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12-WTP-0037

The Honorable Peter S. Winokur
Chairman
Defense Nuclear Facilities Safety Board
625 Indiana Avenue, NW, Suite 700
Washington, DC 20004-2901

TRANSMITTAL OF DEFENSE NUCLEAR FACILITIES SAFETY BOARD (DNFSB) RECOMMENDATION 2010-2 IMPLEMENTATION PLAN (IP) DELIVERABLE 5.3.3.4

Dear Mr. Chairman:

This letter provides you the deliverable responsive to Commitment 5.3.3.4 of the U. S. Department of Energy (DOE) plan to address Waste Treatment and Immobilization Plant (WTP) Vessel Mixing Issues; IP for DNFSB Recommendation 2010-2.

The attached report provides an assessment of design parameters of WTP Pulse Jet Mixer (PJM) equipped vessels, an analysis of existing experimental data sets, and identifies gaps between data provided by existing experimental data sets, and the data needed to complete the verification and validation (V&V) of the FLUENT Computational Fluid Dynamics (CFD) models of PJM-mixed vessels. An independent review of the attached report will be performed by the DOE National Energy Technology Laboratory (NETL) (Commitment 5.3.3.5). Information from the NETL review will be used to inform a decision regarding the viability of completing CFD V&V prior to obtaining additional large scale integrated testing data sets beyond those specified in the attached report (Commitment 5.3.3.6). Deliverables for Commitments 5.3.3.5 and 5.3.3.6 will be provided to the DNFSB later this year per the IP.

If you have any questions, please contact me at (509) 376-6727 or you may contact Ben Harp, WTP Start-up and Commissioning Integration Manager at (509) 376-1462.

Sincerely,

Dale E. Knutson, Federal Project Director
Waste Treatment and Immobilization Plant

WTP:RB

Attachment

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TRANSMITTAL OF DEFENSE NUCLEAR FACILITIES SAFETY BOARD (DNFSB) RECOMMENDATION 2010-2 IMPLEMENTATION PLAN DELIVERABLE 5.3.3.4

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Acronyms

APEL	Advanced Product Evaluation Laboratory
ASME	American Society of Mechanical Engineers
BNFL	British Nuclear Fuels Limited
CFD	Computational Fluid Dynamics
CFD Code	FLUENT
CFD Model	FLUENT model (computation)
ECR	Effective Clearing Radius
ES	Energy Solutions
LTTS	Large-Tank Test Stand
MCE	Mid-Columbia Engineering
PJM	Pulse Jet Mixer
PNNL	Pacific Northwest National Laboratories
PSD	Particle Size Distribution
SRNL	Savannah River National Laboratories
V&V	Verification and Validation
WTP	Waste Treatment and Immobilization Plant
WSU	Washington State University
ZOI	Zone of Influence

Executive Summary

This report documents the gap between the existing and available data from experiment and the data necessary for application to the Verification and Validation (V&V) effort associated with the FLUENT Computational Fluid Dynamics (CFD) code. The data necessary for the V&V effort is documented in 24590-WTP-PL-ENG-11-0002, Rev. A, *The V&V Plan for Computational Fluid Dynamics Modeling of the PJM Vessels for the Hanford Tank Waste Treatment and Immobilization Plant Project* – referred to as the V&V Plan. The V&V Plan documents the methodology employed for V&V, which is based on ASME V&V 20-2009, Standard for Verification and Validation in Computational Fluid Dynamics and Heat Transfer (referred to as V&V 20) and provides the basis for application to the WTP PJM equipped vessels (24590-WTP-ES-ENG-09-001, Revision 2).

The V&V 20 Standard requires the comparison error between experiment and CFD, as well as uncertainty in the CFD model, be determined. A key to establishing the comparison error and uncertainty is to compare experimental measurements from credible datasets to CFD simulations for Application Points – i.e., data variables from representative WTP PJM equipped vessels, which provide values for parameters that are directly compared to the WTP Vessel Functional Mixing Requirements. These data variables are defined as Validation Variables because they correlate the required data for CFD V&V.

The WTP Vessel Functional Mixing requirements (24590-WTP-ES-ENG-09-001, Revision 2) are satisfied by the following Validation Variables -

1. Fluid Velocity: Velocity measurements within the bulk fluid after a specified number of PJM cycles satisfies the cool to transfer requirement (#1) (Note exception for vessels HLP 27 A/B, HLP-28, and UFP-2 A/B as discussed later).
2. Peak and Cycle-averaged Suction Line Concentration: Peak and average suction line concentration measurements by constituent, over a specified number of PJM cycles, satisfies the prevent plugging, criticality, hydrogen generation rate estimation, and the process control requirements (#2, 5, 6, and 7).
3. Miscible Fluid Blending: Density measurements within the bulk fluid after a specified number of PJM cycles satisfies the blend liquids and neutralization requirements (#3 and 4).
4. Multiple-PJM ZOI: The ZOI/ECR measured at the end of PJM drive provides data indicative of settled solids mobilization, which is applied to satisfy the mix to release gas requirement (#8).
5. Bulk Concentration in the Heel: The bulk concentration in the heel measured by constituent after pump-down satisfies the solids accumulation limit described in requirement #10.

A full description of how the Validation Variables are determined is provided in 24590-WTP-PL-ENG-11-0002, Rev. A. A summary is provided in Table 1-1.

Table 1-1 Functional Mixing Requirements with Validation Variable Summary

Number	Vessel Mixing Function	Mixing Criteria	Validation Variable	Requirement Satisfied?
1	Transfer	Cool for Transfer	Fluid Velocity	Fluid velocity used for heat transfer calculations
2	Transfer	Prevent Plugging	Average & Peak Suction Line Concentration	Slurry density and viscosity at the suction line inlet for pump requirements
3	Blend	Blend Liquids	Miscible Fluid Blending	Resulting concentration gradient shows mixing

Number	Vessel Mixing Function	Mixing Criteria	Validation Variable	Requirement Satisfied?
4	Blend	Neutralization	Miscible Fluid Blending	Same as #3
5	Sample	Criticality	Average & Peak Suction Line Concentration	Same as #2 - for retrievability
6	Sample	Hydrogen Generation Rate (HGR) Estimation	Average & Peak Suction Line Concentration	Same as #2 - for retrievability
7	Sample	Process Control	Average & Peak Suction Line Concentration	Same as #2- for retrievability
8	Store	Mix to Release Gas	Multiple PJM ZOI	Demonstrates movement of solids
10	Store	Limit Solids Accumulation	Bulk Concentration in Heel by Constituent	Concentration in heel at end of pump-down

Application Points do not necessarily need to be extracted from actual WTP PJM equipped vessel design-specific tests or operations. However, these points need to represent the relevant Validation Variable at scale and under conditions that adequately reflect the actual WTP design/operation space. In cases where such Application Point test data is not available, data from other tests performed at varying scale and conditions may be used for V&V provided the test occurs at a scale based on standard industry practice from the WTP design/operation configuration. Typical recommended geometric scaling in industrial practice is 1:10 (by vessel diameter). Conservative scaling is recommended to be on the order of 1:5 (PNNL report TP-RPP-WTP-480). Scaling is appropriate, since CFD (FLUENT) is a first-principles-based program, where the governing equations are explicitly applied at actual scale and the geometrical issues are explicitly incorporated through the mesh. Thus if the test data used for V&V is representative of the WTP PJM equipped vessels, then that data is adequate for V&V. If such data does not exist, additional testing would be required.

For the Data Gap Analysis presented in this report the following tasks were undertaken –

- Define the list of dimensional parameters that represent the physical design, operational conditions, and waste/stimulant properties of the WTP PJM equipped vessels.
- Conduct a comprehensive survey and compile all WTP PJM equipped vessel data (including design drawings) and summarize the ranges for the key dimensional parameters. This is presented in Section 2.
- Compile qualified experimental test data collected previously in support of WTP and summarize the ranges for the key dimensional parameters (note that "qualified" refers to quality in terms of NQA-1, traceability, repeatability, proximity to the variables and conditions of concern, etc.). Compare the ranges of parameters for the WTP PJM equipped vessels and the selected experiments for each of the five Validation Variables. This is presented in Section 3.
- Analyze the overlap and gaps for each key parameter between the WTP PJM equipped vessels and the selected experimental datasets in such a manner that encompasses relevant combinations of parameters that describe the key physical behaviors in the vessel at various scales. This is presented in Section 4.

It is important to emphasize the difference between a V&V effort and design studies. In the V&V effort presented here, geometrical issues are explicitly incorporated into the CFD model through the mesh. This leaves the fidelity to which the CFD represents the physical processes as the principal concern. Unless a situation arises in which new physical processes are introduced, the situation need not be incorporated into the V&V effort. With an understanding of the comparison error and uncertainty for the CFD for a

particular context, design studies may proceed to investigate the impact of various candidate design changes on vessel performance. As a result, gaps determined from pure vessel scale measurements, such as vessel diameter, are not of specific concern for the V&V effort.

The findings from the Gap Analysis specific to each validation variable are summarized as follows -

1. Cool-To-Transfer - Gaps are identified between existing experimental data for velocity near the vessel wall and the WTP PJM equipped vessel dimensional and non-dimensional parameters.
   - Use of existing data from 336 vessel tests is possible but is not recommended because of the expectation for high values for model error and uncertainty.
   - Alternatively, collection of near wall velocity data from additional 8 ft vessel tests is recommended.
   - A gap for cool-to-transfer velocity data specific to HLP-27, HLP-28, and UFP-2 is identified due to non-Newtonian fluid sparging not being represented in the V&V testing dataset
2. Suction Line - Gaps are identified between existing experimental data for concentration at the suction line inlet and the WTP PJM equipped vessel dimensional and non-dimensional parameters.
   - The sole recommendation is to collect additional data in a larger scale vessel. 8 ft vessel testing is recommended.
3. Blending - Gaps are identified between existing experimental data for miscible liquids blending and the WTP PJM equipped vessel dimensional and non-dimensional parameters.
   - Use of existing data is not recommended because of the expectation for high values for model error and uncertainty.
   - Alternatively, collection of appropriate data (ex. concentration measurements within fluid at various heights and PJM cycles) from 8 ft vessel testing is recommended.
   - A gap for miscible liquids blending specific to HLP-27, HLP-28, and UFP-2 is identified due to non-Newtonian fluid sparging not being represented in the V&V testing dataset
4. Existing experimental data for multiple PJM ZOI demonstrates overlap for a majority of the WTP PJM equipped mixing vessel dimensional and non-dimensional parameters. The existing tests are acceptable for V&V of CFD for PJM vessel design confirmation.
   - Inclusion of additional data from 8 ft vessel tests would improve the V&V dataset overlap with the WTP PJM equipped vessel parameters and provide significantly improved alignment with PJM array configuration similarity.
5. Gaps are identified between existing experimental data for concentration at the heel concentration and the WTP PJM equipped vessel dimensional and non-dimensional parameters.
   - The sole recommendation is to collect additional data in a larger scale vessel. 8 ft vessel testing is recommended.

With the inclusion of specific 8 ft vessel tests, the gaps between plant vessel parameters and the available data for V&V of CFD are narrowed or closed for most criteria.

- The ranges for the dimensional parameters significantly overlap.
- The ranges for relevant dimensionless parameters significantly overlap.
- The dynamic range of parameters for CFD is spanned.

Several criteria are suggested for possible, future 8ft vessel tests. First, the 8 ft vessel test experiments should include use of half-scale or larger pulse tubes. Second, they should allow for the repeat of pumpdown tests to measure heel accumulation for representative simulants and supernate properties. Lastly, these tests should provide repeated measurements of time-averaged suction line concentration.

Possible configurations for 8 ft diameter vessel testing, which satisfy the requests above, are -

- Single centerline mounted pulse tube configuration with 4" nozzle to establish a link to full scale via testing,
- Single centerline mounted pulse tube configuration with 2" nozzle to establish a link between full scale and half scale,
- Four pulse tube array without a centerline mounted pulse tube with 2" nozzles and inter-pulse tube spacing characteristic of WTP vessel standard arrays,
- Five pulse tube array with a centerline mounted pulse tube with 2" nozzles and inter-pulse tube spacing characteristic of WTP vessel chandelier arrays.

This list represents an overview of the recommended tests in the 8ft vessel for the V&V. The detailed list of specific tests and associated measurement quantities/locations will be included in the RTD (Test Plan) that will be issued by the Project testing team.

The non-Newtonian vessels (HLP-27 A/B, HLP-28, and UFP-2 A/B) include two vessel mixing requirements, #1 and #3 representing the cool to transfer and the liquid blending respectively, for which there exists a gap that the proposed 8 foot vessel testing will not fill. There are no test recommendations for these vessels at this time because such testing would need to include the sparging operation in the upper part of the vessels. The bottom portion of these vessels is driven directly by the PJM jet velocity wall shear effects which create Newtonian fluid mixing in this region. This allows for the proposed 8 foot vessel testing to fill the gap in experimental data as applicable to the validation variables at the bottom of the vessel - suction line concentration, Zone of influence, and heel accumulation.

1 Introduction

1.1 Purpose and Scope

The purpose of this document is to provide a summary of potential gaps between the information provided by existing experimental data sets and the information needed to perform the FLUENT V&V in the context of WTP PJM equipped vessels. The required information for the FLUENT V&V, in the form of five validation variables, is based on the functional mixing requirements from 24590-WTP-ES-ENG-09-001, Rev. 2 and as described in the V&V 20 plan (24590-WTP-PL-ENG-11-0002, Rev. A).

Beginning with this section, the data gap analysis provides an overview of CFD with a discussion of solution methods and scale independence. A short discussion of the primary validation variables as defined in 24590-WTP-PL-ENG-11-0002, Rev. A and their relationship with the WTP vessel functional mixing requirements (24590-WTP-ES-ENG-09-001, Rev. 2) is in Section 1.3. Section 1.3 also includes the requirements for individual WTP PJM equipped vessels as aligned with the five primary validation variables. Section 2 provides an assessment of the anticipated operating conditions for the WTP PJM equipped vessels. Section 3 provides an assessment of the experimental data sets, reduced to reflect those tests that are both usable and useful. Section 4 presents an analysis of the WTP PJM equipped vessels and experimental data to determine if gaps exist for any of the five validation variables, and which, if any, will require additional experimental testing. In such cases where a gap is determined to exist, proposed vessel test configurations are described in Section 4. Conclusions of this data gap analysis the presented in Section 5. References are provided in Section 6. Detailed information for the WTP PJM equipped vessels and the existing experimental data sets are included in two appendices. The first appendix, Appendix A, provides a detailed description of the pertinent experimental results for the data sets that have been deemed relevant to this V&V activity. In Appendix B, details are found describing the conditions of the WTP PJM equipped vessels.

1.2 Background on CFD

The commercial CFD solver FLUENT is used for evaluation of the WTP PJM equipped vessels. The CFD models created solve ensemble-averaged equations governing mass, momentum, and energy conservation in gas-liquids-solids multiphase flows. The Eulerian-Granular multiphase model is used in FLUENT. FLUENT solutions are statistical predictions of mean flow quantities, like solids and fluid velocities, and concentrations, with full coverage in space and time. A complete accounting of the multiphase model equations for PJM vessel mixing is provided in Appendix A of project document 24590-WTP-PL-ENG-11-0002, Rev. A.

1.2.1 Solution Methods in FLUENT

The equations solved by FLUENT are derived from formally exact, first-principles-based, equations for gas-liquids-solids transport. Ensemble-averaging of the equation set yields the statistical equations underlying the Eulerian-Granular multiphase model. The ensemble-averaging process introduces higher-order statistics that are closed through modeling. These physics models are semi-theoretical/semi-empirical closures that have been shown to emulate the correct fluid-solids interaction responses across multiple datasets from multiple configurations over a wide range of flow conditions. Demonstration that these closures remain appropriate for WTP PJM equipped vessel mixing is the purpose of solution validation in the V&V process.

The approach in CFD is to discretize the flow domain into a very large number of interfacing control volumes. Local control volume sizes are chosen to resolve mean flow gradients at that location. Demonstrating that this goal is accomplished is the purpose of grid refinement during solution validation in the V&V process. Time is also discretized into small time increments, which resolve temporal changes in the flow. The mass, momentum, and energy balances of the discretized governing equations are enforced within each control volume for each time-step increment. Discretization of fluxes into and out of the control volumes links neighboring cells. Direct exchange of information is local. Boundary conditions are only directly experienced by the control volumes adjacent to the boundaries. Boundary information propagates into the flow field through the network of locally interacting cells.

By enforcing governing equations directly within each local control volume discretizing a flow field, CFD embeds core physical processes like transport, diffusion, production, and destruction, directly enabling a CFD model to be locally sensitive to non-linear system responses to local changes in a flow field and sensitive to the effects of geometry.

1.2.2 Scale Independence

The same governing equations apply to all WTP PJM equipped vessels (plant vessels) and flows from test vessel scale to plant vessel scale. Because CFD is locally sensitive to the core physical processes of the governing equations, all mechanisms for fluid behavior are possible at each point within a flow field. The primary mechanisms observed depend on the local flow conditions. CFD does not enforce a particular behavior and allows primary mechanisms to change with vessel scale. A governing-equations-based approach like CFD avoids the need to identify *a priori* appropriate exponents for scale-up and scale-down, and thus extends predictability to systems like PJM driven vessel mixing, where the available experimental data may be insufficient, and is available to derive trusted data-driven correlations.

1.3 Validation Variables

The following sections provide a summary of the WTP PJM equipped vessel functional mixing requirements and the associated validation variables for both Newtonian and non-Newtonian fluid rheologies.

1.3.1 Vessel Functional Mixing Requirements

The performance of each WTP PJM equipped vessel is assessed based on the functional mixing requirements as determined by the project (24590-WTP-ES-ENG-09-001, Rev. 2) and repeated in Table 1-1. These nine requirements form a natural basis on which to select validation variables.

Table 1-1 Functional Mixing Requirements

Number	Vessel Mixing Function	Mixing Criteria	Functional Requirement
1	Transfer	Cool for Transfer	Transfer Slurry: The PJM mixing system shall mix the slurry to ensure the maximum slurry temperature is below the specified temperature limit.
2	Transfer	Prevent Plugging	Transfer Slurry: The PJM mixing system and pump suction shall be capable of maintaining the fluid properties to meet the pump suction requirements.
3	Blend	Blend Liquids	Blend Liquids: The PJM mixing system shall blend the liquid fractions to ensure the concentration gradient throughout the vessel is less than the value specified for the liquid characteristic of interest.

Number	Vessel Mixing Function	Mixing Criteria	Functional Requirement
4	Blend	Neutralization	Blend Liquids: The PJM mixing system shall blend the liquid fractions to ensure the concentration gradient throughout the vessel is less than the value specified for the liquid characteristic of interest.
5	Sample	Criticality	Mix Slurry: The PJM mixing system shall mix the slurry to ensure the process control requirements are met and a representative sample can be obtained.
6	Sample	Hydrogen Generation Rate (HGR) Estimation[1]	Mix Slurry: The PJM mixing system shall mix the slurry to ensure the process control requirements are met and a representative sample can be obtained.
7	Sample	Process Control	Mix Slurry: The PJM mixing system shall mix the slurry to ensure the process control requirements are met and a representative sample can be obtained.
8	Store	Mix to Release Gas[2]	Release Gas: The PJM mixing system shall mobilize solids to release gas.
10	Store	Limit Solids Accumulation[3]	Limit Solids Accumulation: The PJM vessel systems shall be designed, considering the mixing and transfer systems, such that solids will not accumulated from batch to batch and limit the bulk density and solids weight percent to less than or equal to the limits established for the Unit Liter Dose calculation.

Note (s):

1. Details on sample requirements for HGR estimation are in 24590-WTP-ES-ENG-09-001, Rev. 2.
2. See 24590-WTP-PSAR-ESH-01-002-02 for details on hydrogen concentration limits.
3. For details on the Unit Liter Dose (ULD) calculation, see 24590-WTP-ES-ENG-09-001, Rev. 2.
4. Number 9 is not shown in this table since it was superceded by Number 10 (24590-WTP-ES-ENG-09-001, Rev. 2).

1.3.2 Primary Validation Variables

The five primary validation variables that have been identified for this V&V effort are described in 24590-WTP-PL-ENG-11-0002, Rev. A. They are:

1. Velocity measurements within the bulk fluid after a specified number of PJM cycles – (Vessel functional mixing criteria #1)
2. Peak and cycle-average slurry concentration by constituent at the suction line inlet over a specified number of PJM cycles - (Vessel functional mixing criteria #2,5,6 and 7)
3. Concentration measurements of miscible fluids within the bulk fluid of vessels after a specified number of PJM cycles - (Vessel functional mixing criteria #3 and 4)
4. Multiple-PJM ZOI/ECR at the end of drive - (Vessel functional mixing criteria #8)
5. Bulk concentration in the heel by constituent - (Vessel functional mixing criteria #10)

The validation variables are quantities of interest that are to be evaluated in both CFD and experiment for the purposes of establishing comparison error and validation uncertainty per V&V 20 (24590-WTP-PL-ENG-11-0002, Rev. A). The validation points correspond to the experimental data collected in this report. The application points are associated with the WTP PJM equipped vessels. The validation variables and the methods and values used to correlate the validation points with the application points for the V&V are not necessarily the same as those used in the CFD calculations for vessel confirmation. The vessel confirmation calculations provide inputs and information for the assessment of the as-built WTP PJM

equipped vessels compared to the vessel operational requirements. Where applicable, the difference between the data needed for the V&V and the values provided as inputs to the vessel mixing assessments is stated.

A key challenge of the present V&V activity, is that the validation points may be substantially different from the application points. Quantifications of conditions for both the validation and application points will be discussed in Section 1.4.

In the event that circumstances make a primary validation variable partially or fully inaccessible, measurements of "secondary" validation variables – i.e., surrogates - could be considered to augment the V&V dataset. Substantial measurements of data such as cloud height and U_{cs} (critical suspension; minimum PJM velocity required to clear the vessel bottom) have been obtained. While these do not directly correlate to the specific validation variables for the V&V, based on physical mechanisms in the vessels they are related in a meaningful way (such as measurements of ZOI in single-PJM experiments or rate-of-ZOI). The five primary validation variables are now discussed in greater detail.

1.3.2.1 Fluid Velocity for Heat Transfer

For each velocity probe, compute the average fluid velocity component in direction i, $\overline{u}_i$, at a fixed location,

$$\overline{u}_i = \frac{1}{\Delta t} \int_{t_{begin}}^{t_{begin}+\Delta t} u_i \, dt$$

over a period, Δt, of one PJM cycle after the flow field has reached a quasi-steady state. If the probe only returns the velocity magnitude, the average above is taken on the magnitude.

This validation variable is based on predicting the cooling of a hot vessel and is related to Mixing Requirement #1 (Table 1-1). Since heat transfer correlations exist for natural, mixed, and forced convection, heat transfer may be calculated from the local velocity field within the vessel. Therefore, if the velocity is known from CFD, the heat transfer may be determined with a high degree of confidence and accuracy from the velocity measurements and resulting heat transfer correlation. Direct heat transfer calculations from CFD are not necessary to generate accurate solutions for this validation variable.

