfate solution with SG of ~1.31). The transient fluid densities at three locations in the tank were then measured at different operating conditions of the mixer. All experiments employed a video camera for flow/mixing visualization.

In addition to the SS-PJM tests, simulations were intended to be performed using the TEMPEST CFD model of the PJM system to:

1. Validate the model using the data from at least one SS-PJM test-data set.
2. Predict PJM performance in the plant-scale vessel.

This report documents the results of small-scale pulsed-jet mixer (SS-PJM) testing focused on addressing several issues associated with the effectiveness of the PJMs in the baseline design of strontium/transuranic (Sr/TRU) precipitation and sludge-washing processes in the U.S. Department of Energy (DOE) RPP-WTP. Section 5 of the Research and Technology Plan (BNI 2002) identifies the research needs for pulsed jet mixers. The tests (demonstrate ability to mix) are also addressed in Scoping statement B-56, which is included in Appendix C of the Research and Technology Plan.

Section 2 presents the test conditions and calculations. Testing procedures are explained in Section 3, and results are presented in Section 4. Section 5 describes the modeling with the TEMPEST code. Conclusions are presented in Section 6, and details of specific energy calculations are included in the appendix.

2.0 Test Formulation

2.1 Specific Energy Calculations

The test matrix for the SS-PJM experiments was designed for applying the specific energy (energy/volume) of proposed full-scale PJM designs to solutions that closely simulate the density of the waste in the full-scale PJM tanks (~1.3 SG) and the density of the reagent to be added (~1.0 SG). Tank and pulse-tube dimensions from the full-scale evaporator concentrate buffer-vessel PJM were used in conjunction with compressor-performance projections for cycle times to derive the specific energy targets for the SS-PJM test series (dimensions and calculations may be found in the appendix). The target specific energy (9.21×10^{-5} hp/gal) for a 52,100-gallon vessel was based on eight pulse tubes receiving a 19-second pulse during a 77-second total cycle time, producing an average exit velocity of 19.8 ft/sec and assuming a fluid SG of 1.3. Total simulant/reagent quantities were based on a tank fill-height/ diameter ratio of unity (H/D = 1). Applying this ratio to SS-PJM dimensions gives a total fill volume of 132 gallons.

While the full-scale design specified a top-of-tank reagent addition method, SS-PJM experiments showed that the mixing effect from this method of reagent addition at *small-scale* would significantly impact test results. Instead, a static layer of reagent was introduced on the simulant surface before initiating the test. This produced a test configuration that was conservative with respect to actual plant mixing conditions, in that no mixing effect was produced by the addition of reagent.

2.2 Preliminary Test Conditions

The experimental conditions initially set for this test series had specific energy ratios ranging from 24 to 0.2. Preliminary mixing tests using the SS-PJM indicated that the lower specific-energy bounds were unlikely to produce an acceptable level of mixing in the requisite <1-hour time interval derived from pilot-scale tests at the Savannah River Site (SRS). Furthermore, drive times to produce the higher specific energy ratios would be too short (<1 sec) to be reasonably achieved using the SS-PJM as currently constructed. These factors were taken into account in the design of the revised test matrix for the SS-PJM test series.

A preliminary test at a specific energy ratio of 1 was carried out using the sample-loop recycle tank described in Section 3.2. A mixing time of approximately one hour was observed. The three sample loops drained the mixer-tank contents at ~0.15 gpm (3 x 0.05 gpm) into a recycle tank and reduced the mixer-tank solution volume by approximately 12 gallons (the amount of reagent simulant added) over the ~1-hour time-span of the test. (Two subsequent tests at the same specific energy produced mixing times of longer than 93 minutes, illustrating the significant impact the solution withdrawal had on mixing performance by lowering the liquid-layer interface and increasing the energy deposition from pulse-tube operation). All tests in the revised test matrix were carried out using a sample return-tube assembly that returned the sample-loop contents to the mixer tank at the same elevations as the sampling intakes.

2.3 Final Test Conditions

The revised test matrix employed in this test series is given in Table 2.1. The highest specific energy ratio is within the capabilities of the SS-PJM as currently constructed, and the lowest specific energy ratio is a reasonable lower bound given the mixing performance expected. The test plan (TP-RPP-WTP-160 Rev. 0) details the testing procedures using aqueous sodium thiosulfate solutions in the SS-PJM system.

Table 2.1. Operating Conditions for Small-Scale PJM Testing

Test	Specific Energy Ratio[(a)]	Drive/Refill Phase Duration	Total Cycle Time
1	~1	5-sec drive/22-sec refill	27 sec
2	~14	2-sec drive /10-sec refill	12 sec
3	~5	3-sec drive /12-sec refill	15-sec
4	~3	3-sec drive /22-sec refill	25-sec
(a) Ratio of the specific energy of the test to that of actual plant conditions.			