1.3.2.2 Average and Peak Concentration at Suction Line Inlet

Using either slurry density, particle mass fraction, or particle volume fraction for the variable X, the average concentration at the suction line inlet is defined as

$$\overline{X} = \frac{1}{\Delta t} \int_{t_{begin}}^{t_{begin}+\Delta t} X \, dt$$

where X is the cross-sectionally averaged concentration and the ending time is the beginning time plus one PJM cycle-time. Peak concentration is calculated for a moving 3s interval, where the average concentration value at the face of the suction line inlet during the 3s window is used as the increase over the PJM cycle average value. This new, calculated value is defined as the peak at the suction line. Both

the average and peak concentration validation variables provide understanding on whether the suction line will suffer clogging or not, satisfying Mixing Requirements 2, 5, 6, and 7 (Table 1-1). Concentration will be used to compute slurry density and viscosity for the V&V effort. These values are used to verify that the waste properties (viscosity, density, and weight percent) in the vessel do not exceed the established limits for the evaluated vessels.

1.3.2.3 Miscible Fluid Blending

Blending in a miscible fluid will focus on time-dependent density measurements taken at several different locations inside a vessel. The need for this variable is to estimate the time required for a caustic liquid, introduced from a lid on top of the vessel, to mix in and react with the solids inside the vessel. In practice, this caustic liquid is denser than the liquid contents of the vessel and, consequently, sinks directly to the vessel bottom. In 24590-WTP-PL-ENG-11-0002, Rev. A, it was envisioned that blending experiments would be done by introducing a saline solution into water. Subsequently, it was decided that testing reported in WTP-RPT-077 would be used where a positively buoyant fluid is introduced from above.

Because of the PJM drive-suction cycle, there will be a fine-scale periodic variation in the density imposed on a nearly monotonic change as the density approaches the completely mixed value. For each densitometer present in the experiment, the average density, $\overline{\rho}_i$ is taken over each individual PJM cycle where the subscript i identifies a specific densitometer. Also, for each densitometer, there will an initial and final density. The validation variable is defined as the time it takes the fluid density, $\overline{\rho}_i$, for a given densitometer, to reach a density equal to the average of the initial and final (completely mixed) densities.

The miscible fluid blending satisfies mixing requirements 3 and 4 (Table 1-1) by providing the information necessary to compare to the homogeneity requirements listed for each evaluated vessel. For the purposes of vessel confirmation, the requirement is defined as the time for the fluid additive to be mixed at all locations in the vessel to within 20% of the perfectly mixed value.

1.3.2.4 Multiple-PJM ZOI

The Zone-of Influence (ZOI) indicates the extent of solids mobilization and clearing at the vessel bottom upon completion of PJM drive. Depending on the extent of clearing in multiple-PJM systems, three situations may arise. If bottom clearing beneath each respective PJM is minimal, there will be a number (N_{PJM}) of distinct, quasi-circular and unmerged ZOI regions. With better bottom clearing performance, ZOI regions belonging to adjacent PJMs merge after the (wall jet) stagnation line between them is cleared of sediment. This situation is shown in Figure 1-1. Still better bottom clearing performance results in the full clearing of the vessel bottom. The last regions to clear are typically (wall jet) stagnation points which are geometrically situated between at least three PJMs. Definitions for the measurements of ZOI are contingent on which regime occurs in the experiment or simulation. They are also subject to where the experimental measurements were taken because comparisons between experiment and CFD can only done where measurements were made. Figure 1-1 shows two possible directions, A and B, in which to measure ZOI. Therefore, the direction in which ZOI is measured and the location of the ZOI boundaries must be clearly defined for meaningful comparisons to be made between simulation and experiment.

The solids volume fraction should provide an unambiguous indicator of the ZOI boundary in CFD. Computationally, accuracy between regions can be impacted by numerical (CFD computation) diffusion. The computational thickness which separates the zero-volume-fraction region from the fully packed

region would be expected to be several mesh widths. Depending on the visualization software, it is found to be approximately two to three grid cell widths. Hence, the ZOI boundary will be taken as the volume fraction contour of 0.20-0.30, depending on the visualization software. In a different context such as ZOI determinations while the rate-of-ZOI is still large, this definition might need to be revisited. Additional discussion on ZOI as calculated in CFD may be found in Section 4.4.

ZOI measurements support mixing requirement 8 (the mix to release gas, Table 1-1) by establishing the ability of the configuration to mobilize solids in the vessel by moving particles off of the bottom. The ability to mobilize solids off of the bottom of the vessel is related to the ability to release gas and prevent hydrogen build-up [24590-WTP-PL-ENG-11-0002, Rev. A].

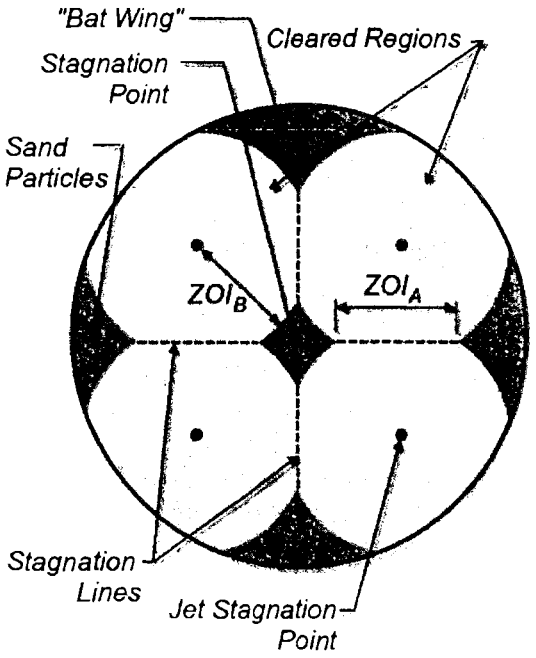


Figure 1-1 Plan View of a Substantially Cleared Bottom (4-PJM vessel)

1.3.2.4.1 Measuring Distinct ZOI Regions

To measure ZOI in this case, draw the line that connects the jet stagnation points beneath two adjacent PJMs. Along this line, measure the distance between the jet stagnation point of the PJM and the edge of the sand dune.

1.3.2.4.2 Measuring Merged ZOI Regions

For the case presented in Figure 1-2, that of a two-PJM configuration inside of a box flume, ZOI will be measured as the distance between adjacent sediment peninsulas along the (wall jet) stagnation line between the two adjacent PJMs. In other words, draw the line that connects the jet stagnation points beneath two adjacent PJMs. Based on the respective PJM jet velocities of two adjacent PJMs (V_1 and V_2), it is possible to determine the location along the connecting line that constitutes the approximate location of the (wall jet) stagnation line. The calculation of the connecting line is determined as follows:

- If the distance from each PJM to this point is r_1 and r_2, respectively, then the location of this stagnation point is given approximately by $r_1*V_2 = r_2*V_1$.
- From this point, determine the line which is perpendicular inter-PJM line and intersects the stagnation point/line discussed above.
- Along the stagnation line, measure the distance between the bottom of both sand dunes at the end of the drive cycle.

This will be the ZOI distance when adjacent ZOI regions have merged.

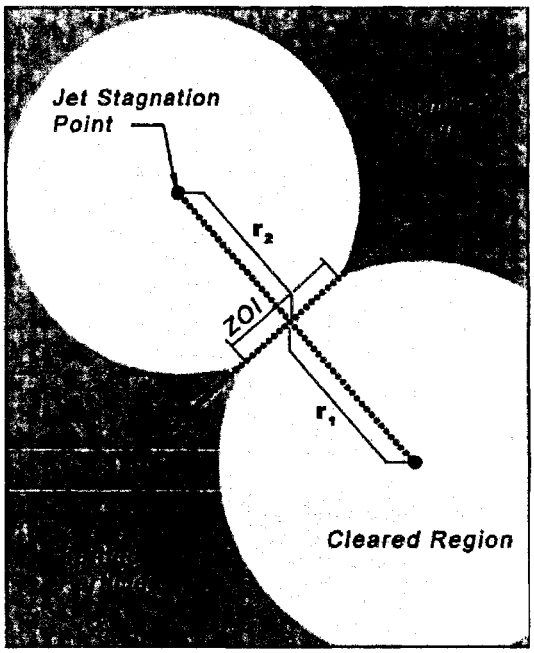


Figure 1-2 Plan View for a Partially Cleared Two-PJM Box Flume

1.3.2.5 Bulk Concentration in the Heel by Constituent

The validation variable for bulk concentration, *Cs*, (by mass fraction or volume fraction) in the heel is measured by constituent. Upon completion of a vessel pump-down, the total mass of each particular constituent, $(Cs)_{Final}$, is measured and compared to the initial constituent concentration at full batch, $(Cs)_{initial}$, where $(Cs)_{Final} \leq (Cs)_{initial}$. This validation variable is to determine if batch-to-batch accumulation occurs for any and all sediment classes (Mixing Requirement 10, Table 1-1). For the purposes of vessel confirmation, the functional mixing requirement #10 will be treated similarly to the V&V effort.

1.3.3 Functional Mixing Requirements - Validation Variable Summary

Table 1-2 provides a summary of the vessel functional mixing requirements as compared to the validation variables summarized in the previous sections.

Table 1-2 Functional Mixing Requirements with Validation Variable Summary

Number	Vessel Mixing Function	Mixing Criteria	Validation Variable	Requirement Satisfied?
1	Transfer	Cool for Transfer	Fluid Velocity	Fluid velocity used for heat transfer calculations
2	Transfer	Prevent Plugging	Average & Peak Suction Line Concentration	Slurry density and viscosity at the suction line inlet for pump requirements
3	Blend	Blend Liquids	Miscible Fluid Blending	Resulting concentration gradient shows mixing
4	Blend	Neutralization	Miscible Fluid Blending	Same as #3
5	Sample	Criticality	Average & Peak Suction Line Concentration	Same as #2 - for retrievability
6	Sample	Hydrogen Generation Rate (HGR) Estimation	Average & Peak Suction Line Concentration	Same as #2 - for retrievability
7	Sample	Process Control	Average & Peak Suction Line Concentration	Same as #2- for retrievability
8	Store	Mix to Release Gas	Multiple PJM ZOI	Demonstrates movement of solids
10	Store	Limit Solids Accumulation	Bulk Concentration in Heel by Constituent	Concentration in heel at end of pump-down

1.3.4 Validation Variable – WTP PJM Equipped Vessel Matrix

To accurately assess the applicability of the available test data for the V&V, it is necessary to assign the appropriate validation variables to the respective WTP PJM equipped vessels [24590-WTP-ES-ENG-09-001, Rev. 2]. By associating the WTP PJM equipped vessels with the validation variables, the comparison between the test data and the WTP PJM equipped vessels may be refined and increased accuracy in the determination of potential gaps is achieved. The WTP PJM equipped vessels as grouped by validation variable is presented in Table 1-3.

Table 1-3 WTP PJM Equipped Vessels and Applicable Validation Variables

PJM Vessel Name	Fluid Velocity for Heat Transfer [a]	Ave. & Peak Suction Line Concentration [b]	Miscible Fluid Blending [c]	Multiple PJM ZOI [d]	Bulk Concentration in Heel by Constituent [e]
CNP-VSL-00003	X				
CNP-VSL-00004			X		
CXP-VSL-00004 [g]		Δ [f]	X		
CXP-VSL-00026A/B/C		Δ [f]	X		Δ [f]
FEP-VSL-00017A/B		X		X	X
FRP-VSL-00002A		X		X	X
FRP-VSL-00002B/C/D		X		X	X

PJM Vessel Name	Fluid Velocity for Heat Transfer [a]	Ave. & Peak Suction Line Concentration [b]	Miscible Fluid Blending [c]	Multiple PJM ZOI [d]	Bulk Concentration in Heel by Constituent [e]
HLP-VSL-00022	X	X		X	X
HOP-VSL-00903/904		X			X
PWD-VSL-00015/16		X	X		X
PWD-VSL-00033		X		X	X
PWD-VSL-00043		X		X	X
PWD-VSL-00044		X	X	X	X
RDP-VSL-00002A/B/C		X [h]			
RLD-VSL-00007	X	X	X		X
RLD-VSL-00008		X	X		X
TCP-VSL-00001		Δ [f]	X		Δ [f]
TLP-VSL-00009A/B		Δ [f]	X		Δ [f]
UFP-VSL-00001A/B	X	X	X	X	X
UFP-VSL-00002A/B	X	X	X	X	X
UFP-VSL-00062A/B/C		Δ [f]	X		Δ [f]

Note(s):
All information in this table is determined from Appendix A in 24590-WTP-ES-ENG-09-001, Rev. 2 and includes anticipated changes to be incorporated into Revision 3.

a. Velocity for Heat Transfer is equivalent to Mixing Criteria #1.
b. Average and Peak Suction Line Concentration is equivalent to Mixing Criteria #2, 5, 6, and 7 (solids sampling).
c. Miscible Fluid Blending is equivalent to Mixing Criteria #3, 4, and 7 (pH sampling).
d. Multiple PJM ZOI is equivalent to Mixing Criteria #8.
e. Bulk Concentration in the Heel is equivalent to Mixing Criteria #10.
f. Symbol (Δ) indicates off-normal conditions exist that may require analysis against Mixing Criteria #2 and 7.
g. Note that the function of vessel CXP-VSL-00004 has been modified to match UFP-VSL-00062A/B/C, although the official documents have yet to be issued confirming this change.
h. Per 24590-WTP-RPT-ENG-08-021-02, Rev. 0, Mixing Criteria #2 and 7 are satisfied using an alternate analysis method and results from FLUENT are not necessary to satisfy this requirement.

Note that WTP PJM equipped vessels HLP-VSL-00027A/B, HLP-VSL-00028, and UFP-VSL-00002A/B are not listed in Table 1-3. These vessels are discussed separately.

1.3.5 Vessel Mixing with Non-Newtonian Fluid Rheologies

This document evaluates the gap based on a CFD model that uses sub-models appropriate for Newtonian fluid rheologies and non-cohesive particles (see Appendix A of the V&V plan, Section A.2.4). These assumptions may not be appropriate for vessels having fluids exhibiting non-Newtonian fluid rheologies, specifically HLP-VSL-00027A/B, HLP-VSL-00028, and UFP-VSL-00002A/B. Table 1-4 shows the applicable validation variables for the vessels containing non-Newtonian fluids.

Table 1-4 WTP PJM Equipped Vessels and Applicable Validation Variables - Non Newtonian Fluid Rheologies

PJM Vessel Name	Fluid Velocity for Heat Transfer [a]	Ave. & Peak Suction Line Concentration [b]	Miscible Fluid Blending [c]	Multiple PJM ZOI [d]	Bulk Concentration in Heel by Constituent [e]
HLP-VSL-00027A/B	X	X	X	X	X
HLP-VSL-00028	X	X	X	X	X
UFP-VSL-00002A/B	X	X	X	X	X

Note(s):
All information in this table is determined from Appendix A in 24590-WTP-ES-ENG-09-001, Rev. 2

a. Velocity for Heat Transfer is equivalent to Mixing Criteria #1. Per 24590-WTP-RPT-ENG-08-021-03, Rev 1, Mixing Criteria #1 is satisfied using an alternate analysis method. Results from FLUENT are not necessary to satisfy this requirement, based on the alternate evaluation.
b. Average and Peak Suction Line Concentration is equivalent to Mixing Criteria #2, 5, 6, and 7.
c. Miscible Fluid Blending is equivalent to Mixing Criteria #3 and 4. Note that this condition is not currently evaluated using FLUENT.
d. Multiple PJM ZOI is equivalent to Mixing Criteria #8.
e. Bulk Concentration in the Heel is equivalent to Mixing Criteria #10.

The current V&V plan does not specifically address the evaluation of vessels containing slurry with non-Newtonian rheologies or those containing cohesive particles. Based on the listed PJM vessel mixing assessments for HLP-VSL-00027A/B, HLP-VSL-00028, and UFP-VSL-00002A/B [24590-WTP-RPT-ENG-08-021-03, Rev 1], the evaluation of these vessels with respect to the vessel functional mixing requirements may be separated into two conditions.

Based on details from 24590-WTP-RPT-ENG-08-021-03, Rev 1, the first condition occurs while the spargers are in operation (not stand-by) and the PJMs are driving, the vessel contents behave as Newtonian fluids (see Figure 1-3). In this situation, the evaluation of the vessel for the validation variables is possible with the current FLUENT physics models for Newtonian, non-cohesive solids. However, the current geometric models would need modification to include the spargers, which account for approximately 2/3 of the mixing power in the vessel. Also, test data supporting the use of spargers would need to be found to complete the V&V activity.

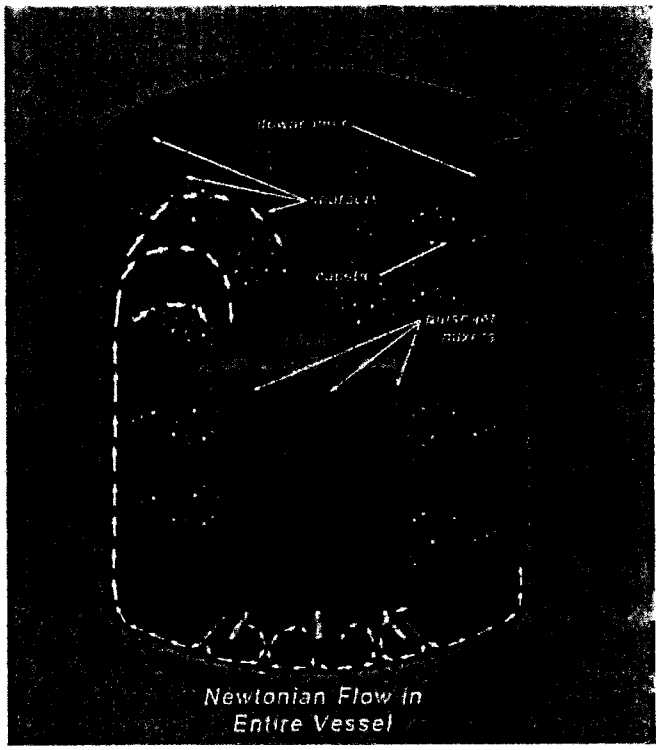


Figure 1-3 Non-Newtonian Fluid Rheology Vessel Flow with Spargers and PJMs in Drive

The second condition occurs when the spargers are not in full operation (stand-by mode) and the PJMs are supplying all of the mixing drive. In this instance, it is possible that some of the slurry may gel. Per 24590-WTP-RPT-ENG-08-021-03, Rev 1, the area of solidification occurs in the upper portion of the vessel while the lower portion, containing the settling solids, is mixed using the PJMs. For this lower vessel portion (see 24590-WTP-RPT-ENG-08-021-03, Rev 1 for details on zone definition), the contents may be identified as Newtonian in nature (see Figure 1-4) while the PJMs are driving. For this condition, only three of five validation variables are available: Average and Peak Suction Line Concentration, Multiple PJM ZOI, and Bulk Concentration in the Heel Concentration by Constituent. Both Fluid Velocity and Miscible Fluid Blending rely on information in the upper regions of the vessel, which are subject to non-Newtonian fluid rheologies and cannot be evaluated with the current FLUENT physics model configurations.

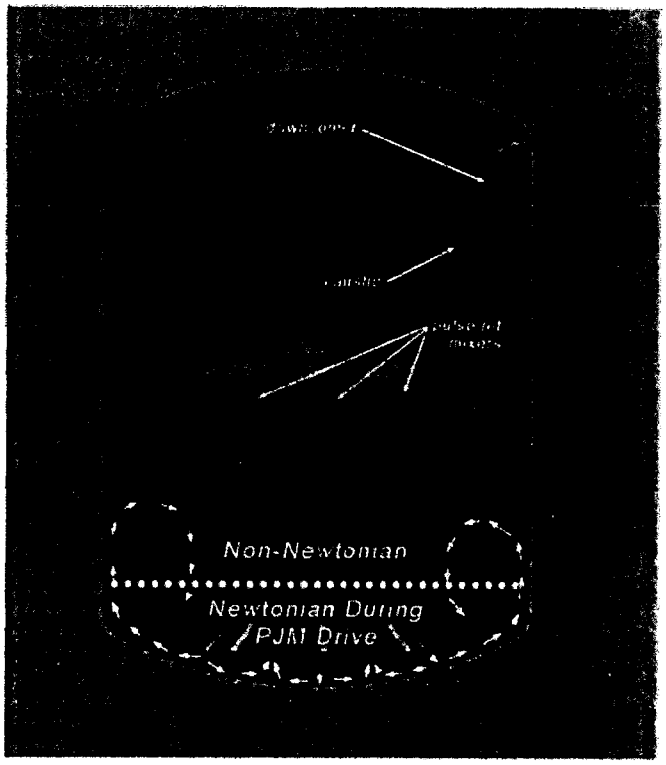


Figure 1-4 Non-Newtonian Fluid Rheology with PJMs Operating (Spargers on Stand-By)

Details on the possible gaps generated by both of these conditions are discussed in this document (Section 4).

1.4 Dimensional Parameter Space

In order to describe the physical conditions found in the experimental test vessels and the WTP plant vessels, many individual quantities are needed. The collection of these quantities constitutes a parameter space in which all vessels, plant scale or test scale, may be placed. The quantities presented here are not intended to be a complete list of the parameters used in the V&V effort, but represent a basis for comparison for the purposes of this gap analysis.

To describe the supernate, the fluid in the absence of the particle phase, we use the shear viscosity, μ_L, the fluid density, ρ_L, and the total fluid mass, m_L, within a vessel. Solids contained in a vessels are described based on their mean particle diameter, d_p, and mean density, ρ_p, for a given particle class (e.g. tungsten carbide, silicon dioxide). Additionally, the total mass of all particle classes, m_p, is needed.

From material properties, vessel geometry details are needed. These include the overall vessel inside diameter, D_T, the vessel head shape, and the vessel fill level; the height to which the vessel is full of slurry See Figure 1-5 for details (PJMs are shown in blue).

Note that another configuration for PJMs is used for some vessels, most notably HLP-VSL-00027A/B, HLP-VSL-00028, and UFP-VSL-00002A/B, identified as "chandelier" configurations, where there is a central PJM included with the inner PJM ring and connected as a single structure. See Figure 1-7.