3.0 Experimental Approach

3.1 Small-Scale PJM Design

The simulants used in the small-scale PJM (SS-PJM) system are a 50 wt% solution of sodium thiosulfate pentahydrate that simulates the dense waste solution (SG ~1.31) in the full-scale waste tank. The less-dense reagent is simulated by process water (SG ~1.00). It was planned to use a ring-shaped reagent addition manifold and pump/rotameter combination to simulate reagent introduction to the SS-PJM at controlled flow rates, but preliminary experiments showed the gravitationally induced mixing (reagent impacting the salt solution surface) produced by this method was greater than was desirable for this test series. Instead, the tests were carried out by slowly introducing the requisite amount of process water (~12 gal) onto the surface of the thiosulfate solution through a feed-tube/deflector-plate assembly that minimized vertical impingement velocity and produced distinct, stagnant layers of waste and reagent simulant prior to initiation of mixing tests.

The SS-PJM test facility is installed in the Battelle area of the APEL high bay and includes the following equipment (shown in Figure 3.1):

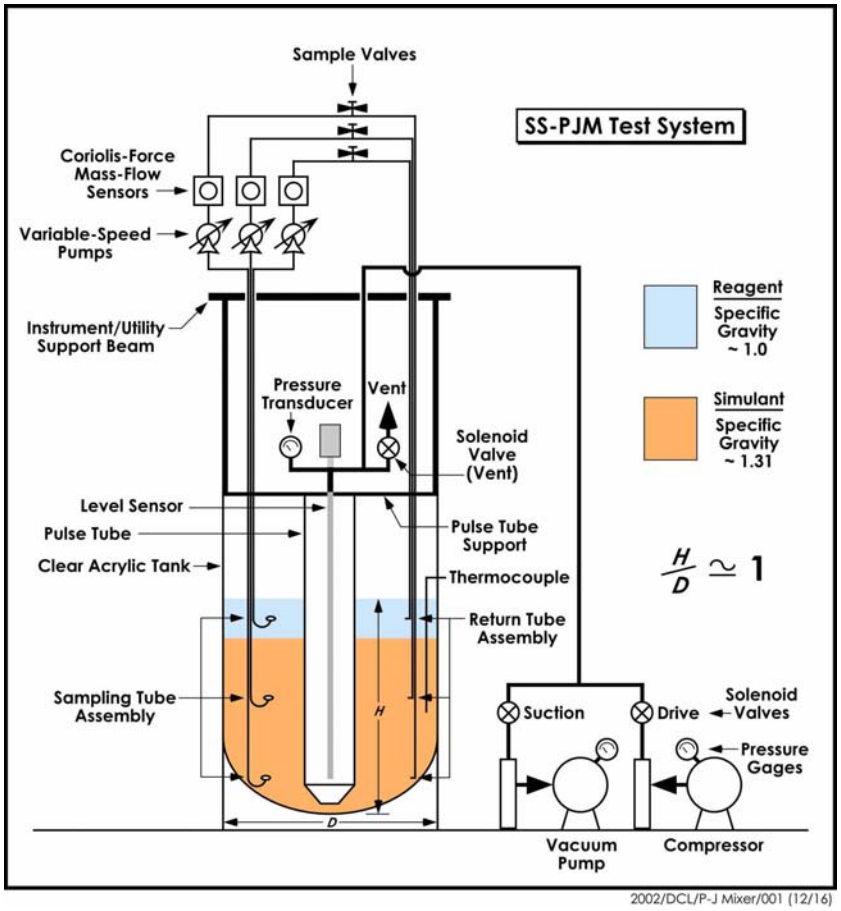

Figure 3.1. Schematic of the SS-PJM Test System in the APEL High-Bay Area

1. A 3-ft inner-diameter (ID) x 7-ft (h) dish-bottomed mixer tank made of clear acrylic plastic (Plexiglas); the bottom is of semi-elliptical cross-section (2:1 ellipse).
2. A 10-in.-ID, 4-ft-long clear acrylic plastic pulse tube with a 60^{o} cone at the bottom centrally mounted within the tank. The mounting brackets permit both vertical and lateral adjustment of pulse-tube nozzle position. (The tank/pulse-tube assembly is shown schematically in Figure 3.1.) A capacitance-level probe assembly (AMTEK/Drexelbrook model 408-8200) is mounted on top of the pulse tube to measure the fill and discharge height of liquid in the pulse tube, and a strain-gauge pressure transducer (Omega PX series) is co-mounted with the capacitance probe to monitor pulse-tube air pressure.
3. A compressor/vacuum/receiver-tank system supplies the pressurized air and vacuum required through a control manifold and solenoid-actuated valves. A 35-CFM, 100-psig compressor supplies air for the drive phase of system operation; the air pressure is regulated to ~20-psig or less to achieve the desired drive conditions. A vacuum pump (capable of ~28 in. Hg) and volume enhancing receiver tank are used for the suction phase of PJM operation. (A liquid trap is located between the vacuum pump and receiver tank). Wire-reinforced 1½-in. PVC tubing (vacuum capable; maximum operating pressure of 100 psig) is used to connect the control manifold to the pulse tube, compressor tank, and vacuum-pump receiver tank. The tubing rises to a height of 25 ft over the SS-PJM tank (suspended from an attachment point on the scaffold structure) to prevent liquid crossover to the vacuum pump from condensate in the pulse tube. The pulse-tube exhaust is vented through 1½-in. PVC tubing into a vented carboy container covered by a plastic barrel to trap droplets of solution that might be entrained in the pulse-tube exhaust.
4. A data acquisition and control system (DACS) computer (with control logic program and Strawberry Tree 5.2 data acquisition and control program installed) controls the drive, suction, and vent phases of SS-PJM operation by delivering control signals for sequential operation of the appropriate solenoid valves. It also performs system monitoring and data acquisition tasks.
5. An array of holding tanks for transfer and disposal of wastewater from the tests. (These tanks are located outside the test area. The test solutions were pumped out of the mixer tank into the holding tanks as necessary.)
6. Scaffolding to access the pulse-tube assembly and associated instrumentation.