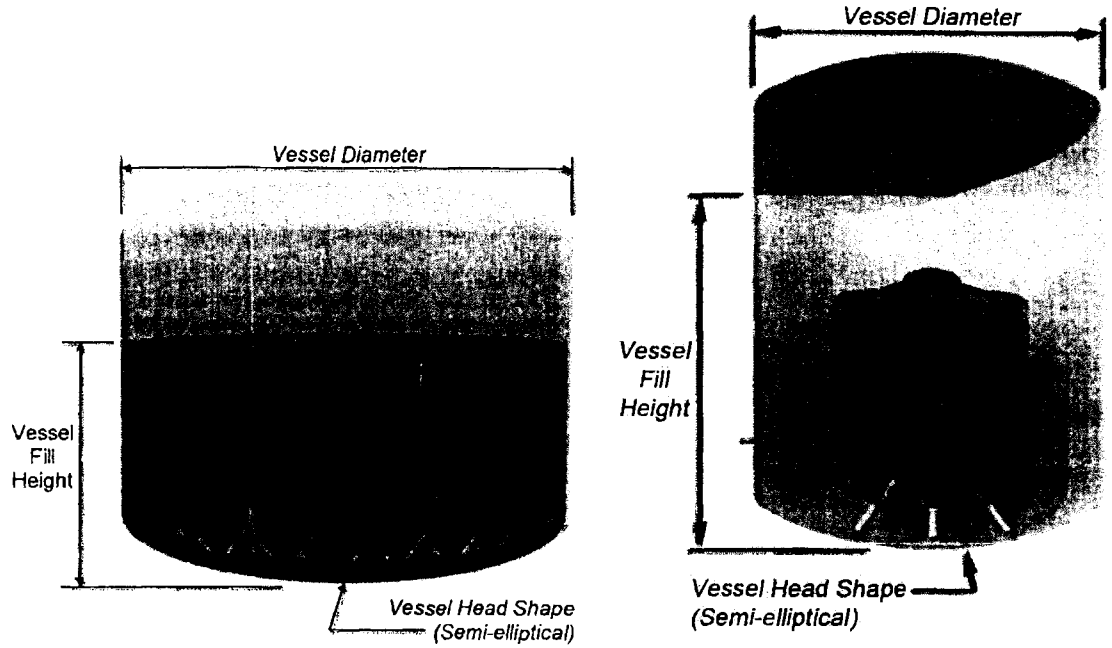


Figure 1-5 Vessel Side-View: Diameter and Slurry Fill Height (Standard and Chandelier Configurations)

In a plan view of an N_{PJM} = 18-PJM vessel, Figure 1-6 shows an inner pitch ring having six PJMs and an outer ring with 12 PJMs. The radius of the inner pitch ring is denoted as Δ. It measures the distance from an inner PJM centerline to the vessel centerline. Adjacent to the PJMs numbered (arbitrarily) as 1 and 2 are two suction line pipes used to withdraw slurry near the vessel centerline.

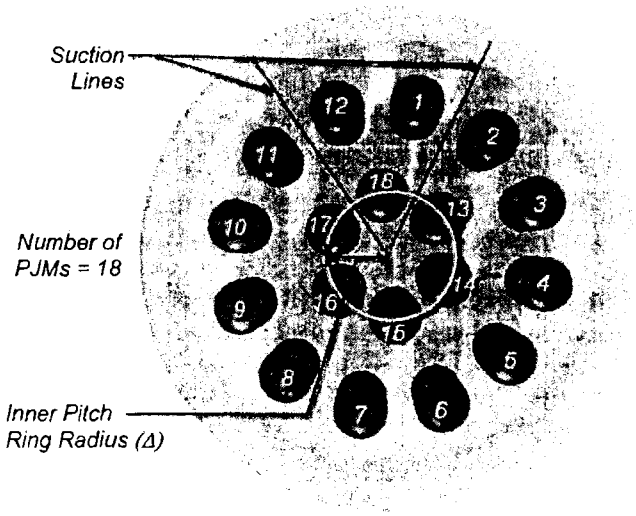


Figure 1-6 Vessel Plan-View: 18 PJMs (in blue) with Inner Ring (6) and Outer Ring (12), and Two Suction Lines

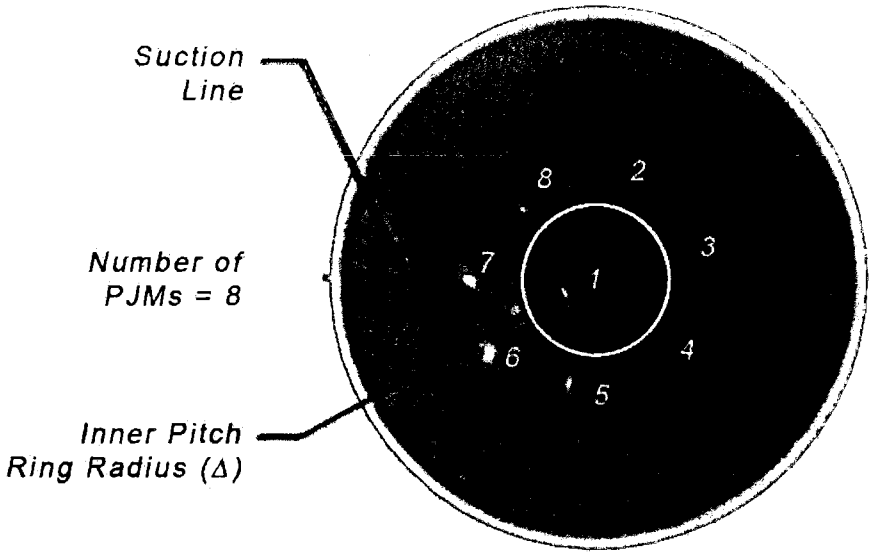


Figure 1-7 Vessel Top-View: PJM 'Chandelier' Configuration

In Figure 1-8, we zoom in on the bottom of the vessel, near the vessel centerline. PJM nozzles are characterized by their height/offset from the vessel floor, H_0, their inner diameters, D_0. Similarly, the suction line is characterized by the suction line pipe diameter, D_{sli}, the local height above the vessel bottom, H_{sli}, and the radial distance from the suction line inlet to the vessel centerline, R_{sli}. Suction line flow rate, q_{sli}, is another quantity of interest.

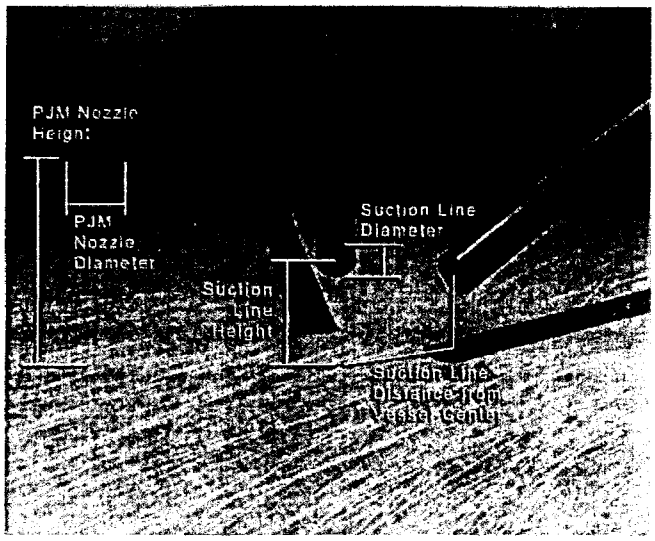


Figure 1-8 Vessel Bottom View: Suction-Line Configuration (Diameter, Height, and Distance from Centerline)

Lastly, characterizations of vessel operational quantities are needed. These include the time over which the PJM is in its drive phase, t_d, and the total PJM cycle time, $t_c = (t_d + t_r)$ where t_r is the refill time. Additionally, PJM jet velocity, U_0 is the average jet velocity of the PJM once drive has been established.

A summary of the parameters described above are shown in Table 1-5.

Table 1-5 Summary of Dimensional Parameters

Component Name	Variable	Units	Description
Vessel Diameter	D_T	*in*	Inner vessel diameter
Vessel Head Shape	-	-	Elliptical, 2:1 semi-ellipse and Flanged and Dished
Vessel Fill Level	L_V	*in*	Vessel fluid fill height as measured from the bottom head crown
PJM Count	N_{PJM}	-	Number of PJMs in vessel
Inner Pitch Ring Radius	Δ	*in*	Distance from the vessel centerline to the PJM centerline. For a single PJM vessel, this distance is half the vessel diameter. For a chandelier configuration, the distance is measured from the vessel center to the first PJM cluster
PJM Offset	H_0	*in*	Distance from vessel bottom head to the PJM cone
PJM Nozzle Diameter	D_0	*in*	PJM nozzle inner diameter
PJM Drive Time	t_d	*s*	Time of the PJM in drive phase
PJM Refill Time	t_r	*s*	Time to refill PJM after drive
PJM Total Cycle Time	t_c	*s*	$= t_d + t_r$; total time for drive + refill
PJM Jet Velocity	U_0	*m/s*	PJM fluid velocity
Supernate Viscosity	μ_L	*kg/(m·s)*	Supernate shear viscosity
Supernate Density	ρ_L	kg/m^3	
Supernate Mass	m_L	*kg*	
Particle Diameter	d_p	*μm*	Solids mean particle diameter
Particle Density	ρ_p	kg/m^3	
Particle Mass	m_p	*kg*	Total solids mass
Relative Cross-Sectional Area	-	-	$= D_T^2/(N_{PJM} \times D_0^2)$; Compares the vessel cross-sectional area with the total PJM cross-sectional area
PJM Nozzle Offset Ratio	H_0/D_0	-	Compares the PJM nozzle offset with the Nozzle diameter
Duty Cycle	DC	-	$= t_d/(t_d + t_r)$; Ratio of the drive time to the total cycle time
Relative PJM Inner Pitch Ring Radius	Δ/D_0	-	Inner Pitch Ring Radius compared to the PJM nozzle diameter

It is important to emphasize the difference between the V&V effort and design studies. In the V&V effort, referenced by this Gap Analysis, geometrical issues are explicitly incorporated into the CFD model through the mesh. This leaves the fidelity to which the CFD represents the physical processes as the principal concern. Unless new physical processes are introduced to the WTP PJM vessel mixing requirements, changes need not be incorporated into the V&V effort. In contrast, design studies may proceed to investigate the impact of various candidate design changes on vessel performance, but those studies do not influence the underlying physical processes verified through the V&V effort.

2 WTP PJM Equipped Mixing Vessels

2.1 Vessel Space - Dimensional Parameters

Thirty-eight (38) vessels in WTP, listed in Table 1-3, are mixed using PJM devices. The vessel design and contained fluid span a wide range both in size and composition. Table 2-1 and Table 2-2 provide a summary of the ranges of design and simulant (particle) characteristics categorized by the five primary validation variables. A more comprehensive list of the vessel parameters categorized by vessel can be found in Table 6-48 and Table 6-49 in Appendix B.

The vessel parameters are compiled from a variety of data sources and from the most recent information available. The two primary references are Process Inputs Basis of Design (PIBOD), 24590-WTP-DB-PET-09-001 and the EFRT Issue M3 PJM Vessel Mixing Assessments, Volumes 1-10, 24590-WTP-RPT-ENG-08-021-01 thru 24590-WTP-RPT-ENG-08-021-10. The majority of data is taken from the appendices of the Mixing Assessments. The data includes vessel, PJM, material and solids composition information. These data are directly referenced in the table or used to compute the dimensional parameters such as Relative Cross Sectional Area, PJM nozzle offset ratio, PJM pulse tube duty cycle, PJM array characteristic spacing, for example.

Some of the vessel parameter data are from other sources. Based on the mixing assessments, HLP-VSL-00022 and UFP-VSL-00001A/B required design changes to the PJMs array configuration. The vessel design parameters for these vessels are taken from the vessel design drawings, 24590-PTF-MV-UFP-00027002, Rev 0 and 24590-PTF-MV-HLP-00003002, Rev 0. HLP-VSL-00022 has 18 PJMs, 6 located at an inner ring and 12 at an outer ring. UFP-VSL-00001A/B has 12 PJMs, 8 located at an inner and outer radius and 4 at the center of the vessel. Input data for CNP-VSL-00003, CNP-VSL-00004, CXP-VSL-00004 and RDP-VSL-00002A/B is taken from the design drawings, PIBOD, and from 24590-WTP-M0C-50-00004, *Wear Allowances for WTP Waste Slurry Systems*.

Table 2-1 lists the design parameters for the WTP PJM equipped mixing vessels categorized by validation variable. The vessel diameters range from 113 in. (CNP-VSL-00004) to 564 in (FRP-VSL-00002A/B/C/D). The vessel cross sectional area per total PJM cross sectional area per nozzle area ranges from 200 (CNP-VSL-00004) to 1,657 (FRP-VSL-00002A/B/C/D). The PJM nozzle diameters range from 4 in. to 4.25 in. The PJM offset ratio ranges from 1.4 to 4.5. The PJM nozzle velocity ranges from 8 to 16 m/s. The PJM Pulse tube duty cycle ranges from 0.07 to 0.35. The PJM array characteristic spacing, or inner pitch ring radius per nozzle diameter ranges from 6.3 (UFP-VSL-00002A/B) to 21 (PWD-VSL-00033 and PWD-VSL-00043). A detailed list of the individual vessel design parameters is found in Table 6-49.

A summary of the vessels and their shapes are in Figure 2-1.

Table 2-2 lists the fluid composition parameters for the WTP PJM Equipped Mixing Vessels categorized by validation variable. The supernate viscosity ranges from 0.0004 to 0.03 kg/m·s. The supernate density ranges from 996 to 1,392 kg/m^3. The total solids loading ranges from 0% to 20%. Note that the PIBOD lists the minimum and maximum weight percent for each vessel and that most vessels have a minimum content of 0%. Particle diameters range from 4 to 700 microns. Particle density ranges from 2,900 to 11,400 kg/m^3. Total particle loading ranges from 0% to 15.2% percent. A detailed list of particles per vessel is in Table 6-48.

Table 2-1 Design Parameter Summary - WTP PJM Equipped Mixing Vessels

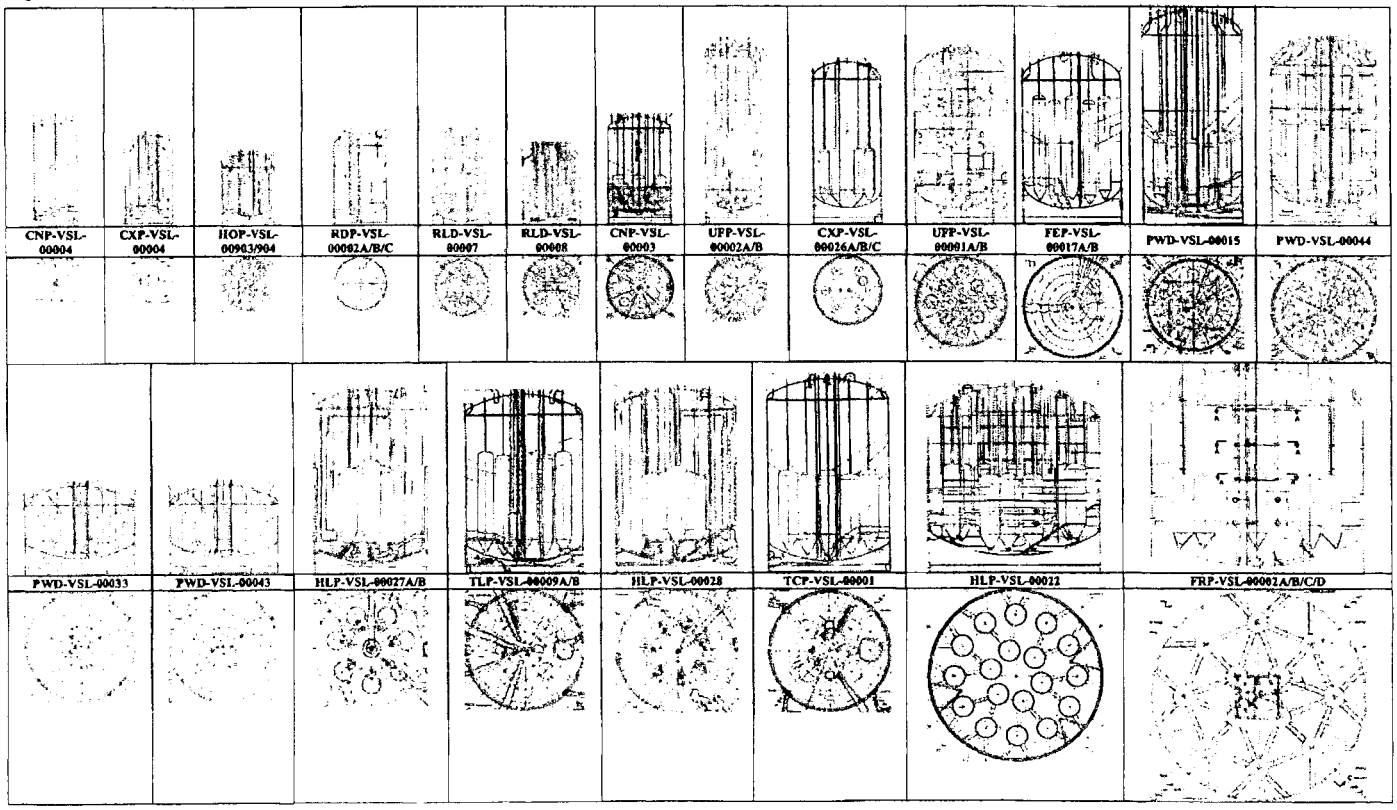
Validation Variable	Range	Vessel Diameter	Relative Cross-Sectional Area	PJM Nozzle Diameter	PJM Nozzle Offset Ratio	PJM Nozzle Velocity	PJM Pulse Tube Duty Cycle	Relative PJM Inner Pitch Ring Radius
		D_T	$D_T^2/(N_{PJM}\times D_0^2)$	D_0	H_0/D_0	U_0	$DC = t_d/(t_d+t_r)$	Δ/D_0
		[in]	[ ]	[in]	[ ]	[m/s]	[ ]	[ ]
Fluid Velocity for Heat Transfer	Min	156	266	4	1.4	8	0.16	6.3
	Max	456	790	4.25	1.5	12	0.26	16.5
Concentration at Suction Line	Min	126	266	4	1.4	8	0.13	6.3
	Max	564	1,657	4.25	1.5	12	0.35	21.0
Miscible Fluid Blending	Min	113	200	4	1.4	8	0.13	6.3
	Max	318	992	4.25	1.5	12	0.35	18.8
Multiple PJM ZOI	Min	168	266	4	1.4	11	0.13	6.3
	Max	564	1,657	4.25	1.5	12	0.30	21.0
Bulk Concentration in Heel	Min	144	266	4	1.4	8	0.13	6.3
	Max	564	1,657	4.25	1.5	12	0.35	21.0

Table 2-2 Simulant/Particle Parameter Summary - WTP PJM Equipped Mixing Vessels

Validation Variable	Range	Supernate Viscosity μ_l [kg/(m·s)]	Supernate Density ρ_l [kg/m^3]	Total Solids Loading Wt% [ ]	Particle Diameter d_p [μm]	Particle Density ρ_p [kg/m^3]
Fluid Velocity for Heat Transfer	Min	0.0006	996	0.0	4	2,710
	Max	0.03	1,374	20.0	700	11,400
Concentration at Suction Line	Min	0.0004	996	0.0	4	2,710
	Max	0.03	1,392	20.0	700	11,430
Miscible Fluid Blending	Min	0.0004	996	0.0	4	2,710
	Max	0.03	1,374	20.0	700	11,400
Multiple PJM ZOI	Min	0.0005	1,001	0.0	4	1,802
	Max	0.03	1,392	20.0	700	11,430
Bulk Concentration in Heel	Min	0.0004	996	0.0	4	1,802
	Max	0.03	1,392	20.0	700	11,430

Note that the low supernate viscosity (less than 1 cP, associated with room temperature water) is due to either the heating of the supernate during vessel operation or occurrences of supernate fluids other than water. The low end of the supernate viscosity occurs for RLD-VSL-00007, however ten other vessels have supernate viscosities less than 0.8cP.

Figure 2-1 WTP PJM Equipped Mixing Vessels to Scale by Internal Diameter



3 Test Vessels

In support of the evaluation of the WTP PJM Equipped Mixing Vessels during mixing operations, a number of independent tests were conducted. These tests covered a range of vessel configurations and mixing conditions, while recording several measurements of interest. The following sections detail a reduced set of test conditions, which align with the vessel functional mixing requirements through the validation variables as described in Section 1.3.1.

3.1 Test Data Availability

Since multiple tests and configurations are available for study, the tests are selected based on the validation variables from Section 1.3.2.

Table 3-1 Data Set Availability - Test Data

Test Set for Comparison	Validation Variable				
	Fluid Velocity for Heat Transfer	**Concentration at Suction Line**	**Miscible Fluid Blending**	**Multiple PJM ZOI**	**Bulk Concentration in Heel**
PNNL (WTP-RPT-077)	N/A	1	5	N/A	N/A
PNNL (WTP-RPT-081)	38	N/A	N/A	N/A	N/A
PNNL (WTP-RPT-182)	N/A	66	N/A	57	N/A
MCE Phase-2	N/A	24	N/A	33	N/A
MCE Pump-down	N/A	5	N/A	5	5
WSU Flume	N/A	N/A	N/A	19	N/A
Total Tests Available	29	96	5	114	5

Note(s):

a. The number of tests listed count the individual tests, not the number of measurements made for each test. The total count varies by test and measurement.
b. PNNL (WTP-RPT-077) refers to the tests described in WTP-RPT-077.
c. PNNL (WTP-RPT-081) refers to the tests described in WTP-RPT-081.
d. PNNL (WTP-RPT-182) refers to the tests described in WTP-RPT-182.
e. MCE Phase-2 refers to the tests described in 24590-WTP-ES-PET-09-001, Rev. 0.
f. MCE Pump-down refers to the tests described in CCN 232596, CCN 218353, and 24590-WTP-RPT-ENG-11-013, Rev. 0.
g. WSU Flume refers to the tests described in 24590-WTP-ES-PET- 10-001, Rev. 0.

Note that the tests presented above are a reduced set of tests from the total available. Details on the selection of tests is in Appendix A. Note that some of the selected data is still under evaluation for use in the V&V effort.

3.1.1 Data Quality

Data quality, as applied to the test data, specifically addresses confidence in the reported data in the form of input and data uncertainty. Data uncertainty is further separated into both systematic and random uncertainty. For the tests selected for use, the data uncertainty may be calculated. The calculation of the uncertainty on a per test (or input/validation variable) basis is not shown here, but may be calculated based on the information in Appendix A.

All test data that are to be used for the validation of FLUENT are NQA-1. Details on the selection of the test cases for use is briefly discussed in Appendix A.

3.1.2 Selection of Test Data Sets

As noted in the previous section, the presented sets only represent a portion of the total tests conducted. Discussed in Section 1.3, and in addition to WTP project requirements on quality, there are two supplementary requirements that a test must fulfill to be useful for the data gap analysis: (1) the dataset measures a validation variable that is relevant to the WTP PJM equipped mixing vessel validation variables, and (2) the dataset is well documented, with the appropriate uncertainty (or error). A discussion of the various available tests and those selected for evaluation are briefly discussed below. Appendix A provides detailed descriptions of the selected test suites from the listed test operators (e.g. PNNL).

3.1.2.1 Test Program - Pacific Northwest National Laboratories (PNNL)

For the PNNL testing data, 22 separate tests were conducted in support of the WTP PJM equipped mixing vessels. These tests covered the following:

- Eleven (11) reports focused principally on slurries having non-Newtonian rheologies
- One (1) report focuses on cohesive solids
- One (1) report focuses on PJM over-blow testing
- Two (2) reports study the effects of anti-foam agents on gas retention and release behavior
- One (1) report assessed the development of a computational model for the PJM mixing systems
- Two (2) reports focused on the control and instrumentation testing of PJMs
- One (1) report is an attempt to reconcile different findings from Phase 1 and Phase 2 testing (no actual test conducted)

None of the 19 tests listed above addressed any of the five validation variables. The remaining three tests provide information on miscible phases, provide fluid velocity, and ZOI measurements.

- WTP-RPT-077 focuses on mixing in a small scale vessel, demonstrating miscible phases (Vessel functional mixing requirements #3 and 4)
- WTP-RPT-081 focuses on a larger scale vessel and measured fluid velocity at several elevations and concentration values at the suction line (Vessel functional mixing requirement #1)
- WTP-RPT-182 focuses on non-cohesive solid mixing at three different scales and provides ZOI measurements for several operational and physical configurations (Vessel functional mixing requirements #2, 5, 6, 7, and 8)

3.1.2.2 Test Program - Mid-Columbia Engineering (MCE)

The MCE tests are in two categories (1) the Phase-2 testing, and (2) the Pump-down testing. The Phase-2 testing suite used two PJM configurations (8 and 12), two PJM nozzle sizes (*4in* and *5in*), and a variety of proposed 'performance enhancements' such as angled nozzles and bubblers, for a total of 92 separate tests. Based on the criteria established in Section 1.1, numbers from those tests which used bubblers or other performance enhancing physical configurations (those that do not correspond with an existing WTP PJM vessel design) are not used. Instead, data from the remaining 70 (of 92) representative tests are used for evaluation, corresponding to the vessel functional mixing requirements #2, 5, 6, 7, and 8.

The Pump-down testing suite used the same physical configuration as the Phase-2 tests, with a smaller number of performance enhancing modifications and overall number of tests (10 total). Of the ten (10) total tests, three (3) were run while spargers were in operation (UFP-01-NQA-003, HLP-27-LOAM-005, and HLP-27-LOAM-006), one (1) experienced particle agglomeration (FRP-02-NQA-002), and another presented a mass discrepancy of 26% at the end of draw down (HLP-27-LOAM-001). The remaining five (5) data sets are available for consideration, corresponding to vessel functional mixing requirement #2, 5, 6, 7, 8, and 10. Note that the term 'LOAM' in the context of this document, represents a referenced document and not the Low Order Accumulation Model.

3.1.2.3 Test Program - Washington State University (WSU)

The WSU Flume tests were conducted to specifically address ZOI. The test configuration included a box flume with two, non-symmetrically spaced pulse tubes within the flume. The tests were conducted with sand as the simulant, and with variations in sand configuration (spread evenly along the flume floor or contained within a specified shape of varying depth). A total of 19 separate experimental tests were performed and all 19 are acceptable for use in this evaluation. These results correspond to vessel mixing requirement #8.

3.1.2.4 Test Program - Savannah River National Laboratories (SRNL)

Five (5) documents are available from the Savannah River National Laboratories (SRNL), however none of them are used in this evaluation.

3.1.2.5 Test Program - British Nuclear Fuels Limited (BNFL)

One (1) document is available from the British Nuclear Fuels Limited (BFNL), however it is not used in this evaluation.

3.2 Test Space - Dimensional Parameters

Based on the reduced set of tests from Table 3-1, the following range of parameters from the current test data sets are available for each validation variable.

Table 3-2 lists the design parameters for the test Vessels categorized by validation variable. The test vessel diameters range from 14.4*in* (PNNL WTP-RPT-182) to 158*in* (PNNL WTP-RPT-081). The vessel cross sectional area per total PJM cross sectional area ranges from 289 (PNNL WTP-RPT-077) to 1,630 (PNNL WTP-RPT-182). The PJM nozzle diameters range from 0.13*in* (PNNL WTP-RPT-182) to 4.03*in* (WSU Flume). The PJM offset ratio ranges from 0.89 (PNNL WTP-RPT-077) to 2.4 (PNNL WTP-RPT-081). The PJM nozzle velocity ranges from 1.9*m/s* (PNNL WTP-RPT-182) to 13*m/s* (MCE Phase-2). The PJM Pulse tube duty cycle ranges from 0.12 (PNNL WTP-RPT-077) to 0.67 (PNNL WTP-RPT-182). The PJM array characteristic spacing ranges from 8 (PNNL WTP-RPT-182) to 18.9 (PNNL WTP-RPT-182, MCE Pump-down, and WSU Flume).

Table 3-2 Design Parameter Summary - Test Configurations

Validation Variable	Range	Vessel Diameter	Relative Cross-Sectional Area	PJM Nozzle Diameter	PJM Nozzle Offset Ratio	PJM Nozzle Velocity	PJM Pulse Tube Duty Cycle	Relative PJM Inner Pitch Ring Radius
		D_T	$D_T^2/(N_{PJM} \times D_0^2)$	D_0	H_0/D_0	U_0	$DC = t_d/(t_d+t_r)$	Δ/D_0
		[in]	[ ]	[in]	[ ]	[m/s]	[ ]	[ ]
Fluid Velocity for Heat Transfer	Min	-	-	-	-	-	-	-
	Max	153	378	3.94	2.38	10	0.22	11.8
Concentration at Suction Line	Min	14.4	295	0.13	1.0	1.9	0.16	8.0
	Max	70	1630	0.92	1.5	13.0	0.67	18.9
Miscible Fluid Blending	Min	-	-	-	-	3.2	0.12	-
	Max	34	289	2.0	0.89	8.1	0.20	8.5
Multiple PJM ZOI	Min	14.4	295	0.13	1.0	1.9	0.16	8.0
	Max	138	1630	4.03	1.5	13.0	0.67	18.9
Bulk Concentration in Heel	Min	-	545	0.40	-	-	0.16	8.0
	Max	43.3	702	0.65	1.5	5.0	0.18	18.9

Note(s):
a. Values identified with a '-' indicate that there is only a single value for that dimension/variable over the tests selected for that validation variable.

Table 3-3 lists the fluid composition parameters for the test Vessels categorized by validation variable. The supernate viscosity ranges from 0.0007 (PNNL WTP-RPT-182) to 0.01 *kg/m·s* (PNNL WTP-RPT-081, MCE Phase-2, and WSU Flume). The supernate density ranges from 994kg/m^3 (PNNL WTP-RPT-182) to 1,141kg/m^3 (MCE Phase-2). The total solids loading ranges from 0% (PNNL WTP-RPT-077) to 20% (PNNL WTP-RPT-081). Particle diameters range from 7 microns (MCE Phase-2) to 775 microns (MCE Pump-down). Particle density ranges from 1,307kg/m^3 (PNNL WTP-RPT-077) to 11,200kg/m^3 (MCE Pump-down).

Table 3-3 Simulant/Particle Parameter Summary - Test Configurations

Validation Variable	Range	Supernate Viscosity μ_l [kg/(m·s)]	Supernate Density ρ_l [kg/m^3]	Total Solids Loading Wt% [ ]	Particle Diameter d_p [μm]	Particle Density ρ_p [kg/m^3]
Fluid Velocity for Heat Transfer	Min	-	-	5	10	-
	Max	0.001	998	20	35	2490
Concentration at Suction Line	Min	0.001	994	0.17	5	2420
	Max	0.010	1141	31.6	775	11200
Miscible Fluid Blending [b]	Min	0.0009	-	-	-	-
	Max	0.0014	998	-	-	1307
Multiple PJM ZOI	Min	0.001	994	0.17	5	2420
	Max	0.010	1141	31.6	775	11200
Bulk Concentration in Heel	Min	0.001	994	0.17	4.7	2420
	Max	0.008	1130	31.6	775	11200

Note(s):
a. Values identified with a '-' indicate that there is only a single value for that dimension/variable over the tests selected for that validation variable.
b. For the Miscible Fluid Blending , the single test associated with that validation variable is essentially treated as a single phase and therefore no information on the particle diameter or density is available.

The tables presented in this section are a summary of the available test parameters and represent the range of values covered by the existing tests. Details on individual test configurations and information on a specific test may be found in Appendix A. A summary of the validation variables and the selected tests are in Sections 3.2.1 through 3.2.5.

3.2.1 Fluid Velocity for Heat Transfer

Experimental results for fluid velocity are available from PNNL report (WTP-RPT-081). A total of 38 data sets are available for the comparison of fluid velocity, all of which are from report WTP-RPT-081. Within these 38 data sets, the following information is available:

1. Twenty (20) of these tests contain no solids, while of the remaining eighteen (18), nine (9) have 5% (by weight) of 10 micron particles (effectively single-phase), and nine (9) have 20% (by weight) of 35 micron particles.
2. Velocity probes are located at five distinct vertical positions and at radial distances (from the vessel centerline) of zero to 24 inches (total vessel diameter is 153*in*)
3. Within these 29 data sets, data is taken between 13 and 69 PJM cycles.

The design parameter range (Table 3-2) for this test is limited, since only a single physical configuration was tested. The simulant parameters are varied and have ranges in the supernate density (998 at ρ_l), particle diameter ($10 \leq d_p \leq 35$), and particle loading ($5 \leq Wt\%_p \leq 20$).

3.2.2 Average and Peak Concentration at the Suction Line Inlet

Experimental results for average particle concentration at the suction line are available from the PNNL report (WTP-RPT-182), the MCE Phase-2 report (24590-WTP-ES-PET-09-001, Rev. 0), HLP-22 draw-down testing (CCN 218353), FEP-17 draw-down testing (CCN 232596), HLP-27 draw-down testing (24590-WTP-RPT-ENG-11-013, Rev. 0) and LTTS vessel testing (WTP-RPT-081). Specifically, the PNNL (WTP-RPT-182) measures the concentration of a single particle class, but has no suction line. MCE Phase-2 measures density with a loop sampler but no suction-line, per se. The pump-down runs (FEP-17, HLP-27, and HLP-22) measure instantaneous density using a suction line and measure concentration on quarter-batch intervals.

3.2.3 Miscible Fluid Blending

Five data sets are available for miscible fluids blending, all from report WTP-RPT-077. From the point of view of WTP-RPT-077, they exhibit a span in terms of power per unit volume, by virtue of velocity and duty-cycle differences. Together, time-to-mix (as defined in the report) varies from 15 minutes to greater than 94 minutes.

3.2.4 Multiple-PJM ZOI

Multiple-jet ZOI measurements are available from four general sources: PNNL Phase-1 testing (WTP-RPT-182), the WSU flume (24590-WTP-ES-PET- 10-001, Rev. 0), MCE Phase-2 testing 24590-WTP-ES-PET-09-001, Rev. 0 and each of the vessel Pump-down cases (HLP-22 - CCN 218353, FEP-17 - CCN 232596, and HLP-27 - 24590-WTP-RPT-ENG-11-013, Rev. 0).

3.2.5 Bulk Concentration in the Heel by Constituent

The bulk concentration in the heel on a constituent basis is defined as the concentration of individual constituents in the residual volume of a PJM vessel after Pump-down. It is inversely related to the concentration at the suction line inlet, i.e. heel concentrations increases with decreasing concentration at the suction line, and vice-versa. Heel concentration is a long-time integrated quantity, which depends on the physical mechanisms that are active at any time during the PJM vessel Pump-down. In contrast, the concentration measurements at the suction line (or any measurement station), depend on the physical measurements only at the instant of sampling. These measurements are from the four MCE Pump-down

testing cases (HLP-22 - CCN 218353, FEP-17 - CCN 232596, and HLP-27 - 24590-WTP-RPT-ENG-11-013, Rev. 0).

3.3 Comparison of WTP PJM Equipped Vessels and Test Vessels

The figures in Sections 3.3.6 through 3.3.10 provide a qualitative comparison of the as-designed WTP PJM Equipped Mixing Vessels and the current available Test Vessels. Each page compares a different validation variable (see Section 1.3.2) and is based on the test cases associated with that variable (Table 3-1). The charts compare eleven (11) variables defining the vessel geometry and operation (see Section 1.4). A summary of the comparison is as follows:

3.3.1 Fluid Velocity

For this variable there was a single applicable test set (PNNL WTP-RPT-081) for six (6) vessel sets (CNP-VSL-00003, HLP-VSL-00022, HLP-VSL-00027 A/B, HLP-VSL-00028, UFP-VSL-00001A/B, and UFP-VSL-00002 A/B). For most design conditions, the test set has a point within the WTP PJM vessel space. The PJM offset ratio and the nozzle diameter both have test values outside of the established range. The supernate and particle parameters for the selected test also span well for the WTP PJM vessels, with the exception of the particle density, where the test vessel is outside the WTP PJM vessel range (low).

3.3.2 Suction Line Concentration

The suction line results are from three (3) separate tests (PNNL WTP-RPT-182, MCE Phase-2 and MCE Pump-down) compared to 18 vessel sets (see Table 1-3). For the design variables all test conditions are within the WTP PJM Equipped Mixing vessels with the exception of the PJM nozzle velocity (misses the upper end) and the duty cycle (misses the lower operating end). However, all supernate and particle parameters are within range.

3.3.3 Miscible Fluids Blending

A single test (PNNL WTP-RPT-077) compares with ten (10) vessel sets (see Table 1-3). For this variable, the test vessel misses the cross sectional area comparison (Vessel section to total PJM section, low), the nozzle offset ratio (low), and the PJM velocity (low). The simulant and particle definitions do not span the expected WTP PJM Equipped Mixing vessel information and are low compared to the WTP vessels in most instances.

3.3.4 Multiple PJM ZOI

Four tests (PNNL WTP-RPT-182, MCE Phase-2, MCE Pump-down, and WSU Flume) compare with eight (8) vessel sets (see Table 1-3). The comparison of the design variables show that the current test cases span the WTP PJM Equipped Mixing vessel cases for most parameters. Both the PJM velocity (misses the higher operating end) and the duty cycle (misses the lower operating end) are outside of the stated WTP PJM Equipped Mixing vessel span. The values for the supernate and particle parameters are all within the stated WTP PJM Equipped Mixing vessel range.

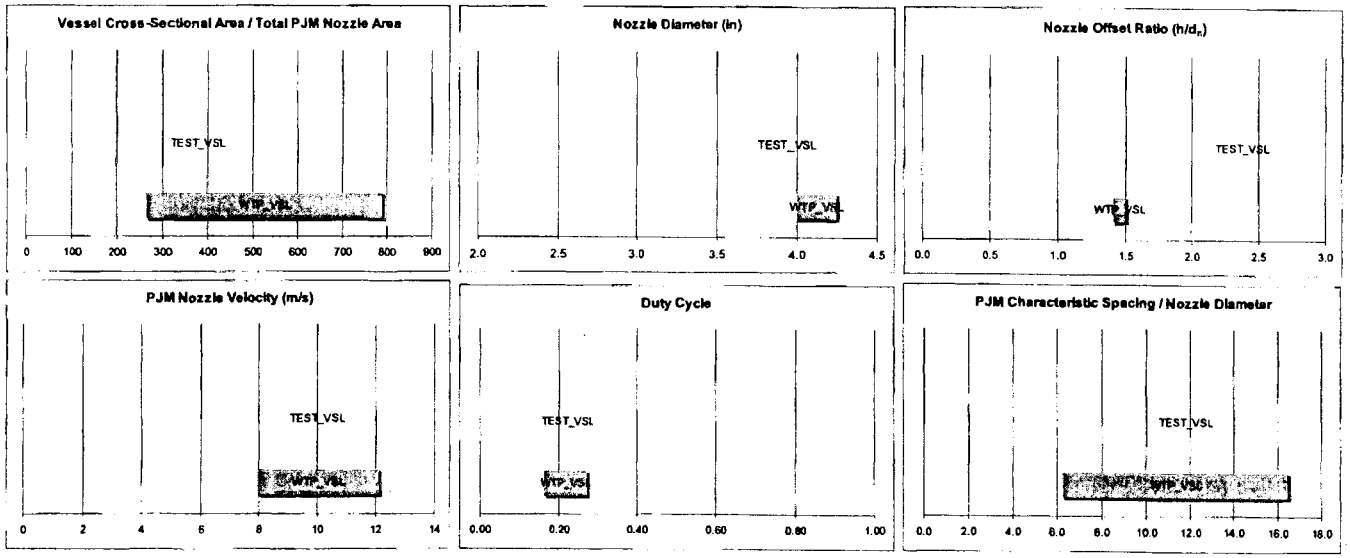
3.3.5 Heel Concentration

A single test (MCE Pump-down) is used for this variable, compared with a total of 17 vessel sets (see Table 1-3). The design parameters show some overlap for most conditions, with the PJM nozzle velocity displaying the least. The supernate and particle parameters show consistent overlap for all variables.

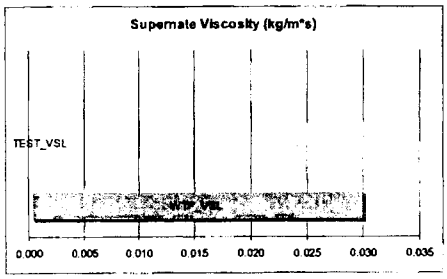
3.3.6 Fluid Velocity for Heat Transfer - Figures

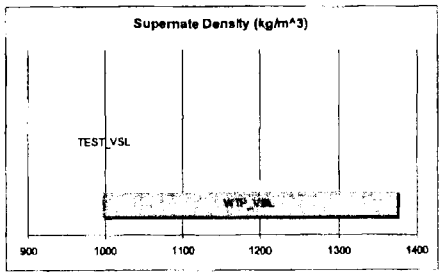
The vessels and test used for this comparison are based on the information from Table 1-3 and Table 3-1. Note that for this comparison, the WTP PJM Equipped Mixing Vessel (WTP_VSL) and Test Vessel (TEST_VSL) diameters are not shown. Those locations where there is no 'bar' indicate that there is a single data point for that characteristic, with the value centered on the test title (e.g. at the '_' of the 'WTP_VSL'). See Table 2-1, Table 2-2, Table 3-2, and Table 3-3 for actual values.

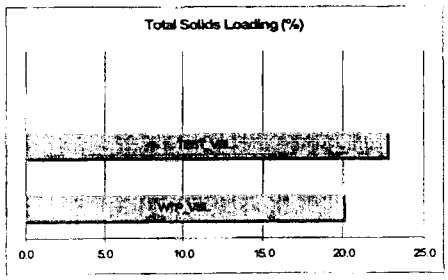
The first set of images are of the Design Parameters from Table 2-1 and Table 3-2.

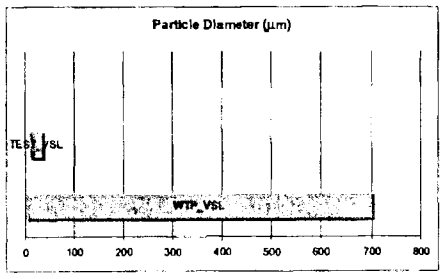


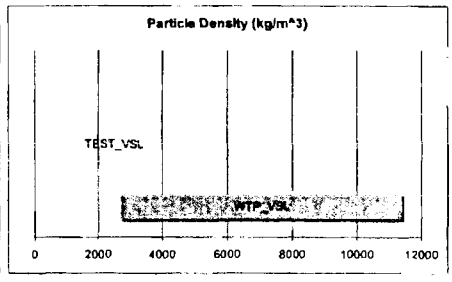
The second set of images are of the simulant/particle Parameters from Table 2-2 and Table 3-3.







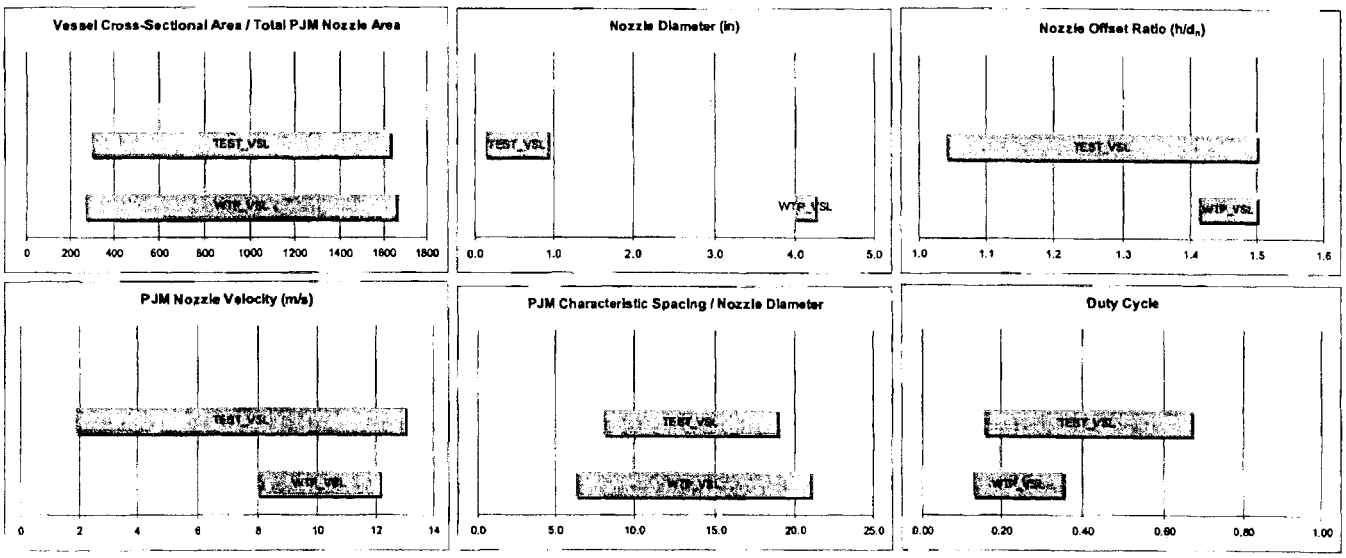




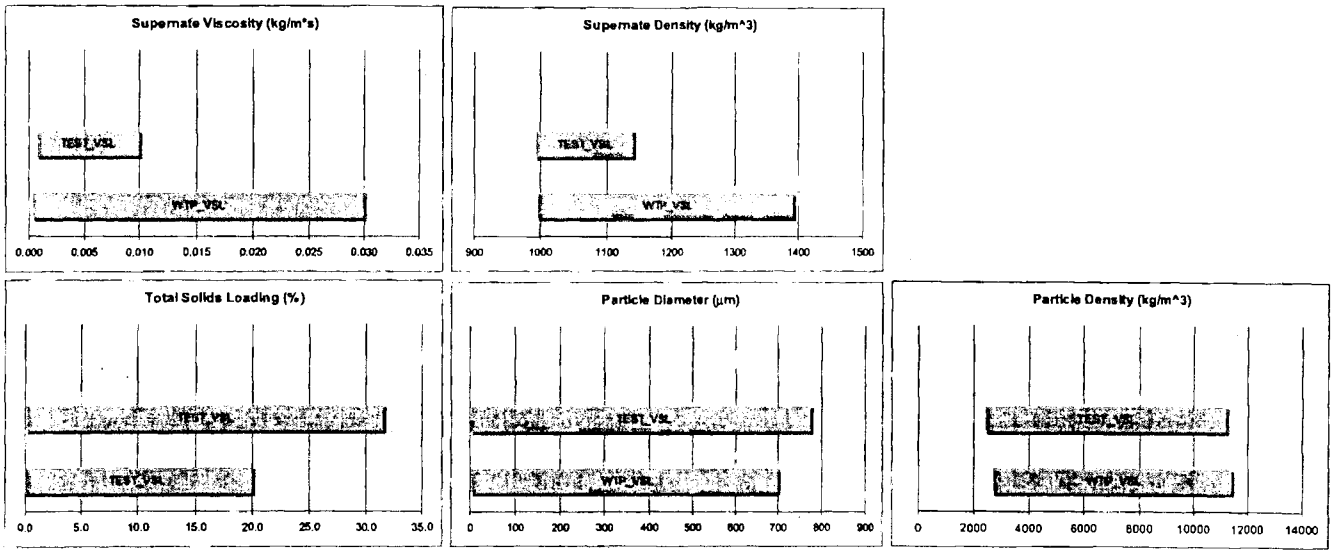
3.3.7 Suction Line Concentration - Figures

The vessels and test used for this comparison are based on the information from Table 1-3 and Table 3-1. Note that for this comparison, the WTP PJM Equipped Mixing Vessel (WTP_VSL) and Test Vessel (TEST_VSL) diameters are not shown. Those locations where there is no 'bar' indicate that there is a single data point for that characteristic, with the value centered on the test title (e.g. at the '_' of the 'WTP_VSL'). See Table 2-1, Table 2-2, Table 3-2, and Table 3-3 for actual values.