7. A 12-gallon process-water tank with discharge-control valve is mounted on the scaffold to facilitate control of simulated reagent introduction; a feed-tube/deflector plate assembly minimized gravitational mixing caused by vertical impingement velocity of the reagent feed.

Figure 3.2 is a photograph of the SS-PJM test facility. To the right of the mixer tank is the compressor (background, with large horizontal tank) and vacuum receiver tank (smaller horizontal tank). The exhaust line is supported from the top of scaffold structure, and the tank drain line is in the foreground.

Figure 3.2. The Small-Scale PJM Test Facility

3.2 Instrumentation and Measurements

The simulant/reagent density was the primary parameter measured as an indicator of fractional mixing completion. Three MicroMotion model CMF010N Coriolis-type mass flow meters in three sampling loops provided density and sampling-loop flow data. The inlets for sampling loops were located approximately 10, 22, and 34 in. above the tank bottom. Sampling-loop return lines originally fed into a recycle tank, but the simulant volume reduction over the time span of an average test (approximately 10% of the initial waste-simulant volume) prompted fabrication of a return-tube assembly that re-injected solution into the tank at approximately the same elevation as the sampling inlets (Figure 3.1). This eliminated the need for a recycling tank. Flow in the sampling loops was set at a target rate of 0.05 gpm (via IDEX series 120 GJ-N23 variable-flow micropumps) to minimize any extraneous mixing effects, and large-diameter inlet/outlet ports on the sampling and return manifolds were used to minimize sampling-loop entrance/exit velocities. Tee fittings and valves were fitted to each sampling loop to enable archival grab samples (approximately 100 mL) to be taken for gravimetric confirmation of liquid specific gravities. Data on density, pulse-tube liquid level height, pulse-tube air pressure, and solution temperature were input to the Strawberry Tree software on the DACS computer.

Liquid levels in the pulse tube were measured to verify energy input and cycle stability. An AMTEK/ Drexelbrook model 408-8200 capacitance level probe extended 4 ft down into the center of the pulse tube from the upper bulkhead and provided liquid-level data. The on-board signal processor averages outputs to a minimum of 0.5 seconds, which is too long a window for the liquid level changes in the SS-PJM application, so the raw probe response data (response time of 20 msec) was captured from the level probe electronics (with guidance from the instrument vendor) and recorded to the DACS. Air pressure in the pulse tube was measured by a strain-gauge-type pressure transducer (Omega PX series) located on a tee connection off the capacitance probe mounting assembly on top of the pulse tube (see Figure 3.1).

Simulant solution temperature was measured by a 40-in. Omega type K metal-sheathed thermocouple probe placed along the inner wall of the tank. Standard Bourdon-tube pressure and vacuum gauges were used to indicate air pressure in the compressor tank, at the pressure regulator, and at the vacuum receiver tank for tuning the PJM operations.

3.3 Data Acquisition

The Strawberry Tree software on the DACS computer recorded six channels of drive function data and six channels of solution properties at a 10 Hz sampling rate (see Table 3.1).

Table 3.1. Data Acquisition Matrix

Drive Function Data	**Solution Property Data**
Time Stamp	Density (10 in. above tank bottom[a])
Level Probe (mA)	Sample loop flow (10 in. above tank bottom[a])
Level Probe (inches via transfer function)	Density (22 in. above tank bottom[a])
Pulse-Tube Air Pressure	Sample loop flow (22 in. above tank bottom[a])
Temperature	Density (34 in. above tank bottom[a])
Drive Solenoid Status (on/off)	Sample loop flow (34 in. above tank bottom[a])
[a]Note that tank bottom is 8.75 inches below cylindrical section at center of pulse tube.	