The first set of images are of the Design Parameters from Table 2-1 and Table 3-2.



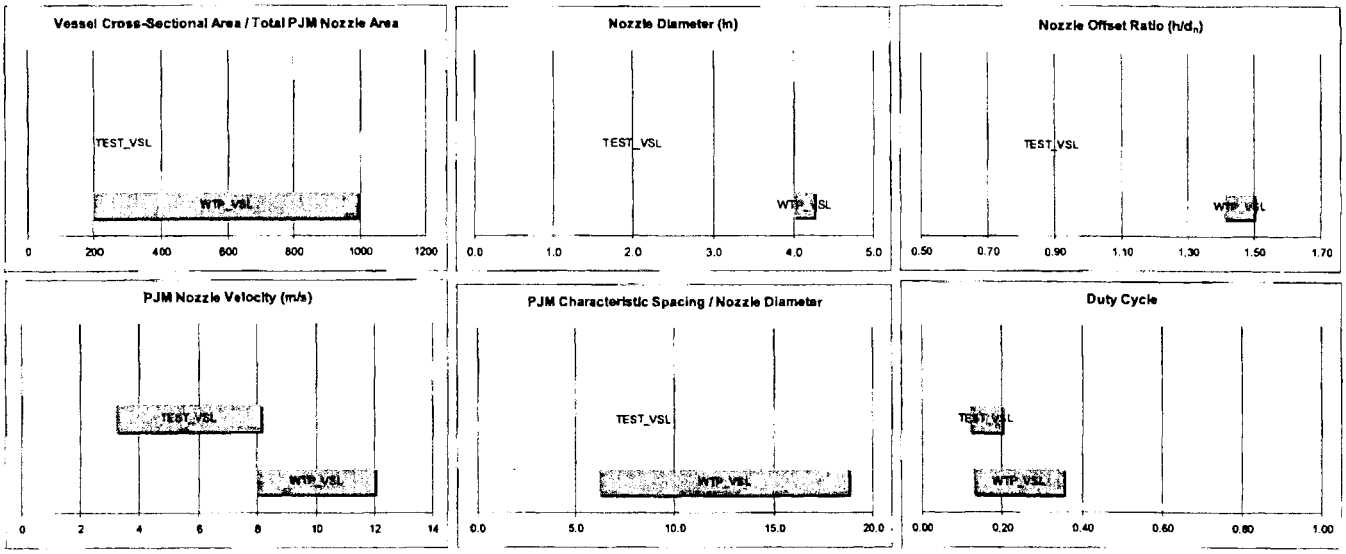
The second set of images are of the simulant/particle Parameters from Table 2-2 and Table 3-3.



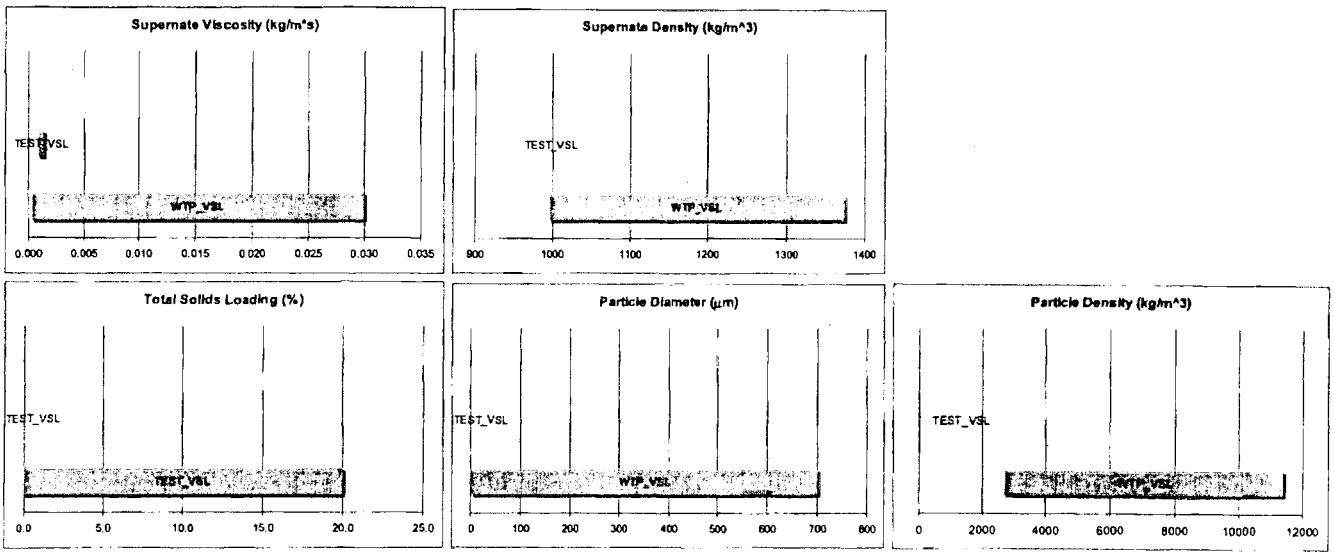
3.3.8 Miscible Fluid Blending - Figures

The vessels and test used for this comparison are based on the information from Table 1-3 and Table 3-1. Note that for this comparison, the WTP PJM Equipped Mixing Vessel (WTP_VSL) and Test Vessel (TEST_VSL) diameters are not shown. Those locations where there is no 'bar' indicate that there is a single data point for that characteristic, with the value centered on the test title (e.g. at the '_' of the 'WTP_VSL'). See Table 2-1, Table 2-2, Table 3-2, and Table 3-3 for actual values.

The first set of images are of the Design Parameters from Table 2-1 and Table 3-2.



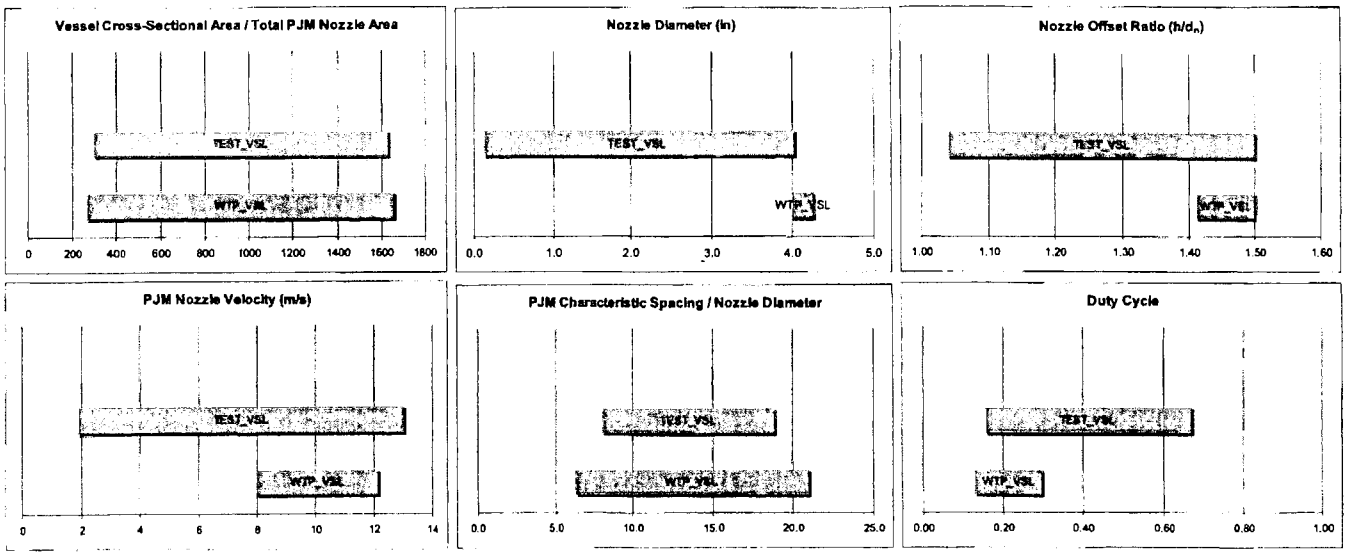
The second set of images are of the simulant/particle Parameters from Table 2-2 and Table 3-3.



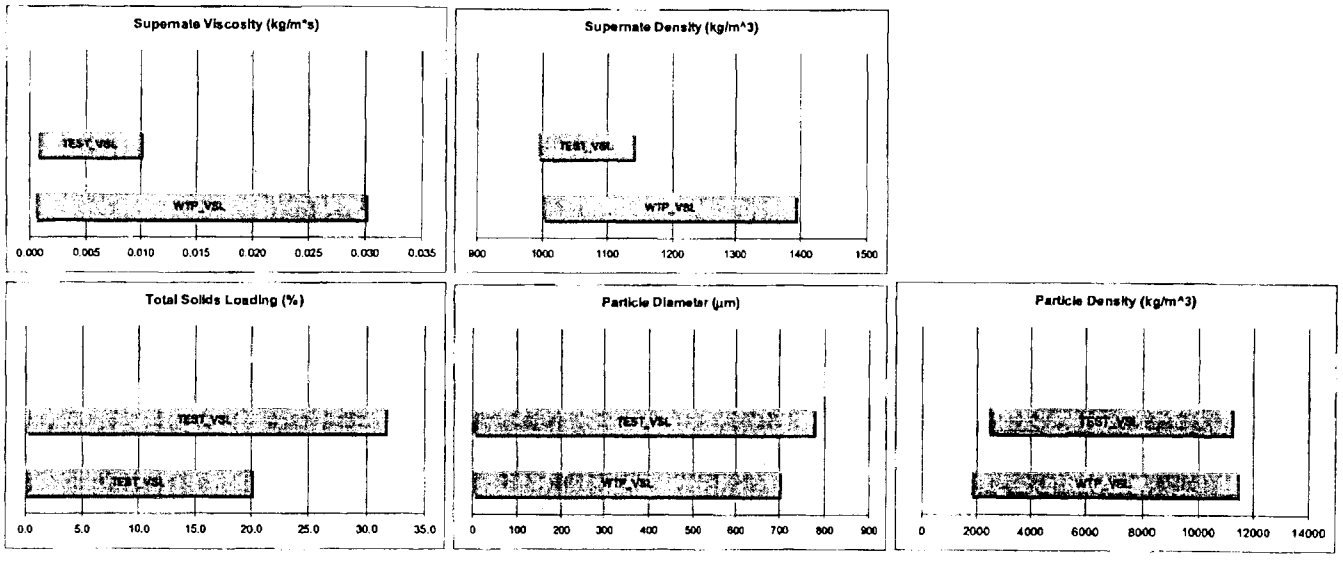
3.3.9 Multiple PJM ZOI - Figures

The vessels and test used for this comparison are based on the information from Table 1-3 and Table 3-1. Note that for this comparison, the WTP PJM Equipped Mixing Vessel (WTP_VSL) and Test Vessel (TEST_VSL) diameters are not shown. Those locations where there is no 'bar' indicate that there is a single data point for that characteristic, with the value centered on the test title (e.g. at the '_' of the 'WTP_VSL'). See Table 2-1, Table 2-2, Table 3-2, and Table 3-3 for actual values.

The first set of images are of the Design Parameters from Table 2-1 and Table 3-2.



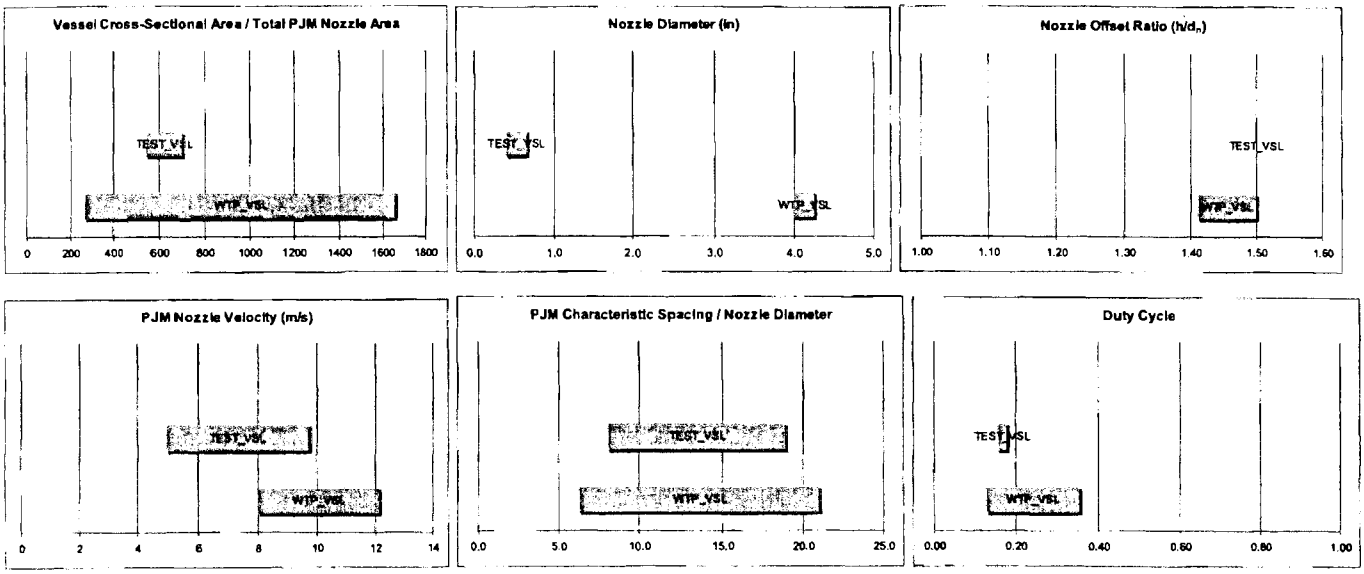
The second set of images are of the simulant/particle Parameters from Table 2-2 and Table 3-3.



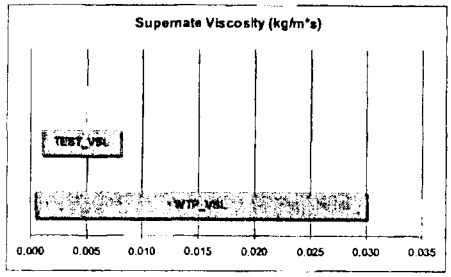
3.3.10 Heel Concentration - Figures

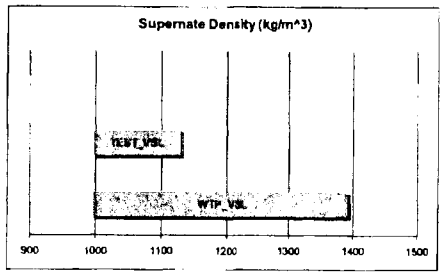
The vessels and test used for this comparison are based on the information from Table 1-3 and Table 3-1. Note that for this comparison, the WTP PJM Equipped Mixing Vessel (WTP_VSL) and Test Vessel (TEST_VSL) diameters are not shown. Those locations where there is no 'bar' indicate that there is a single data point for that characterisnc, with the value centered on the test title (e.g. at the '_' of the 'WTP_VSL'). See Table 2-1, Table 2-2, Table 3-2, and Table 3-3 for actual values.

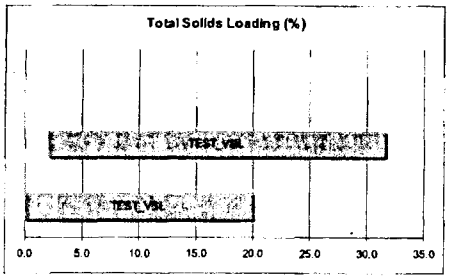
The first set of images are of the Design Parameters from Table 2-1 and Table 3-2.

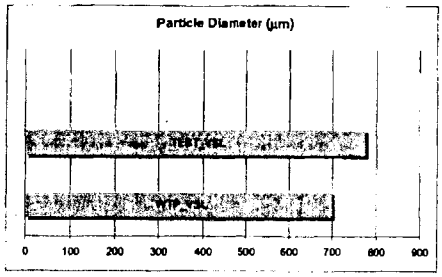


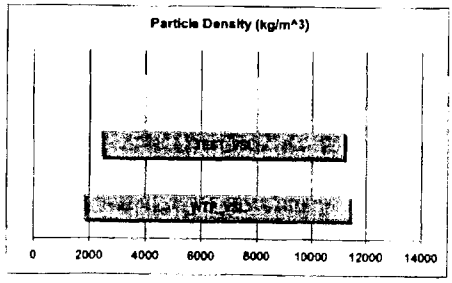
The second set of images are of the simulant/particle Parameters from Table 2-2 and Table 3-3.











3.3.11 Summary of Comparison Charts

The charts in the previous five sections provide a visual comparison of the WTP PJM Equipped Mixing vessels with the test vessels for a variety of parameters. Those charts are summarized in table format (Table 3-4 and Table 3-5).

Table 3-4 Design Parameters - Comparison WTP PJM Equipped to Test Vessels

Name	Vessel Diameter		Relative Cross-Sectional Area		PJM Nozzle Diameter		PJM Nozzle Offset Ratio		PJM Nozzle Velocity		PJM Pulse Tube Duty Cycle		Relative PJM Inner Pitch Ring Radius	
	D_T		$D_T^2/(N_{PJM} \times D_0^2)$		D_0		H_0/D_0		U_0		$DC = t_d/(t_d+t_r)$		Δ/D_0	
	[in]		[ ]		[in]		[ ]		[m/s]		[ ]		[ ]	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Fluid Velocity for Heat Transfer														
WTP	168	456	266	790	4.0	4.3	1.4	1.5	8.0	12.1	0.16	0.27	6.3	16.5
Test	153	153	378	378	3.9	3.9	2.4	2.4	10.0	10.0	0.22	0.22	11.8	11.8
Concentration at Suction Line														
WTP	144	564	266	1657	4.0	4.3	1.4	1.5	8.0	12.1	0.13	0.35	6.3	21.0
Test	14.4	70	295	1630	0.1	0.9	1.0	1.5	1.9	13.0	0.16	0.67	8.0	18.9
Miscible Fluid Blending														
WTP	113	318	200	992	4.0	4.3	1.4	1.5	8.0	12.0	0.13	0.35	6.3	18.8
Test	34	34	289	289	2.0	2.0	0.9	0.9	3.2	8.1	0.12	0.20	8.5	8.5
Multiple PJM ZOI														
WTP	168	564	266	1657	4.0	4.3	1.4	1.5	8.0	12.1	0.13	0.30	6.3	21.0
Test	14.4	138	295	1630	0.1	4.0	1.0	1.5	1.9	13.0	0.16	0.67	8.0	18.9
Heel Concentration														
WTP	144	564	266	1657	4.0	4.3	1.4	1.5	8.0	12.1	0.13	0.35	6.3	21.0
Test	43.3	43.3	545	702	0.4	0.7	1.5	1.5	5.0	9.7	0.16	0.18	8.2	18.9

Table 3-5 Simulant/Particle Parameters - Comparison WTP PJM Equipped to Test Vessels

Test Name	Supernate Viscosity		Supernate Density		Total Solids Loading		Particle Diameter		Particle Density	
	μ_l		ρ_l		Wt%		d_p		ρ_p	
	[kg/(m·s)]		[kg/m^3]		[ ]		[μm]		[kg/m^3]	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Fluid Velocity for Heat Transfer										
WTP	0.000	0.030	996	1374	0.0	20.0	3.9	700	2710	11400
Test	0.001	0.001	998	998	0.0	22.7	10	35	2490	2490
Concentration at Suction Line										
WTP	0.000	0.030	996	1392	0.0	20.0	3.9	700	2710	11430
Test	0.001	0.010	994	1141	0.2	31.6	4.7	775.1	2420	11200
Miscible Fluid Blending										
WTP	0.000	0.030	996	1374	0.0	20.0	3.9	700	2710	11400
Test	0.001	0.001	998	998	0.0	0.0	0	0	1307	1307

Test Name	Supernate Viscosity		Supernate Density		Total Solids Loading		Particle Diameter		Particle Density	
	μ_l		ρ_l		Wt%		d_p		ρ_p	
	[kg/(m·s)]		[kg/m^3]		[ ]		[μm]		[kg/m^3]	
Multiple PJM ZOI										
WTP	0.001	0.030	1001	1392	0.0	20.0	3.9	700	1802	11430
Test	0.001	0.010	994	1141	0.2	31.6	4.7	775.1	2420	11200
Heel Concentration										
WTP	0.000	0.030	996	1392	0.0	20.0	3.9	700	1802	11430
Test	0.001	0.008	998	1130	2.0	31.6	4.7	775.1	2420	11200

4 Gap Analysis

The gap analysis is conducted in five steps:

1. A global survey of dimensional WTP PJM equipped vessel parameter ranges is conducted in Section 4.1 and identifies overall gaps in the available test data.
2. A survey of the WTP PJM equipped vessel dimensional parameter ranges by validation variable is conducted in Section 4.2 to identify specific gaps in the available test data..
3. The governing equations for the Fluent Eulerian-Granular multiphase model are presented in dimensionless form in Section 4.3 and identifies a minimum set of independent parameters for simulation of WTP PJM equipped vessel performance.
4. A discussion of WTP PJM equipped vessel physics and operational performance is presented in Section 4.4 and a set of dimensionless parameters are selected based on the shared physics between CFD and WTP PJM equipped vessels.
5. A survey of the dimensionless parameter ranges (defined in Section 4.4) for the V&V dataset and for the plant (WTP PJM equipped vessels) is presented in Section 4.5 and identifies gaps in the V&V dataset relative to the governing equations solved by CFD.

These steps are detailed in Sections 4.3 through 4.5.

4.1 WTP PJM Equipped and Test Vessel Survey - Overall Summary

WTP PJM equipped vessels and test vessel surveys are documented in Sections 2 and 3, respectively. The global survey identifies gaps in the existing test data for suction line performance at plant scale and PJM performance in vessels at the largest plant diameters.