Data-acquisition instruments underwent performance checks before each test. Performance-check procedures are detailed in the Test Procedure (TPR-RPP-WTP-178 Rev. A).

Grab samples were taken from the three pump-driven sample loops at nominal 10-minute intervals during mixing tests and archived for eventual specific gravity measurements. Sampling intervals were adjusted for expected total mixing times at different specific energy levels. A time-stamped digital videotape of each test was recorded that shows the behavior of the density interface between the simulated waste and reagent layers throughout the duration of the test.

3.4 Operating Procedure

Before each test began, the capacitance level probe and the three mass flow meters were performance checked, the PJM drive function parameters for the DACS system were set, and the SS-PJM operation was checked. The tank was filled to the 120-gallon level (tank H/D ~1.0) and thiosulfate concentration adjusted to produce a specific gravity of approximately 1.31. The scaffold-mounted reagent-simulant tank was filled with process water and slowly discharged through the feed-tube/deflector-plate assembly to produce a stagnant layer of approximately 1.0 SG floating on the thiosulfate solution. Measurements of the height of liquid layers in the tank were recorded along with drive cycle pressure. Sampling pumps were started and flow adjusted to a nominal 0.05 gpm rate; initial samples were then taken from the sampling loops. Data acquisition systems and digital video recording were then started and the drive cycle for the SS-PJM initiated. Data acquisition, sampling, and video recording were continued until mixing was complete or approximately 90 minutes had passed.

4.0 Experimental Results

Five tests were performed, two at the full-scale PJM design target energy (specific energy ratio of 1) and one each at specific energy ratios of 3, 5, and 14. Table 4.1 contains a summary of the test results.

Table 4.1. Summary of Test Results

Specific Energy Ratio	Specific Energy (hp/gal)	Drive/Refill Duration[a] (sec)	Initial SG Simulant	Final SG	Well-Mixed SG	Mixing Time (min)	Vol Simulant (gal)	Vol Reagent (gal)	Fill Ht[e] Simulant (in.)	Fill Ht[e] Reagent (in.)
1.01	9.26×10^{-5}	5 Dr/22 Ref	1.31	1.28[b]	1.28[c]	92[d]	~120	~12	23.5	26.6
1.01	9.26×10^{-5}	5 Dr/22 Ref	1.31	1.26[b]	1.23	94[d]	~96	~36	20.2	30.2
3.02	2.78×10^{-4}	3 Dr/22 Ref	1.30	1.22	1.22	40	~96	~36	20.2	30.1
5.03	4.63×10^{-4}	3 Dr/12 Ref	1.31	1.23	1.23	33	~96	~36	19.9	30.1
14.14	1.30×10^{-3}	2 Dr/10 Ref	1.31	1.23	1.23	15	~96	~36	19.9	29.6

(a) Drive/Refill – Dr/Ref.
(b) Variation in relative simulant/reagent volumes resulted in differing final SGs.
(c) Top sampling-tube position did not measure approx. 1 in. left unmixed in top layer at cessation of test.
(d) Test terminated before contents were fully mixed.
(e) Fill height above beginning of cylindrical section; tank bottom is 8.75 inches lower than cyl. section at tank center.

4.1 Specific Energy Ratio of 1

Two tests were performed at this specific energy, the first with all three sampling tubes in the simulant liquid layer at test commencement. The second test was carried out with the uppermost sampling tube in the reagent liquid layer at the beginning of the test (as were all other tests in the revised test matrix). This configuration is pictured in Figure 3.1. Although fill height was the same in both tests, reagent volumes were different: 12 gallons for the first test and 36 gallons for the second test (Table 4.1). The graphs of specific gravity (SG) versus time for the three mixer-tank elevations sampled show the three SG sampling locations ramping down in the first test (Figure 4.1) and the reagent layer SG ramping up as the SGs in the two lower sampling elevations decreased in the second test (Figure 4.2). Both tests were stopped after approximately 90 minutes; mixing was only partially complete at this time.

The vertical distribution of SG trends in tests starting with the uppermost sampling tube in the reagent layer (seen markedly in the top sampling position in Figure 4.2) is an artifact of the level change in the mixer tank due to pulse-tube fill/discharge cycling. Videotapes confirm that during the initial mixing phase, the interface between simulant and reagent layers oscillates above and below the inlet for the uppermost sampling tube. Pulse-tube cycle times were 5 seconds drive and 22 seconds refill for both tests. The difference in final SGs noted in Table 4.1 was due to the difference in initial quantities of simulant versus reagent (see Table 4.1 for initial conditions for these tests).

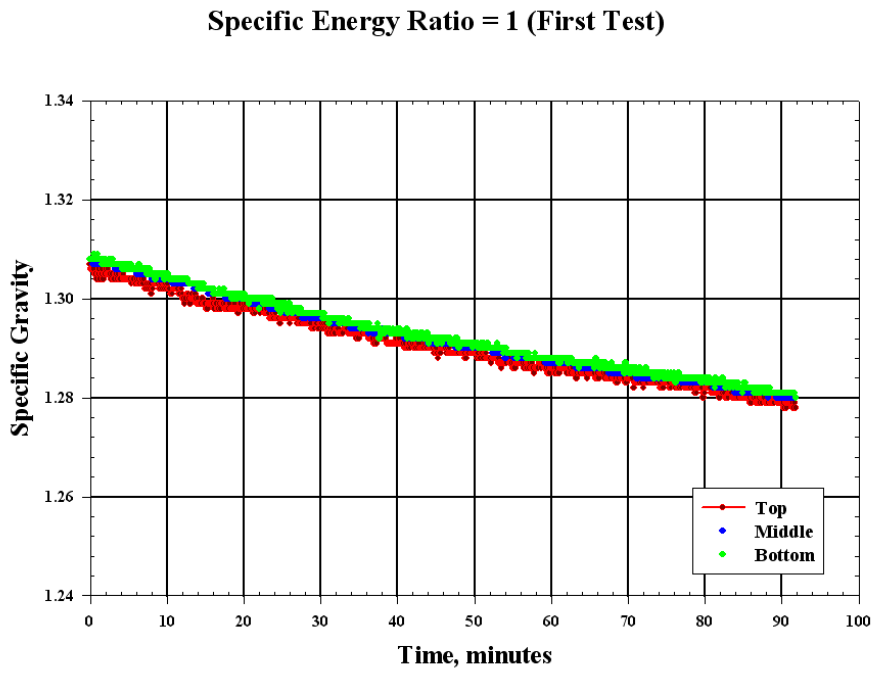

Figure 4.1. Specific Gravity Versus Time for Specific Energy Ratio of 1 (first test)

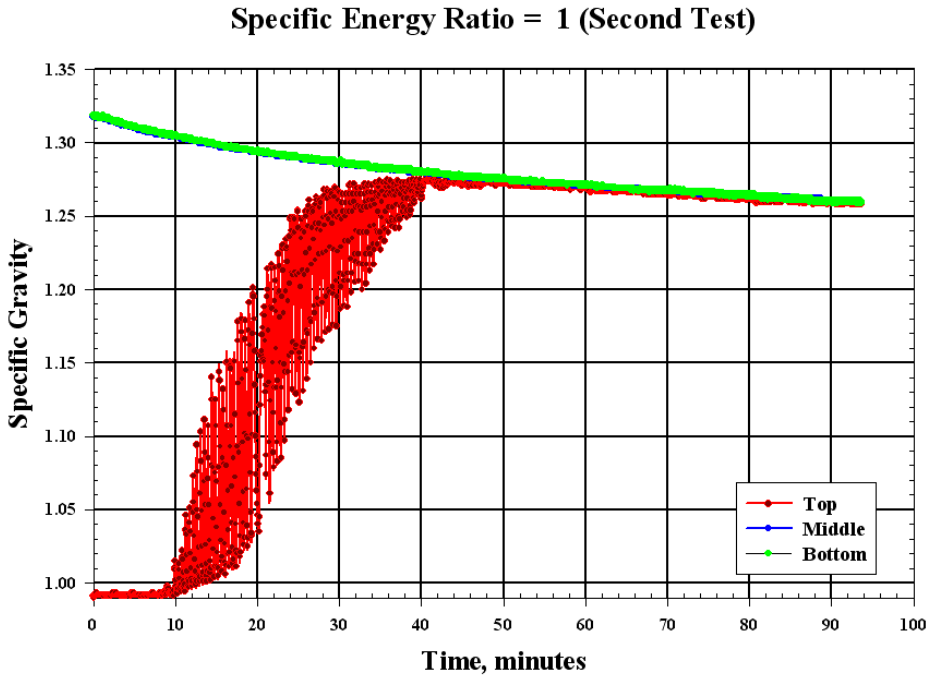

Figure 4.2. Specific Gravity Versus Time for Specific Energy Ratio of 1 (second test)

4.2 Specific Energy Ratio of 3

This test was carried out with the uppermost sampling tube in the reagent liquid layer at the beginning of the test (as were all other tests in the revised test matrix); concentration change was largely accomplished after 30 minutes. Pulse-tube cycle times were 3 seconds drive and 22 seconds refill. Total mixing time (visual equilibration of density gradients) at this specific energy was approximately 40 minutes (Figure 4.3).