4.1.1 Requirements for a V&V Dataset for CFD

An appropriate dataset for V&V of CFD for PJM vessel performance

- must span the ranges of parameters important to the dynamics of the governing equations at plant scale to ensure that the important terms in the governing equations are exercised and
- must span the range of parameters known to be important to PJM vessel physics in order for the validation step in the V&V process to show that the physics models in CFD adequately span the range of local physics.

It is expected that the parameters required for CFD will span the parameters known to be important to WTP PJM equipped vessel physics. This expectation will be evaluated in the following sections.

4.1.2 Design Parameter Range Evaluation

Global minimum and maximum values for PJM vessel parameters from the plant wide and test vessel surveys, Sections 2 and 3, are summarized in Table 4-1.

Table 4-1 Global Summary of Design Parameter Ranges

Platform	Tank Diameter		Nozzle Diameter		Nozzle Offset Ratio	
	[in]		[in]		-	
	min	max	min	max	min	max
WTP VSL	113	564	4.00	4.25	1.4	1.5
TEST VSL	15	153	0.13	4.03	0.9	2.4
Platform	**Relative Area Per Pulse Tube**		**Relative Inter-PJM Spacing**		**Nozzle Velocity**	
	-		-		[m/s]	
	min	max	min	max	min	max
WTP VSL	200	1657	6.3	21.0	8	16
TEST VSL	289	1630	8.0	18.9	2	13
Platform	**Duty Cycle**		**Supernate Viscosity**		**Supernate Density**	
	-		[cP]		[kg/m^3]	
	min	max	min	max	min	max
WTP VSL	0.08	0.35	0.4	30.0	996	1392
TEST VSL	0.12	0.67	0.7	10.0	994	1141
Platform	**Total Solids Loading**		**Particle Diameter**		**Particle Density**	
	Wt%		[μm]		[kg/m^3]	
	min	max	min	max	min	max
WTP VSL	0.0%	20.0%	4	700	1802	11430
TEST VSL	0.0%	31.6%	0	775	1307	11200

Table 4-1 show the global ranges documented for the WTP PJM equipped mixing vessels and the available test data. A comparison of the pure numbers for the tank and nozzle diameter for the test cases, shows that the upper bounds are less than the vessels under consideration. However, for these parameters, standard industry scale (1:5, etc) may be used to extrapolate any error or model bias. Based on geometric scale rules, no gap is determined to exist for either tank or nozzle diameter.

WTP PJM array design strategy bases the number and size of pulse tubes in a vessel based on the floor area coverage. This methodology results in a reduced dependence on specific geometric parameters such as tank diameter, since the relevant measure is the area of the tank relative to the pulse tube area. Additional characteristic length scales for the nozzle diameter, nozzle offset ratio, and PJM spacing are also used. These length scales are used for the selection of V&V datasets due to their influence in WTP PJM equipped mixing vessel design.

4.1.2.1 Suction Line Performance

The plant wide and test vessel surveys could identify only one source of data for pumpdown to heel. The tests were conducted in the Mid-Columbia Engineering (MCE) complex in Richland, WA in a 43.2 in. vessel with scaled suction line geometry and parameters. The absence of data for suction line performance at plant scale is a gap in the existing dataset.

The accuracy of CFD to predict particle removal through the suction line affects two of the five validation variables, suction line concentration and heel concentration. The full suite of multiphase physics options in a CFD model are required to model suction line physics successfully. Assessment of the maturity of current multiphase parameterizations relative to the prediction of PJM vessel performance is a specific

goal of the CFD V&V effort, therefore, there is no historical precedence to suggest the ability of CFD to model suction line performance at plant scale and parameters is not of concern.

It is recommended that the gap in suction line performance data at plant scale be closed through additional pumpdown testing in a large-scale vessel extending the dynamic range of suction line modeling by CFD to larger scale.

4.1.2.2 WTP PJM Equipped Vessels with Spargers

The current design confirmation strategy for use of CFD does not include simulation of vessel sparging. Selection of the V&V dataset, therefore, avoided inclusion of vessel runs with spargers. Sparging will be active in the Chandelier-array vessels (HLP-27A/B, HLP-28, and UFP-2A/B) in order to maintain fluid shearing and Newtonian flow in the upper regions of the vessels. The current strategy is to evaluate these vessels with CFD but without sparging.

Inclusion of the effects of sparging will be considered as a potential gap in the V&V dataset if the project (WTP) maintains the approach of using CFD calculations to satisfy vessel criteria for either cool to transfer or miscible blending.

4.1.2.3 Other Geometry and Flow Parameters

Table 4-1 shows that the following variables demonstrate a significant (or full) overlap between existing tests and plant-scale PJM vessels:

- PJM pulse tube nozzle diameters (standard plant value is 4 in.),
- PJM pulse tube nozzle offset ratios (standard plant value is 1.5),
- Relative cross-sectional areas per pulse tube,
- Relative inter-PJM spacings,
- PJM nozzle velocities,
- PJM duty cycles,
- Supernate properties, and
- Solids properties.

The surveys presented in Sections 2 and 3 also confirm that available datasets for V&V of CFD span the range of PJM array planforms at the plant,

- Standard 4, 8, 12, and 18 pulse tube arrays and
- Chandelier arrays

and span PJM vessel head shapes,

- flanged and dished
- spherical
- semi-elliptic

4.1.3 Summary of Design Parameter Ranges

The following items are determined from an overall view of the WTP PJM equipped vessels to the existing available test data.

1. The lack of plant-scale suction line performance data is identified as a gap in the global assessment of PJM vessel parameters.
2. The lack of sparging runs for HLP-27A/B, HLP-28, and UFP-2A/B is identified as a gap in the global assessment of PJM vessel parameters.

3. A gap in vessel diameter relative to the large vessels in the plant is identified in the global assessment of PJM vessel parameters. Vessel diameter for large plant-scale vessels is a gap that will not be closed through plant-scale testing for each PJM vessel. The significance of this gap is significantly reduced
    a. Through understanding PJM vessel flows in terms of local flow volumes organized by pulse tube array geometry introducing a primary length scale related to cross-sectional area to pulse tube count, and
    b. Through understanding the inherent ability of CFD to explicitly model changes in geometry based on first principle governing equations and model formulations.

Further closure of this gap can be achieved by extending the dynamic range of the CFD V&V dataset to larger scales relative to the parameters governing WTP PJM vessel simulation.

4.1.4 Discussion of Multivariate Techniques

In addition to covering the range of physical behavior, the V&V models also assess the error and uncertainty between the model and the selected test data. In those cases where the assessed model errors and uncertainties for the validation data are similar, the values for error and uncertainty may be extended to plant scale with confidence. However, if a significant difference between model errors and uncertainties is observed, a multivariate approach will be assessed to extend these values to plant scale.

An example of one possible method is Hills' Method of Model-Based Weights, J.R. Hamilton and R.G. Hills (2010a) and J.R. Hamilton and R.G. Hills (2010b). This is a multivariate approach that has been tailored for use with the kind of data set that is currently available for V&V of CFD.

- The method allows use of sparse data, relative to the data requirements for regression.
- The method allows validation variables to be different from the application variable, as long as the significant dependencies are shared.
- The method allows use of validation experiments different from the application experiment.

The principle drawback of Hills method relative to V&V of CFD for confirmation of WTP PJM equipped vessel design, is that community experience with the method is limited. This method is not currently used in the V&V analysis, and discussion of this method is for information only.

4.2 WTP PJM Equipped and Test Vessel Survey - Validation Variable Summary

In Section 1.3.2, five validation variables are selected for V&V of CFD based on data to be supplied from CFD to the WTP project to assess whether the WTP PJM equipped mixing vessel mixing requirements are satisfied. The validation variables are (1) Fluid Velocity at the outer wall, (2) Concentration at the Suction Line, (3) Miscible Fluid blending, (4) Multiple PJM ZOI measurements, and (5) Concentration of the Heel.

Subsets of existing data available for V&V of CFD are different for each of the five validation variables. This section looks at gaps in the existing data available for V&V of CFD for each validation variable separately.

4.2.1 Velocity Measurements

Velocity measurements near the outer walls of PJM vessels are requested by the WTP project to use as input to heat transfer correlations for the non-Chandelier-array PJM vessels. Near-wall velocities are not required for the Chandelier-array vessels (HLP-27, HLP-28, and UFP-2), because the WTP project will

evaluate heat transfer for them using the alternate techniques described in 24590-WTP-RPT-ENG-08-021-03, Rev 1.

The existing datasets for V&V provide no velocity measurements near the outer wall in a PJM vessel, suggesting a gap in this variable. Available velocity probe locations lie along the vessel centerline and at radial offsets remaining close to the centerline.

A summary of the design parameter ranges for velocity measurements is provided in Table 4-2. The tests listed as applicable in Section 3.2.1 provide measurements at the test vessel centerline, but do not provide comprehensive values at the outer wall. Additional detail on the specific tests and the velocity probe locations is found in A.2.2.

Table 4-2 Summary of Design Parameter Ranges for Velocity Measurements

Platform	Tank Diameter		Nozzle Diameter		Nozzle Offset Ratio	
	[in]		[in]		-	
	min	max	min	max	min	max
WTP VSL	168	456	4.00	4.25	1.4	1.5
TEST VSL	153	153	3.94	3.94	2.4	2.4
Platform	**Relative Area Per Pulse Tube**		**Relative Inter-PJM Spacing**		**Nozzle Velocity**	
	-		-		[m/s]	
	min	max	min	max	min	max
WTP VSL	266	790	6.3	16.5	8	12
TEST VSL	378	378	11.8	11.8	10	10
Platform	**Duty Cycle**		**Supernate Viscosity**		**Supernate Density**	
	-		[cP]		[kg/m^3]	
	min	max	min	max	min	max
WTP VSL	0.16	0.27	0.4	30.0	996	1374
TEST VSL	0.22	0.22	1.0	1.0	998	998
Platform	**Total Solids Loading**		**Particle Diameter**		**Particle Density**	
	Wt%		[µm]		[kg/m^3]	
	min	max	min	max	min	max
WTP VSL	0.0%	20.0%	4	700	2710	11400
TEST VSL	0.0%	22.7%	10	35	2490	2490

If it is presumed that fluid velocities near the center of the vessel correlate well to the local wall fluid velocities, then the alignment between test vessel and plant parameters is good.

- The test vessel nozzle diameter of 3.94 in. is representative of the plant scale range from 4 in. to 4.25 in.
- The test vessel nozzle offset ratio of 2.4 is close to the standard plant nozzle offset ratio of 1.5. This geometry difference will be captured in the CFD model. Further, experimental data for impinging axisymmetric jets (Beltaos and Rajaratnam, 1977) shows that the characteristic length scale for the impinging jet is nozzle diameter and not nozzle offset for nozzle offset ratios less than 5.5. Because both the test vessel and the plant vessels have nozzle offsets less than 5.5, their impinging jets will share similar physics.
- The test vessel relative area per pulse tube of 378 lies within the range from 266 to 780 for plant vessels.

- The test vessel relative inter-PJM spacing of 11.8 lies within the range from 6.3 to 16.5 for plant vessels.
- The test vessel nozzle velocity of 10 m/s lies within the range from 8 m/s to 16 m/s for plant vessels.
- The test vessel duty cycle of 0.22 lies at the upper end of the range from 0.08 to 0.27 for plant vessels and is representative of long drive times. Assessment of error and uncertainty in the velocity field for short drive times will not be encompassed. Short drive times occur near the end of batch during pumpdown. By end of batch, much of the rapidly settling solids have been removed from the vessel. The remaining solids are readily suspended and maintain a nearly uniformly distribution within the vessel volume. The slurry behaves like a single phase flow. Single-phase CFD is mature and community experience demonstrates that single CFD is accurate.
- The test vessel supernate viscosity of 1 cP lies at the lower end of the range from 0.6 cP to 30 cP for plant vessels. Assessment of error and uncertainty in the velocity field for high viscosity fluids will not be encompassed. In the high viscosity condition solids are more readily suspended and the slurry behaves more like a single phase flow. Single-phase CFD is mature and community experience demonstrates that single CFD is accurate.
- The test vessel range for total solids loading from 0% to near 23% spans the range from 0.1% to 20% for plant vessels.
- The test vessel range of supernate density from 998 kg/m^3 to 1132 kg/m^3 lies within the range from 996 kg/m^3 to 1374 kg/m^3 for plant vessels.
- The test vessel particle density of 2490 kg/m^3 lies at the lower end of the range from 2900 kg/m^3 to 11400 kg/m^3 for plant vessels. Assessment of error and uncertainty in the velocity field when significant concentrations of dense particles are present will not be encompassed. The large, rapidly settling particles in WTP PJM equipped mixing vessels have a representative density of 2900 kg/m^3, similar to the test vessel density. The high density particles have small diameters and are readily suspended. Readily suspended particles form a slurry that behaves as a single phase with average properties. Single-phase CFD is mature and community experience demonstrates that single CFD is accurate. Because of this particle size to particle density relation, the particle density gap is not assessed to be a serious one.

There are assessed to be two gaps in the data available for V&V of CFD.

- The absence of velocity probe location near the outer wall of the test vessel is a gap in the existing dataset relative to the validation variable of interest; however, centerline predictions will likely have the largest assessed errors and uncertainties due to large velocity gradients around the central upwash.
- The test vessel range of particle diameters from 10 μm to 35 μm lies at the lower end of the range from 5 μm to 700 μm for plant vessels. Assessment of error and uncertainty in the velocity field when significant concentrations of large particles are present will not be encompassed and is a gap.

Summary

Based on this assessment, two recommendations are offered.

1. Proceed at limited risk by accepting the resulting error and uncertainty from the V&V of velocity measurements near the centerline as applicable to velocities extracted from the CFD near the vessel wall.
2. Opportunistically collect additional velocity measurements near the outer wall from additional testing that must be conducted in a larger-scale vessel to close other gaps in the V&V dataset.
    a. The proposed additional test suite is detailed in Section 4.2.2.

b. For the purpose of flow velocity near an outer wall, the proposed tests provide plant-scale pulse tube drive in a vessel with a relative area per pulse tube and relative inter-PJM spacing representative of the largest values at the plant.

Note that in the following figure, data consisting of a single value is represented as a single point with the data title centered over the value.

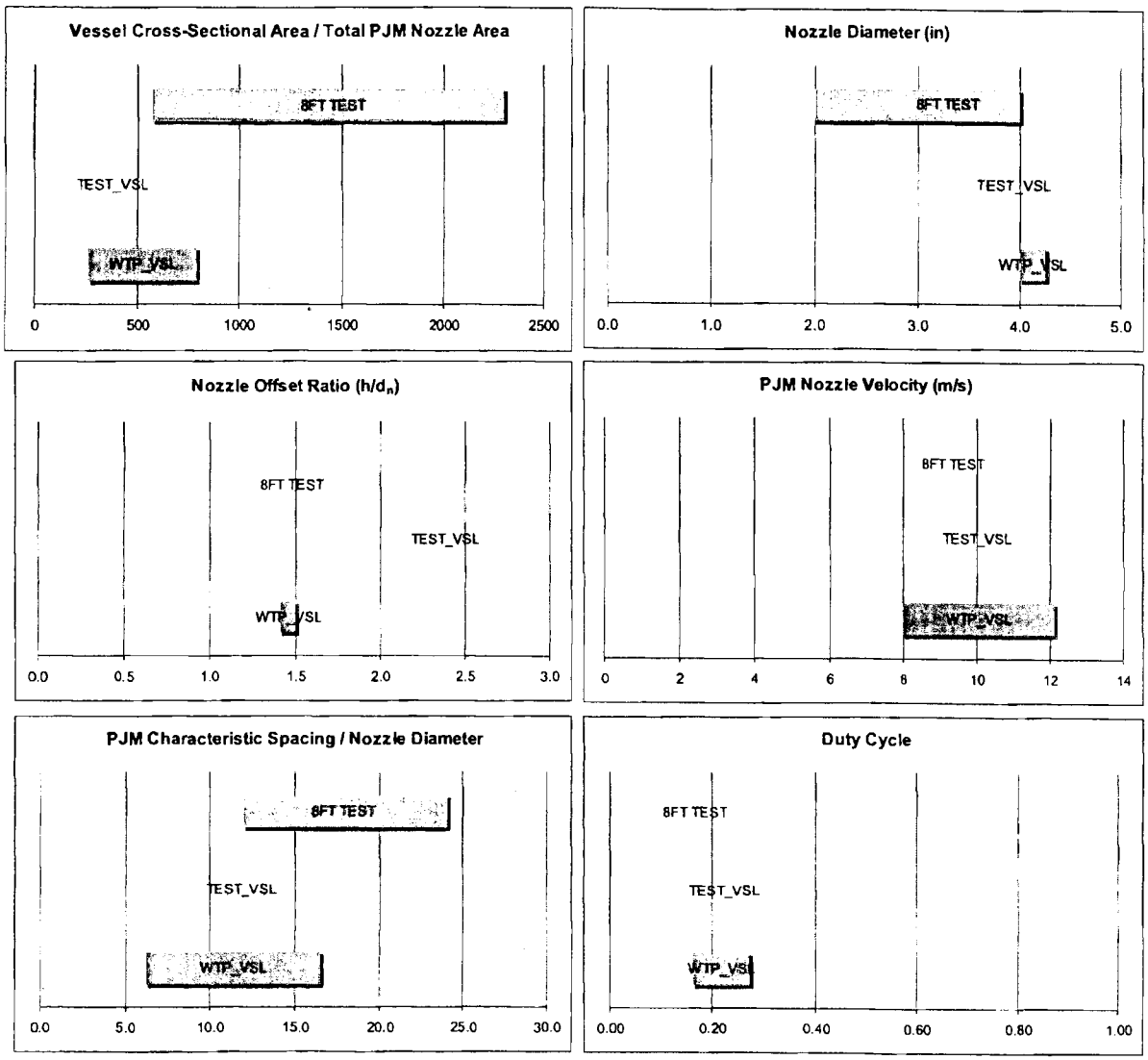


Figure 4-1 Improvements in validation dataset for velocity measurements after addition of 8 ft vessel testing.

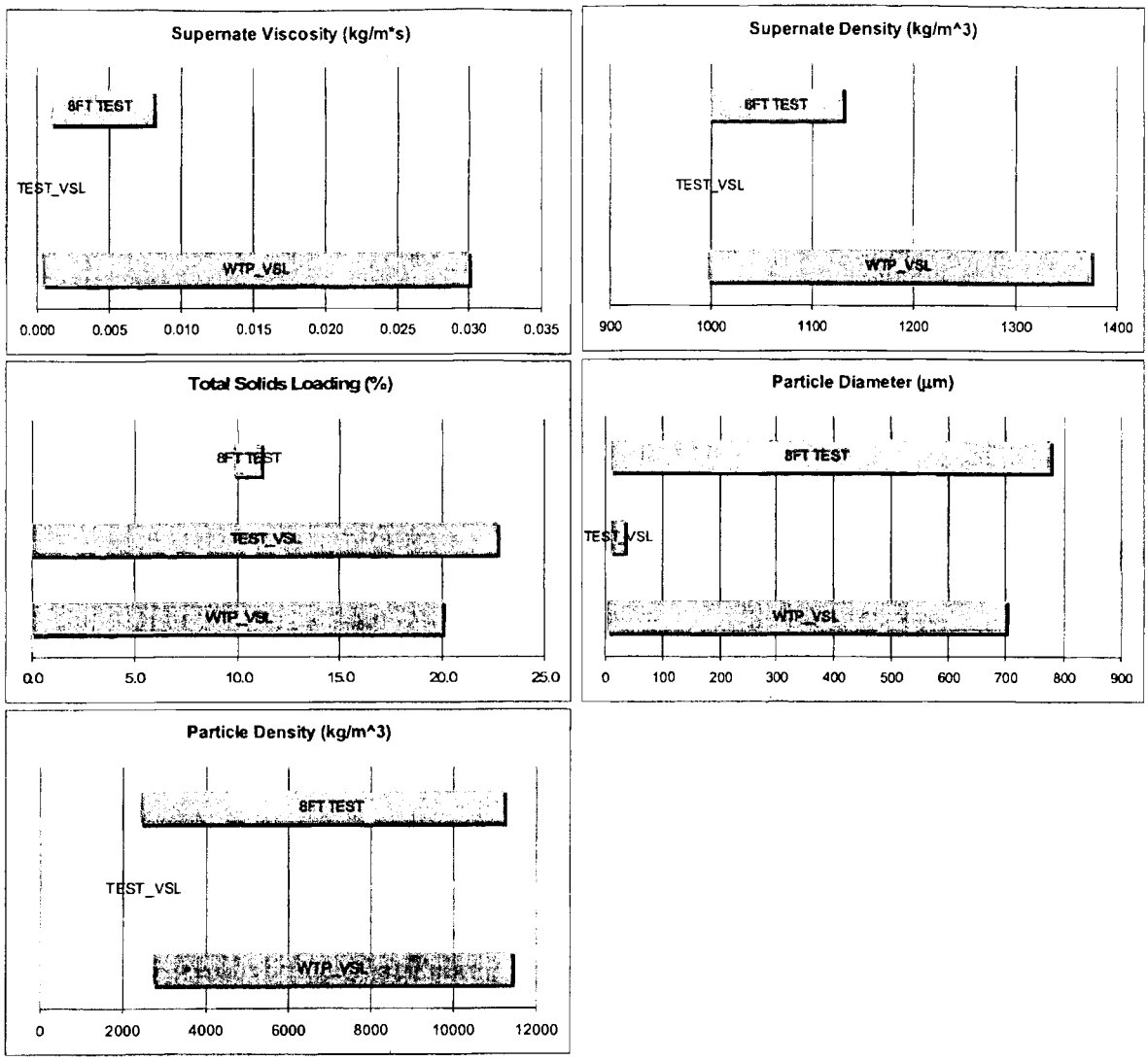


Figure 4-2 Improvements in validation dataset for velocity measurements after addition of 8 ft vessel testing.

Figure 4-1 and Figure 4-2 show the that the addition of 8 ft vessel tests can significantly improve the correspondence between the parameter ranges at plant scale and those covered by a dataset for V&V of CFD.

4.2.2 Peak and Cycle Average Concentration at the Suction Line Inlet

A summary of the design parameter ranges for the peak and cycle average concentration at the suction line inlet is provided in Table 4-3.

The alignment between test vessel and plant parameters is very good, except for vessel scale and suction line properties.

Test data with an active suction line and density measurements exist only for a 43.2 in. vessel tests conducted by the WTP project at the Mid Columbia Engineering (MCE) site. By design, the test geometry was geometrically similar to plant vessels and assessed solids compositions were representative of the current best understanding of Hanford waste. The suction line was also scaled.

The available data can be expanded somewhat by inclusion of test data (with average and peak density measurements) from Pacific Northwest National Laboratories (PNNL). Their test vessels ranged from ~15 in. to 70 in. in diameter. Pulse tube operation was prototypic during drive though the PJM cycle did not include a suction phase. The PNNL concentration data were single point measurements of concentration at multiple vertical locations along the vessel centerline and multiple radial locations close to the centerline. Probe locations in the PNNL tests were considerably above a representative suction line inlet height for WTP PJM equipped mixing vessels.