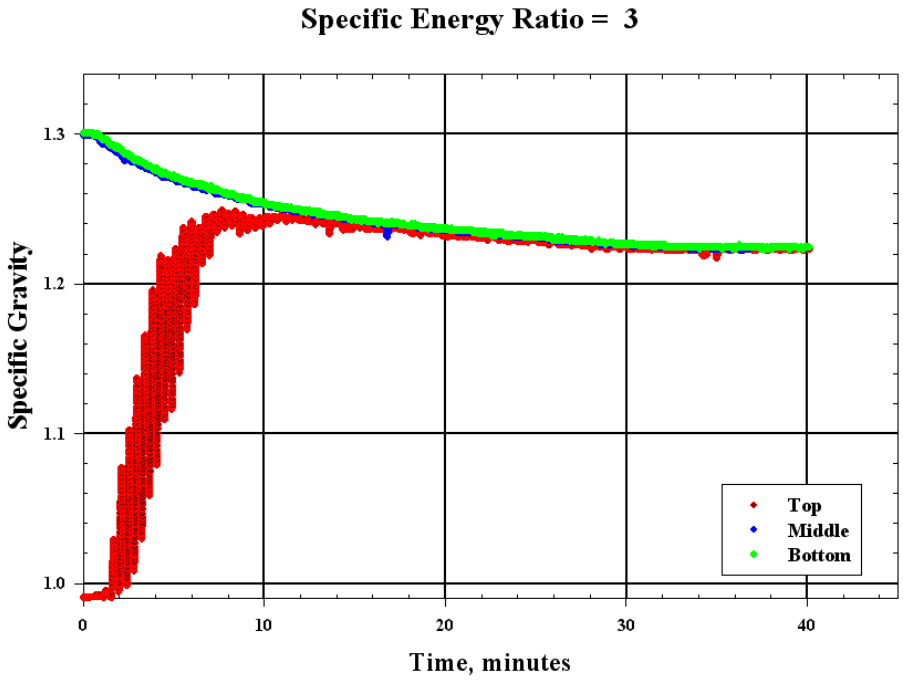

Figure 4.3. Specific Gravity Versus Time for Specific Energy Ratio of 3

4.3 Specific Energy Ratio of 5

This test employed the same 3-second drive time as the test with a specific energy ratio of 3, but the refill cycle was reduced from 22 seconds to 12 seconds. Concentration change was largely accomplished after 24 minutes. Total mixing time (visual equilibration of density gradients) at this specific energy was approximately 34 minutes (Figure 4.4).

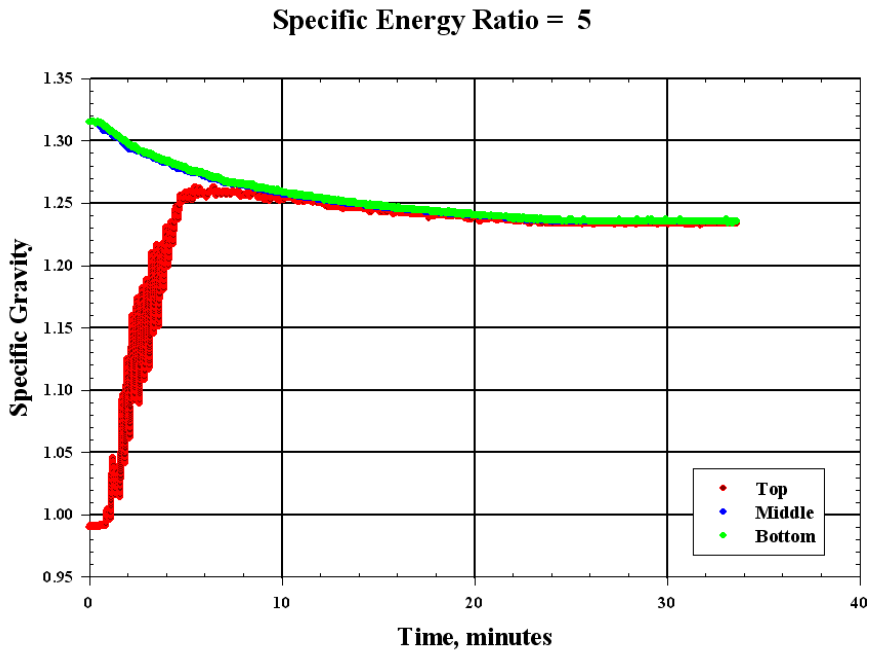

Figure 4.4. Specific Gravity Versus Time for Specific Energy Ratio of 5

4.4 Specific Energy Ratio of 14

This was the highest specific-energy level tested. Pulse-tube cycle times were 2 seconds drive, 10 seconds refill. Total mixing time at this energy was reduced to 15 minutes (Figure 4.5), and concentration change was largely accomplished after 11 minutes.

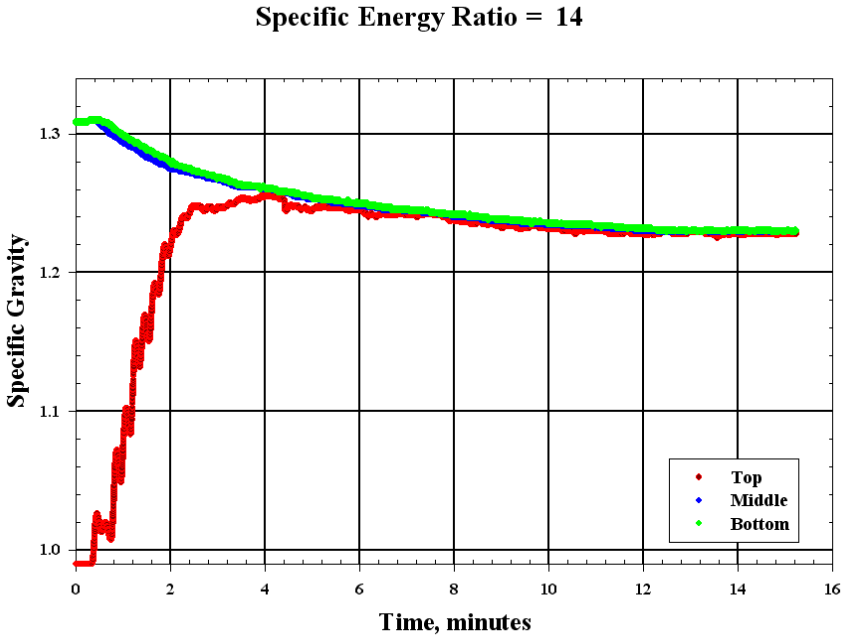

Figure 4.5. Specific Gravity Versus Time Plot for Specific Energy Ratio of 14

5.0 Modeling

The objective of the modeling effort was to validate the CFD model performance in predicting density distributions in prototypic systems. Conditions corresponding to the second experiment with a specific energy ratio of 1 were simulated using the TEMPEST code (see Table 4.1). The version of TEMPEST used for this investigation included modifications for simulating the flow dynamics of the prototypic PJM and particle mixing (TEMPEST T2.11). The simulation was performed using a stair-step grid to model the round bottom of the SS-PJM tank and nozzle-velocity driver functions and initial concentrations as simulation inputs.

Initial simulations showed a significantly slower erosion of the reagent layer than seen in the experiment. This is attributed primarily to the stair-stepped gridding of the elliptically shaped tank bottom for the TEMPEST model. In the case of ascending flow along the bottom ellipse, the stair-stepped grid causes a severe artificial wall drag to occur in the computation, destroying the boundary layer and the directional nature of the flow. This substantially reduces the forces that are required to erode the density gradient. The computational problem associated with stair-stepping the bottom shape has not been observed to cause, nor is it expected to cause, difficulty in simulating flow in prototype vessels with PJMs, where the jet-induced flow descends along the elliptical bottom surface of the tank. The stair-stepping used by the TEMPEST code to form the tank bottom boundary can be eliminated by implementing an elliptical coordinate system (natural coordinates) for that portion of the tank described by an elliptical shape. Because the small-scale test is not similar geometrically and kinematically to the prototype vessels, it was determined that the time and effort required to modify the code for this unique geometry and flow condition was not justified.

6.0 Conclusions and Recommendations

The design-target specific energy of 9.21 x 10^{-5} hp/gal produced mixing times in excess of 90 minutes in the SS-PJM, well above the 60-minute criterion for SS-PJM mixing developed from the pilot-scale work at SRS. Appropriate scaling methodologies must be used to predict mixing times at full scale. In-depth assessment of these methodologies is beyond the scope of the current project. A plot of mixing times versus specific energy is given in Figure 6.1. Only results for specific energy ratios of 3, 5, and 14 are shown because these cases achieved equilibrium during the tests.

If shorter mixing times are desired, using different mixer design parameters should be considered. (It should be noted that a recirculatory-loop is being considered as a method of reagent addition). A comparison of SS-PJM mixer performance at specific energy ratios of 3, 5, and 14 is given in Figure 6.2. Note that the highest specific-energy curve (specific energy of 14) is nearing equilibrium before the specific-energy-ratio-of-3 curve has peaked.