Table 4-3 Summary of Design Parameter Ranges for Concentration at the Suction Line Inlet

Platform	Tank Diameter		Nozzle Diameter		Nozzle Offset Ratio	
	[in]		[in]		-	
	min	max	min	max	min	max
WTP VSL	144	564	4.00	4.25	1.4	1.5
TEST VSL	14.4	70	0.13	0.92	1.0	1.5
Platform	**Relative Area Per Pulse Tube**		**Relative Inter-PJM Spacing**		**Nozzle Velocity**	
	-		-		[m/s]	
	min	max	min	max	min	max
WTP VSL	266	1657	6.3	21.0	8	12
TEST VSL	295	1630	8.0	18.9	2	13
Platform	**Duty Cycle**		**Supernate Viscosity**		**Supernate Density**	
	-		[cP]		[kg/m^3]	
	min	max	min	max	min	max
WTP VSL	0.13	0.35	0.4	30.0	996	1392
TEST VSL	0.16	0.67	0.7	10.0	994	1141
Platform	**Total Solids Loading**		**Particle Diameter**		**Particle Density**	
	Wt%		[μm]		[kg/m^3]	
	min	max	min	max	min	max
WTP VSL	0.0%	20.0%	4	700	2710	11430
TEST VSL	0.2%	31.6%	5	775	2420	11200

There are two gaps for direct use of the data available from MCE tests for V&V of CFD.

- There is a gap in scale. The plant scale to model tank diameter ranged from approximately 6 to 10 for the vessels considered.

- There is a gap in prototypic suction line performance. There is no clear similarity to scale-down the suction line parameters.

There are numerous gaps for direct use of the data available from PNNL testing for V&V of CFD.

- There is a gap in scale. The maximum vessel diameter of 70 in. is approximately 1/7th scale relative to the largest plant vessels.
- Concentration measurements did not include an active suction line. MCE only measured density.
- Concentration measurements are consistently taken above the scaled design height for suction line inlets in plant vessels.
- The size of the suction line as well as the height within the test vessels do not span those for the WTP PJM vessels.

Summary

As a result of these gaps, there is no route to conclude that existing data are sufficient without the use of sophisticated, multivariate approaches. It is strongly recommended that collection of additional data be performed with the following test configurations:

- 8ft vessel with full scale centerline-mounted pulse tube and representative multipart simulant to establish model comparison error and validation uncertainty for CFD at full scale,
- 8ft vessel with half to fifth scale centerline-mounted pulse tube and representative multipart simulant to establish the transfer function relating model scale comparison error and validation uncertainty to model error and uncertainty at full scale, and
- 8ft vessel with half to fifth scale pulse tube arrays (standard and chandelier-like arrays) with a representative multipart simulant to establish performance with PJM arrays.

An example test suite of 8 ft vessel tests to support V&V of CFD for concentration at the suction line inlet are detailed in Table 4-4.

Note that for those parameters not shown, the original testing demonstrated a range that covered the full Plant range without the addition of the 8ft test.

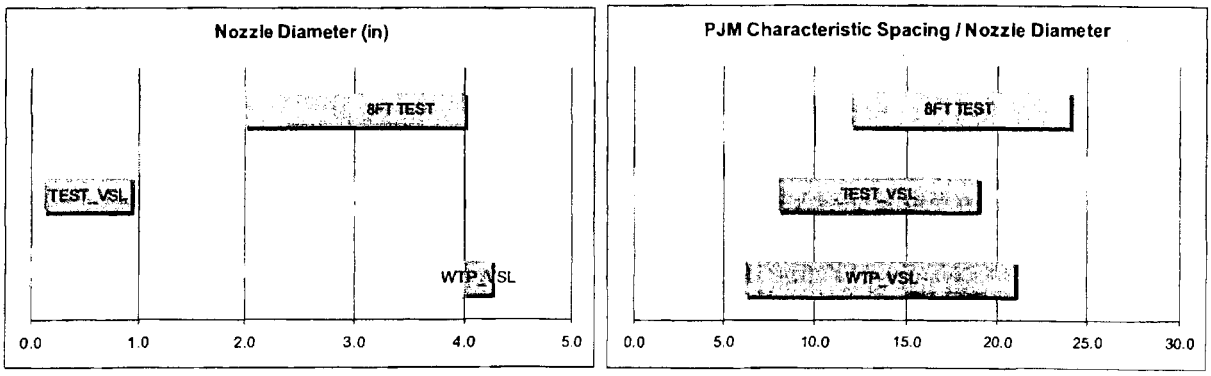


Figure 4-3 Improvements in validation dataset for concentration at the suction line inlet after addition of 8 ft vessel testing.

Figure 4-3 shows that the addition of 8 ft vessel tests can significantly improve the correspondence between the parameter ranges at plant scale and those covered by a dataset for V&V of CFD.

Table 4-4 Example 8 Ft Vessel Test Suite to Support V&V of CFD for Concentration at the Suction Line Inlet (and Heel Concentration)

Test Parameter		Units	8 Ft Vessel Tests				
			#1	#2	#3	#4	#5
FLUID							
Viscosity		cP	1	1	1	8	1
Density		kg/m^3	998	998	998	1130	998
Mass		kg	5723	5723	5723	6480	5723
VESSEL							
Diameter		in	96	96	96	96	96
Nozzle diameter		in	4	2	2	2	2
Inner pitch ring radius		in	48	48	24	24	36
Suction line diameter		in	3	0.75	0.75	0.75	0.75
Suction line inlet height		in	3	1.5	1.5	1.5	1.5
Suction line radial offset		in	12	6	6	6	6
Nozzle height		in	6	3	3	3	6
Pulse Tube Count		-	1	1	4	4	6
PJM Configuration		-	Single	Single	Standard	Standard	Chandelier
Head Shape		-	F&D	F&D	F&D	F&D	F&D
OPERATION							
PJM jet velocity		m/s	12	12	12	12	12
Drive time		s	33.4	16.7	16.7	16.7	16.7
Cycle time		s	194.97	97.50	97.50	97.50	97.50
Suction line flow rate		m^3/s	9.15E-03	2.29E-03	2.29E-03	2.29E-03	2.29E-03
Fill height		in	58	58	58	58	58
SOLIDS			**Representative Simulant**				
Mass Total		kg	635.89	635.89	635.89	635.89	635.89
Particle #1	Diameter	μm	10	10	10	10	10
	Density	kg/m^3	11200	11200	11200	11200	11200
	Mass	kg	25	25	25	25	25
Particle #2	Diameter	μm	21	21	21	21	21
	Density	kg/m^3	2650	2650	2650	2650	2650
	Mass	kg	477	477	477	477	477
Particle #3	Diameter	μm	81.6	81.6	81.6	81.6	81.6
	Density	kg/m^3	2420	2420	2420	2420	2420
	Mass	kg	95	95	95	95	95
Particle #4	Diameter	μm	312	312	312	312	312
	Density	kg/m^3	2650	2650	2650	2650	2650
	Mass	kg	19	19	19	19	19
Particle #5	Diameter	μm	775	775	775	775	775
	Density	kg/m^3	2900	2900	2900	2900	2900
	Mass	kg	19	19	19	19	19

4.2.3 Miscible Liquids Blending

A gap exists in V&V dataset exists for miscible liquids blending in HLP-27A/B, HLP-28, and UFP-2A/B vessels. These vessels operate with sparging that is responsible for a significant portion of the mixing energy. Use of a CFD model with sparging is not currently planned.

A summary of the design parameter ranges for miscible liquids blending is provided in Table 4-5. Only one set of data currently exists for use in V&V of CFD for miscible liquids blending. See Section A.2.3 for additional detail on specific concerns regarding the data available for the miscible liquids blending.

Table 4-5 Summary of Design Parameter Ranges for Miscible Liquids Blending

Platform	Tank Diameter		Nozzle Diameter		Nozzle Offset Ratio	
	[in]		[in]		-	
	min	max	min	max	min	max
WTP VSL	126	318	4.00	4.25	1.4	1.5
TEST VSL	34	34	2.00	2.00	0.9	0.9
Platform	**Relative Area Per Pulse Tube**		**Relative Inter-PJM Spacing**		**Nozzle Velocity**	
	-		-		[m/s]	
	min	max	min	max	min	max
WTP VSL	200	992	6.3	18.8	8	12
TEST VSL	289	289	8.5	8.5	3	8
Platform	**Duty Cycle**		**Supernate Viscosity**		**Supernate Density**	
	-		[cP]		[kg/m^3]	
	min	max	min	max	min	max
WTP VSL	0.13	0.35	0.4	30.0	996	1374
TEST VSL	0.12	0.20	0.9	1.4	998	998
Platform	**Total Solids Loading**		**Particle Diameter**		**Particle Density**	
	Wt%		[μm]		[kg/m^3]	
	min	max	min	max	min	max
WTP VSL	0.0%	20.0%	4	700	2710	11400
TEST VSL	0.0%	0.0%	0	0	1307	1307

The alignments between test vessel and plant parameters are poor.

- The test vessel nozzle diameter is one-half of plant scale.
- The test vessel nozzle offset ratio of 0.9 in. is less than the standard offset ratio of 1.5 at the plant, though, as noted above, this offset ratio will be accommodated in a CFD model.
- The test vessel relative area per pulse tube of 289 lies at the lower end of the range from 266 to 992 at the plant.
- The test vessel relative inter-PJM spacing of 8.5 lies at the lower end of the range from 6.3 to 18.5 for the plant.
- The test vessel nozzle velocity range from 3 m/s to 8 m/s lies at or below the lower bound for the range from 8 m/s to 16 m/s at the plant.
- The test vessel range for duty cycle from 0.12 to 0.2 lies within the range from 0.08 to 0.35 at the plant.

- The test vessel supernate viscosity range from 0.9 cP to 1.4 cP lies at the lower end of the range from 0.6 cP to 30 cP at the plant.
- The miscible liquids condition in the test vessel was a deep layer of heavy fluid mixing with a thin layer of lighter fluid above. The target condition for the plant is the opposite: a thin layer of heavy fluid mixes with a deep layer of lighter fluid.
- Available test data include zero solids loading. The plant vessels require miscible liquids blending in the presence of settling and suspended solids.

Numerous gaps are identified. Significant gaps are:

- There is a gap in scale. Measurements only exist for a half scale pulse tube in an 34in vessel
- The existing measurements are for a single pulse tube (centerline-mounted) and do not include any data for miscible liquids blending in vessels with PJM arrays.
- The fluid layers in the tests are not representative of WTP PJM equipped mixing vessels, where the experiment is a very deep layer of dense fluid with a thin layer of light fluid on top (the actual configuration is a very thin layer of dense fluid within the radial wall jet region of a lighter fluid, which is akin to mobilizing and mixing of a settled solids bed).

Summary

From these observations, it is recommended that:

1. The project proceed at risk with the current dataset only if very large error and uncertainties in margin requirements can be tolerated in the design, otherwise
2. additional testing at a larger scale is strongly recommended. The additional testing could parallel the 8 ft vessel testing described in Section 4.2.2:
   - 8ft vessel with full scale centerline-mounted pulse tube and representative multipart simulant to establish model comparison error and validation uncertainty for CFD at full scale,
   - 8ft vessel with half to fifth scale centerline-mounted pulse tube and representative multipart simulant to establish the transfer function relating model scale comparison error and validation uncertainty to model error and uncertainty at full scale, and
   - 8ft vessel with half to fifth scale pulse tube arrays (standard and chandelier-like arrays) with a representative multipart simulant to establish performance with PJM arrays.

An example test suite of 8 ft vessel tests to support V&V of CFD for miscible liquids blending are detailed in Table 4-6.

Table 4-6 Example 8 Ft Vessel Test Suite to Support V&V of CFD for Miscible Liquids Blending

Test Parameter		Units	8 Ft Vessel Tests		
			#6	#7	#8
FLUID					
Viscosity		cP	1	1	1
Density		kg/m^3	998	998	998
Mass		kg	5723	5723	5723
VESSEL					
Diameter		in	96	96	96
Nozzle diameter		in	4	2	2
Inner pitch ring radius		in	48	48	24
Suction line diameter		in	-	-	-
Suction line inlet height		in	-	-	-
Suction line radial offset		in	-	-	-
Nozzle height		in	6	3	3
Pulse Tube Count		-	1	1	4
PJM Configuration		-	Single	Single	Standard
Head Shape		-	F&D	F&D	F&D
OPERATION					
PJM jet velocity		m/s	12	12	12
Drive time		s	33.4	16.7	16.7
Cycle time		s	194.97	97.50	97.50
Suction line flow rate		m^3/s	N/A	N/A	N/A
Fill height		in	58	58	58
SOLIDS			**Representative Simulant**		
Mass Total		kg	635.89	635.89	635.89
Particle #1	Diameter	µm	10	10	10
	Density	kg/m^3	11200	11200	11200
	Mass	kg	25	25	25
Particle #2	Diameter	µm	21	21	21
	Density	kg/m^3	2650	2650	2650
	Mass	kg	477	477	477
Particle #3	Diameter	µm	81.6	81.6	81.6
	Density	kg/m^3	2420	2420	2420
	Mass	kg	95	95	95
Particle #4	Diameter	µm	312	312	312
	Density	kg/m^3	2650	2650	2650
	Mass	kg	19	19	19
Particle #5	Diameter	µm	775	775	775
	Density	kg/m^3	2900	2900	2900
	Mass	kg	19	19	19

Note that the table above does not include information on the caustic added for miscible blending. However for the purposes of the gap analysis, this information is not necessary. The detailed list of specific tests and associated measurement quantities/locations will be included in the RTD (Test Plan) that will be issued by the Project Testing Team

Note that for those parameters not shown, the original testing demonstrated a range that covered the full Plant range without the addition of the 8ft test.

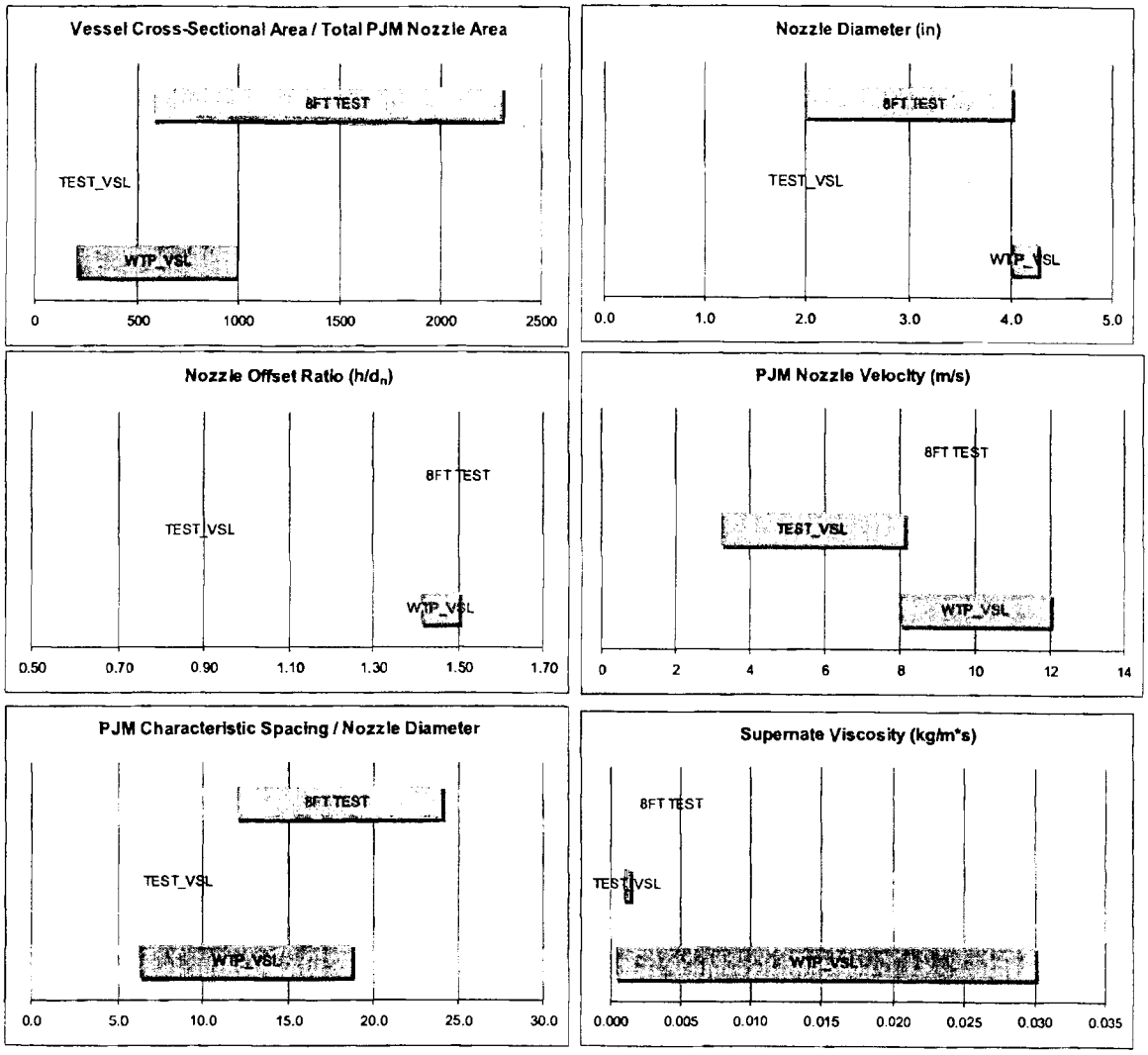


Figure 4-4a Improvements in validation dataset for miscible liquids blending after addition of 8 ft vessel testing

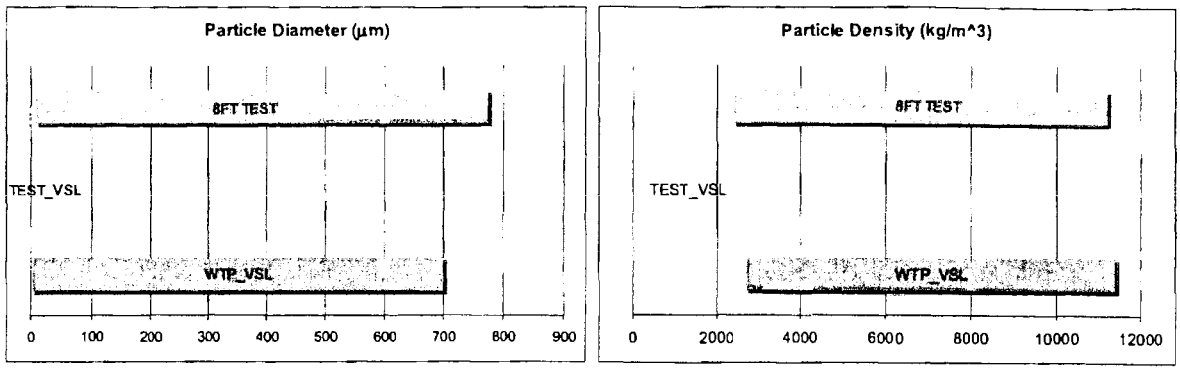


Figure 4-4b Improvements in validation dataset for miscible liquids blending after addition of 8 ft vessel testing

Figure 4-4 shows that the addition of 8 ft vessel tests can significantly improve the correspondence between the parameter ranges at plant scale and those covered by a dataset for V&V of CFD.

4.2.4 Multiple PJM ZOI

A summary of the design parameter ranges for multiple PJM ZOI is provided in Table 4-7.

Table 4-7 Summary of Design Parameter Ranges for Multiple PJM ZOI

Platform	Tank Diameter		Nozzle Diameter		Nozzle Offset Ratio	
	[in]		[in]		-	
	min	max	min	max	min	max
WTP VSL	113	564	4.00	4.25	1.4	1.5
TEST VSL	43.3	138	0.13	4.03	1.0	1.5
Platform	**Relative Area Per Pulse Tube**		**Relative Inter-PJM Spacing**		**Nozzle Velocity**	
	-		-		[m/s]	
	min	max	min	max	min	max
WTP VSL	266	1657	6.3	21.0	8	12
TEST VSL	295	1630	8.0	18.9	2	13
Platform	**Duty Cycle**		**Supernate Viscosity**		**Supernate Density**	
	-		[cP]		[kg/m^3]	
	min	max	min	max	min	max
WTP VSL	0.13	0.30	0.5	30.0	1001	1392
TEST VSL	0.16	0.67	0.7	10.0	994	1141
Platform	**Total Solids Loading**		**Particle Diameter**		**Particle Density**	
	Wt%		[μm]		[kg/m^3]	
	min	max	min	max	min	max
WTP VSL	0.0%	20.0%	4	700	1802	11430
TEST VSL	0.2%	31.6%	5	775	2420	11200

Test vessel coverage of the plant parameters is very good.

Multiple PJM ZOI data are available from primarily two sources, the MCE Phase-2 tests in a 43.3 in. vessel and the Washington State University (WSU) tests in a large radial flume. Additional test data is also contained in MCE Pump-down and PNNL WTP-RPT-182. The MCE test vessels are geometrically similar to the plant vessels. PJM array operation is also prototypic. Particle simulants are representative of the best understanding by the project of the Hanford waste. The WSU tests include 2 pulse tubes with 4 in. nozzle diameters, nozzle offset ratios of 1.5, and an inter-PJM spacing representative of the large vessels in the plant. The particle simulant was nominally 200 μm sand. The particle size distribution was broad: nominal (d_{50}) is 200 μm, d_{95} is 365 μm, and d_{99} is 700+ μm. For ZOI measurements, the bed depth is also considered. For the WSU results the bed depth is measured prior to testing, while for the MCE tests the depth of solids must be determined based on total weight percent. Details are found in Appendix A.

Potential gaps in the data available for V&V of CFD for multiple PJM ZOI are

- the absence of data at significant scale in a vessel with a curved bottom and more than 2 pulse tube flow fields to yield an upwash fountain at a stagnation point and
- the use of a simulant that may not fully represent the best current understanding of Hanford waste.

Summary

Because there are only minor potential gaps relating to PJM array configuration, vessel shape, and clearing of large particles at full scale, it is concluded that no additional information for the ZOI measurements is required for V&V. However, opportunistic collection of additional ZOI data from any proposed new testing with multipart simulants would improve the overall comparison.

Note that no updates to the images from Section 3.3.9 are shown, since the original testing demonstrated a range that covered the full Plant range without the addition of the 8ft test.

4.2.5 Concentration at Heel

A summary of the design parameter ranges for concentration in the heel is provided in Table 4-8.

Similar to the concentration measurements at the suction line, the concentration at the heel also exhibits gaps in the scale range. The recommendations from Section 4.2.2 are applicable.