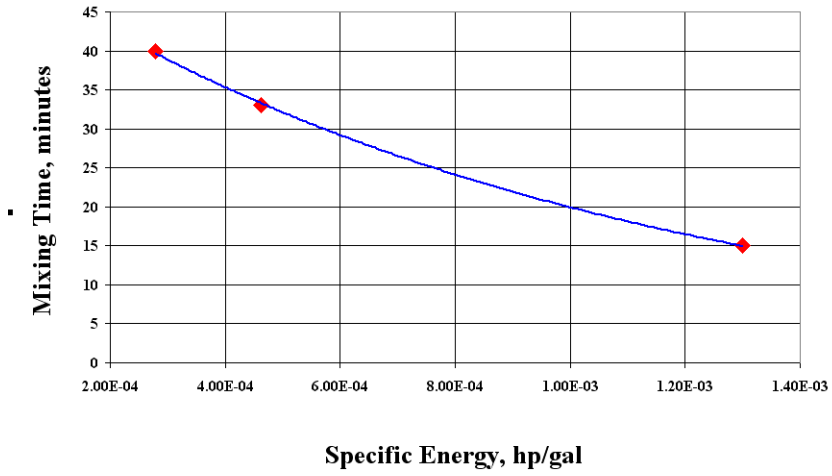

Figure 6.1. Mixing Time Versus Specific Energy

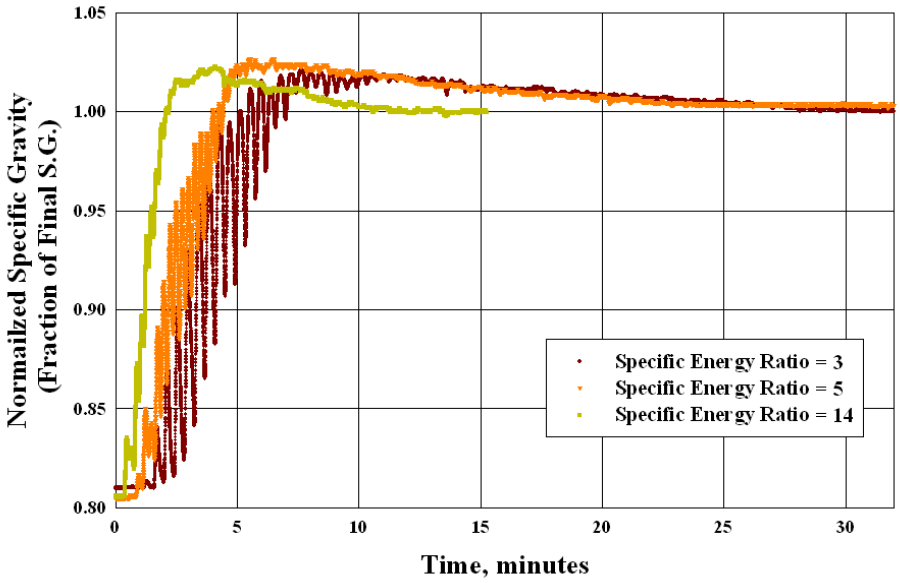

Figure 6.2. Comparison of Mixing Performance (upper sampling position)

7.0 References

Bechtel National, Inc. (BNI). 2002. *Research and Technology Plan*, 24590-WTP-PL-RT-01-002, Rev. 1, U.S. Department of Energy, Office of River Protection, Richland, WA.

Bontha, J R, TE Michener, DS Trent, JM Bates, MD Johnson. 2003. "Development and Validation of the TEMPEST CFD Model of the Pulsed Jet Mixing Systems", WTP-RPT-061, Battelle Pacific Northwest Division, Richland, WA 99352.

Appendix

Specific Energy Calculations

Appendix:

Specific Energy Calculations

Small-Tank PJM System														
SG	Density (lb/ft^3)	Viscosity (lb/ft-sec)	End pulse height (in.)	Vol/pulse (ft^3)	Pulse duration (sec)	Vent duration (sec)	Q (ft^3/sec)	Average velocity exit (ft/sec)	hp during pulse	Total cycle time (sec)	Avg hp over cycle	Total vol (gal)	hp/gal	Specific Energy Ratio
1.3	**81.12**	**0.00201**	**15**	**1.16**	**5**	**22**	**0.232**	**10.625**	**0.06**	**27.00**	**0.01**	**120**	**9.26E-05**	**1.01**
1.3	**81.12**	**0.00201**	**15**	**1.16**	**2**	**10**	**0.580**	**26.563**	**0.94**	**12.00**	**0.16**	**120**	**1.30E-03**	**14.14**
1.3	**81.12**	**0.00201**	**15**	**1.16**	**3**	**12**	**0.386**	**17.708**	**0.28**	**15.00**	**0.06**	**120**	**4.63E-04**	**5.03**
1.3	**81.12**	**0.00201**	**15**	**1.16**	**3**	**22**	**0.386**	**17.708**	**0.28**	**25.00**	**0.03**	**120**	**2.78E-04**	**3.02**
1.3	**81.12**	**0.00201**	**15**	**1.16**	**7**	**20**	**0.166**	**7.589**	**0.02**	**27.00**	**0.01**	**120**	**4.72E-05**	**0.51**
Full-Scale Evaporator Concentrate Buffer Vessel														
SG	Density (lb/ft^3)	Viscosity (lb/ft-sec)	End pulse height (in.)	Vol/pulse (ft^3)	Pulse duration (sec)	Nozzle Diam. (in.)	Q (ft^3/sec)	Avg velocity exit (ft/sec)	hp during pulse	Total cycle time (sec)	Avg hp over cycle	Total vol (gal)	hp/gal	
1.3	**81.12**	**0.00201**		**410.60**	**19**	**5.0**	**21.611**	**19.811**	**19.44**	**77.00**	**4.80**	**52093**	**9.21E-05**	

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