Table 4-8 Summary of Design Parameter Ranges for Heel Concentration

Platform	Tank Diameter		Nozzle Diameter		Nozzle Offset Ratio	
	[in]		[in]		-	
	min	max	min	max	min	max
WTP VSL	144	564	4.00	4.25	1.4	1.5
TEST VSL	43.3	43.3	0.40	0.66	1.4	1.5
Platform	**Relative Area Per Pulse Tube**		**Relative Inter-PJM Spacing**		**Nozzle Velocity**	
	-		-		[m/s]	
	min	max	min	max	min	max
WTP VSL	266	1657	6.3	21.0	8	12
TEST VSL	545	702	8.2	18.9	5	10
Platform	**Duty Cycle**		**Supernate Viscosity**		**Supernate Density**	
	-		[cP]		[kg/m^3]	
	min	max	min	max	min	max
WTP VSL	0.13	0.35	0.4	30.0	996	1392
TEST VSL	0.16	0.18	1.0	8.0	998	1130
Platform	**Total Solids Loading**		**Particle Diameter**		**Particle Density**	
	Wt%		[µm]		[kg/m^3]	
	min	max	min	max	min	max
WTP VSL	0.0%	20.0%	4	700	1802	11430
TEST VSL	2.0%	31.6%	5	775	2420	11200

Note that for those parameters not shown in the following figure, the original testing demonstrated a range that covered the full Plant range without the addition of the 8ft test.

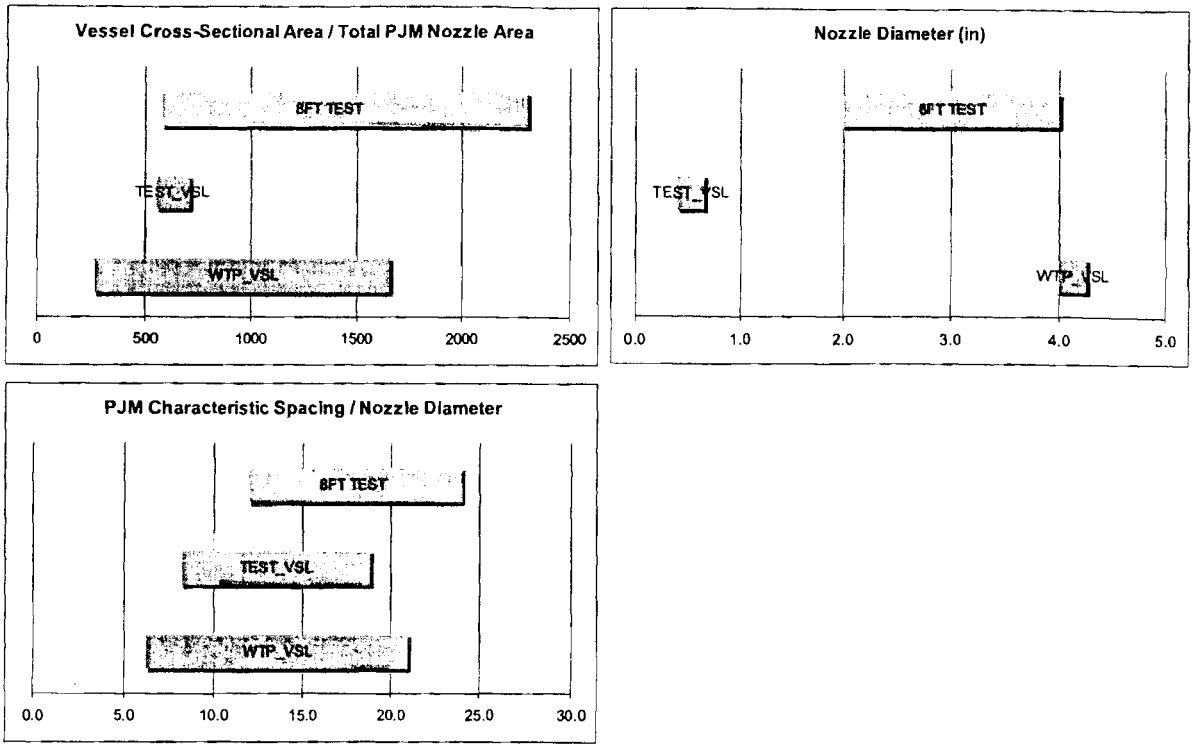


Figure 4-5 Improvements in validation dataset for Heel Concentration after addition of 8 ft vessel testing

4.3 Selection of Non-Dimensional Parameters

A comprehensive reporting of the dimensional form of the Eulerian-Granular multiphase equations, associated physics closure models, and boundary/initial conditions solved by FLUENT to model WTP PJM equipped vessel flows is presented in Appendix A of 24590-WTP-PL-ENG-11-0002, Rev. A. While complete, the dimensional form of the governing equations does not facilitate the identification by inspection of a minimum set of parameters for WTP PJM equipped vessel simulation. The dimensionless form of the governing equations combines dimensional parameters in physically meaningful ways facilitating identification of a minimum set of parameters for WTP PJM equipped vessel simulation.

The dimensionless forms of the governing equations are constructed from the dimensional equations by a change of variables from dimensional to dimensionless. Using nozzle velocity, U_0, nozzle diameter, D_0, and carrier fluid density, ρ_f, as characteristic quantities and defining the ratio D_0/U_0 as a characteristic time, the change of variables from dimensional to dimensionless for lengths x, velocities v_i, densities ρ_i, and time t are

$$x = D_0 \tilde{x},\ v_i = U_0 \tilde{v}_i,\ \rho_i = \rho_f \tilde{\rho}_i, \text{ and } t = (D_0/U_0)\tilde{t}$$

The capping tilde denotes a dimensionless quantity.

Non-dimensionalization of the fluid phase momentum equations yields

$$\frac{\partial}{\partial \tilde{t}}(\alpha_f \tilde{v}_f) + \tilde{\nabla} \bullet (\alpha_f \tilde{v}_f \otimes \tilde{v}_f) = -\alpha_f \tilde{\nabla} \tilde{p} + \tilde{\nabla} \bullet \tilde{\tau}_f + \sum_{i=1}^{N} \left[\tilde{K}_{fi} (\tilde{v}_f - \tilde{v}_i) \right] + \tilde{F}_f$$

The terms on the left side are time change and advection. The pressure term on the right side relates to mass conservation. The remaining terms on the right side are a stress divergence yielding diffusion, momentum interchange, and buoyancy.

For a constant density fluid, $\tilde{F}_f = 0$. The diffusion and momentum interchange terms require closure models.

A closure for the diffusion term is

$$\tilde{\nabla} \bullet \tilde{\tau}_f = \tilde{\nabla} \bullet \left(2\alpha_f \left(Re_{jet}^{-1} + Re_{t,f}^{-1} \right) \left[\tilde{D}_f - \frac{1}{3} I (\tilde{\nabla} \bullet \tilde{v}_f) \right] \right)$$

α_f is the fluid volume fraction. $\tilde{D}_f$ is the dimensionless strain rate. I is the identity matrix. This closure introduces dependencies on the jet Reynolds number, $\mathrm{Re}_{jet} = U_0 D_0 / \nu_f$ and the turbulence Reynolds number, $Re_{t,f}$. ν_f is the fluid kinematic diffusivity. The turbulence Reynolds number is a function of other transport variables and is not a parameter for the system. This closure identifies a system dependence on the jet Reynolds number, Re_{jet}.

A closure for the momentum interchange coefficient for fluid-solids interactions is

$$\widetilde{K}_{fs} = \widetilde{K}_{sf} = \frac{3}{4}\frac{\alpha_s \alpha_f}{v_{r,s}^2}\frac{D_0}{d_s} C_D \left|\widetilde{v}_f - \widetilde{v}_s\right|$$

$$= \frac{3}{4}\frac{\alpha_s \alpha_f}{v_{r,s}^2} Re_{jet} Re_p^{-1} Fr_p^{-1/2} C_D \left|\widetilde{v}_f - \widetilde{v}_s\right|$$

d_s is the particle diameter. $Re_p = U_g d_s / \nu_f$ is the densimetric particle Reynolds number. $Fr_p = (U_0 / U_g)^2$ is the densimetric particle Froude number. Both are defined in terms of the gravity velocity, $U_g = \sqrt{s_s\, g\, d_s}$, a characteristic velocity for particle settling. The particle drag and settling functions, C_D and $v_{r,s}$, depend on the slip Reynolds number, $Re_s = \left|v_f - v_s\right| d_s / \nu_f = Re_{d_s} \left|\widetilde{v}_f - \widetilde{v}_s\right|$ and on the fluid volume fraction, α_f. $Re_{d_s} = U_0\, d_s / \nu_f = Re_p Fr_p^{1/2}$ is the nozzle Reynolds number for a particle. This closure identifies system dependencies on the dimensionless size ratio $d_s / D_0 = Re_{jet}^{-1} Re_p Fr_p^{1/2}$ and on the particle nozzle Reynolds number $Re_{d_s} = Re_p Fr_p^{1/2}$, or equivalently, add dependencies on the densimetric particle Reynolds number, Re_p, and on the densimetric particle Froude number, Fr_p.

Non-dimensionalization of the solids phase momentum equations yields

$$\frac{\partial}{\partial \widetilde{t}}(\alpha_s \widetilde{\rho}_s \widetilde{v}_s) + \widetilde{\nabla} \bullet (\alpha_s \widetilde{\rho}_s \widetilde{v}_s \otimes \widetilde{v}_s) = -\alpha_s \widetilde{\nabla}\widetilde{p} - \widetilde{\nabla}\widetilde{p}_s + \widetilde{\nabla} \bullet \widetilde{\tau}_s + \sum_{i=1}^{N}\left[\widetilde{K}_{si}(\widetilde{v}_s - \widetilde{v}_i)\right] + \widetilde{F}_s$$

The terms on the left side represent time change and advection. The terms on the right side represent mass conservation, diffusion, momentum interchange, and buoyancy. The solids buoyancy term, $\widetilde{F}_s$, is a function of the solids volume fraction, α_s, and of the particle Froude number, Fr_p,

$$\widetilde{F}_s = \alpha_s Fr_p \frac{g}{g_0}$$

g/g_0 is the normalized gravity vector. This term leads to additional dimensionless dependencies.

Closure models are needed for the solids pressure, momentum interchange, and diffusion and terms. Non-dimensionalization of the solids pressure closure leads to no dimensionless parameters. The solids-fluid momentum interchange coefficient is identical to the closure for the fluid-solids momentum interchange coefficient. A closure for diffusion is

$$\widetilde{\nabla} \bullet \widetilde{\tau}_s = \frac{d_s}{D_0}\widetilde{\nabla} \bullet \left(2\alpha_s \widetilde{F}_{\mu_s}\left[\widetilde{D}_s - \frac{1}{3}(\widetilde{\nabla} \bullet \widetilde{v}_s) I\right] + \alpha_s \widetilde{F}_{\mu_{bulk}}(\widetilde{\nabla} \bullet \widetilde{v}_s) I\right)$$

$$= Re_{jet}^{-1} Re_p Fr_p^{1/2}\, \widetilde{\nabla} \bullet \left(2\alpha_s \widetilde{F}_{\mu_s}\left[\widetilde{D}_s - \frac{1}{3}(\widetilde{\nabla} \bullet \widetilde{v}_s) I\right] + \alpha_s \widetilde{F}_{\mu_{bulk}}(\widetilde{\nabla} \bullet \widetilde{v}_s) I\right)$$

$\widetilde{D}_s$ is the solids velocity strain-rate tensor. $\widetilde{F}_{\mu_s}$ and $\widetilde{F}_{\mu_{bulk}}$ are dimensionless functions related to solids viscosity. They contain no dimensionless parameters. The solids diffusion closure depends on the size ratio $d_s/D_0 = Re_{jet}^{-1} Re_p Fr_p^{1/2}$. It introduces no additional dimensionless groupings.

Non-dimensionalization of the nozzle velocity profile yields a function that depends on the dimensionless drive time $T_d = (U_0/D_0)\, t_d$; t_d is the dimensional drive time.

Initialization introduces a dependence on solids loading, $wt\%_p$.

Dependencies in the dimensionless governing equations for WTP PJM vessel simulation set are spanned by the parameter set

- The jet Reynolds number, $Re_{jet} = U_0 D_0/\nu_f$
- The densimetric particle Froude number, $Fr_p = (U_0/U_g)^2$
- The particle nozzle Reynolds number, $Re_{d_s} = Re_p Fr_p^{1/2}$
- The dimensionless size ratio, $d_s/D_0 = Re_{jet}^{-1} Re_{d_s} = Re_{jet}^{-1} Re_p Fr_p^{1/2}$
- The dimensionless drive time, $T_d = (U_0/D_0)\, t_d$
- The initial solids loading, $wt\%_p$

Five independent parameters that span the parameter space for WTP PJM vessel simulation are Re_{jet}, Fr_p, Re_p, T_d, and $wt\%_p$.

4.4 Assessment of Non-Dimensional Parameters for WTP PJM Equipped Vessel Physics

Existing knowledge of the WTP PJM equipped vessel physics is used to assess the vessel performance parameter space. The analysis is based on identifying the dimensionless parameters for existing correlations that are known to relate to aspects of WTP PJM equipped vessel physics. These correlations are not used by the CFD model, however they form the basis of discussion for the relevant dimensionless parameters. The physical mechanisms considered are: particle transport/suspension and settling, particle mobilization, and vertical distribution.

4.4.1 Particle Transport/Suspension and Settling

Particle transport is characterized by a drag interaction between a carrier fluid and a transported solids particle. Empirical models for particle drag coefficients for settling in non-turbulent flows exist. One correlation for the particle drag coefficient, C_D, in a non-turbulent medium (from Perry's Handbook for Chemical Engineers) is

$$C_D = \frac{432}{Ar}\left(1 + 0.047\, Ar^{2/3}\right) + \frac{0.517}{1 + 154\, Ar^{1/3}}$$

Ar is the Archimedes number, $Ar = s_s\, g\, d_s^2/\nu_f^2$, s_s is the submerged specific gravity for a solids phase, g is the acceleration of gravity, d_s is the particle diameter, and ν_f is the kinematic diffusivity of the carrier

fluid. The Archimedes number can be expressed in terms of the densimetric particle Reynolds number, $Ar = \mathrm{Re}_p^2$.

Particle settling in a turbulent medium is affected by the local fluctuations of turbulence. Existing models for modifying the particle drag coefficient to account for turbulent flow interactions depend on ratio of the Kolomogorov scale of turbulence, η, and the transported particle diameter, d_p. The Kolomogorov scale for a single phase turbulent jet depends solely on the jet Reynolds number, $\eta/D_0 = f(\mathrm{Re}_{jet})$, where $Re_0 = U_0 D_0 / \nu_t$. U_0 and D_0 are the characteristic nozzle velocity and diameter, which set the turbulence kinetic energy production rate and the characteristic size of the energy containing turbulence eddies. The ratio η/d_p, and thus the turbulence corrections to the particle drag coefficient, can be expressed in terms of a dimensionless particle diameter, d_p/D_0, and a function of the jet Reynolds number:

$$\frac{\eta}{d_p} = \left(\frac{d_p}{D_0}\right)^{-1} f(\mathrm{Re}_{jet})$$

Algebraic manipulation yields $d_p/D_0 = (\mathrm{Re}_p/\mathrm{Re}_{jet}) Fr_p^{1/2}$.

Dimensionless parameters that characterize particle drag appear to be the jet Reynolds number, Re_0, the densimetric particle Reynolds number, Re_p, and the densimetric particle Froude number, Fr_p.

4.4.2 Particle Mobilization

Mobilization of particle beds and layers of negatively buoyant fluid can be described in terms of critical shear stresses for mobilization or, equivalently, minimum local flow velocities for mobilization. For mobilization of non-cohesive settled solids beds, the Shields relations provide an empirical correlation between observed critical shear stresses for mobilization, τ_c, and particle/carrier fluid properties: $\tau_c = (\rho_f s_p g d_p)\theta_c = (\rho_f U_g^2)\theta_c$. θ_c is the critical value for Shields parameter and ρ_f is the carrier fluid density.

The Brownlie, W. R. (1981) form for the Shields relations is one form that is commonly used. It expresses the Shields parameter in terms of the characteristic length $d^* = \left(s_p g / \nu_f^2\right)^{\frac{1}{3}}$:

$$\theta_c = 0.22 d^{*-0.9} + 0.06 \exp\left(-17.73 d^{*-0.9}\right)$$

Another commonly used form for the Shields relations (Z. Cao, G. Pender, and J. Meng (2006)) expresses the Shields relations directly in terms of the particle Reynolds number,

$$\theta_c = \begin{cases} 0.1414\,\mathrm{Re}_p^{-0.2306}, & \mathrm{Re}_p \le 6.61 \\ \dfrac{\left[1+\left(0.0223\,\mathrm{Re}_p\right)^{2.8358}\right]^{0.3542}}{3.0946\,\mathrm{Re}_p^{0.6769}}, & \mathrm{Re}_p \in (6.61, 282.84) \\ 0.045, & \mathrm{Re}_p \ge 282.84 \end{cases}$$

The Z. Cao, G. Pender, and J. Meng (2006) model is reported to be more accurate than the Brownlie model, particularly for small particle sizes.

Particles mobilize when the shear stress exerted by the carrier fluid on the settled solids bed exceeds that critical shear stress for mobilization, or equivalently, particles in the settled bed will mobilize when the local velocity above the bed exceeds a critical value. A model for the growth rate of the cleared zone radius relates it to the difference between the mean shear stress applied to a settled solids bed and the critical shear stress for mobilization of that bed (24590-WTP-RPT-ENG-11-001)

$$\frac{dr}{dt} \sim \sqrt{\frac{\tau_w - \tau_c}{\rho_f}}$$

τ_w is the local wall shear stress. In dimensionless form, the rate of clearing is

$$\frac{d\tilde{r}}{d\tilde{t}} \sim \sqrt{\frac{1}{\mathrm{Re}_w} - \frac{1}{\mathrm{Re}_c}}$$

Where $\tilde{r} = r / D_0$, $\tilde{t} = t\,U_0 / D_0$, $\mathrm{Re}_w = \rho_f U_0^2 / \tau_w$, and $\mathrm{Re}_c = \rho_f U_0^2 / \tau_c$. Re_w and Re_c are the local and critical erosion Reynolds numbers. The maximum radius of the cleared zone is found by integration

$$\tilde{r} \sim \int_{\tilde{t}=0}^{\tilde{t}=t_d U_0 / D_0} \sqrt{\frac{1}{\mathrm{Re}_w} - \frac{1}{\mathrm{Re}_c}}\, d\tilde{t}$$

M. Poreh, Y.G. Tsuei, and J.E. Cermak (1967) provide an empirical model for the radial distribution of mean wall shear stress for submerged radial wall jets

$$\frac{\tau_w H_0^2}{\rho_f U_0^2 D_0^2} \sim \left(\frac{U_0 D_0}{\nu_f}\right)^{-0.3} \left(\frac{r}{H_0}\right)^{-2.3}$$

This expression can be reorganized to show that the local erosion Reynolds number, Re_w, can be expressed in terms of the jet Reynolds number, Re_{jet}, the nozzle offset ratio, H_0/D_0, and the radial distance from the wall jet impingement point, r / D_0,

$$\frac{1}{\mathrm{Re}_w} \sim \left(\frac{1}{\mathrm{Re}_{jet}}\right)^{0.3} \left(\frac{H_0}{D_0}\right)^{0.3} \left(\frac{r}{D_0}\right)^{-2.3}$$

Algebraic manipulation shows that the critical erosion Reynolds number, Re_c, is a function of the particle Froude number, Fr_p, and the Shields parameter, θ_c: $\mathrm{Re}_c = Fr_p\, \theta_c$.

For settled solids beds with broad particle size distributions and particle density distributions, the critical Shields number will be a bed-averaged property. Thus bottom clearing depends on solids loading. Solids loading can be expressed either in terms of the solids mass by constituent, m_p, or in terms of solids weight percent by constituent, $wt\%_p$. The extent of the observed cleared zone on the vessel floor as seen from below depends on the depth of the settled solids bed. This depth is also a function of solids loading.

Because of the dependence of bottom clearing on the pulse tube drive time, t_d, the dimensionless drive time, T_d, is required to describe bottom clearing.

The relevant (non-geometric) dimensionless parameters that characterize particle mobilization appear to be the jet Reynolds number, Re_0, the densimetric particle Reynolds number, Re_p, the densimetric particle Froude number, Fr_p, the solids composition, $wt\%_p$, and the dimensionless drive time, T_d.

4.4.3 Vertical Distribution

Particle vertical distribution in WTP PJM equipped vessels is significantly through vertical transport of a negatively buoyant slurry by the upwash fountains that form where PJM flow fields converge.

H Zhang and R E. Baddour (1998) presents a correlation for the upwash height of a negatively buoyant turbulent circular jet. The relative upwash height, Z/D_0, depends on the jet Froude number, $Fr_{jet} = U_0^2 / s_m\, g\, D_0$,where s_m is the submerged specific gravity for the negatively buoyant slurry:

$$\frac{Z}{D_0} \sim Fr_{jet}^{1/2} \sim \sqrt{\frac{s_s}{s_m}}\, Fr_p^{3/4}\, \mathrm{Re}_p^{1/2}\, \mathrm{Re}_{jet}^{-1/2}$$

The ratio s_p/s_m is a number greater than 1 that depends on details of the slurry composition. This ratio shares the same dimensionless dependencies as bottom mobilization.

The relevant (non-geometric) dimensionless parameters that characterize vertical distribution appear to be the jet Reynolds number, Re_0, the densimetric particle Reynolds number, Re_p, the densimetric particle Froude number, Fr_p, the solids composition, $wt\%_p$, and the dimensionless drive time, T_d.

4.4.4 Summary

An analysis of existing correlations related to the physics of transport/suspension, settling, mobilization, and vertical distribution suggest that five dimensionless parameters are sufficient to characterize WTP

PJM equipped vessel performance. They are the jet Reynolds number, Re_o, the densimetric particle Reynolds number, Re_p, the densimetric particle Froude number, Fr_p, the solids composition, $wt\%_p$, and the dimensionless drive time, T_d.

This set of independent dimensionless parameters is also the set identified for CFD simulation. This result confirms that the CFD model is expected to span the same parameter space as WTP PJM vessel mixing at plant scale.

4.5 Comparison of WTP PJM Equipped Vessels and Test Vessels

Table 4-9 summarizes the dimensionless parameter ranges by validation variable for the WTP PJM equipped vessels (plant vessels) and for the available test vessel data with the proposed 8 ft vessel tests included.

Table 4-9 WTP PJM Equipped and Test Vessel Non-Dimensional Parameter Ranges

Name	Jet Reynolds Number		Particle Reynolds Number		Particle Froude Number		Non-Dimensional Drive Time		Nozzle/Particle Reynolds Number		Particle/Nozzle Diameter Ratio	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Fluid Velocity for Heat Transfer												
WTP_VSL	809810	835849	0.06	22	17417	164096	709	4188	69	2906	4.9E-05	6.5E-03
TEST_VSL	997998	1131730	0.12	1	204431	820959	1000	1000	100	349	1.0E-04	3.5E-04
8FT_TEST	86106	1216762	0.04	71	15991	1465463	362	5984	17	9281	9.8E-05	1.3E-02
Average & Peak Suction Line Concentration												
WTP_VSL	244342	1224480	0.01	81	17417	506650	472	5984	9	12958	3.8E-05	6.9E-03
TEST_VSL	7804	204535	0.04	93	2039	827845	120	12562	4	5105	2.8E-04	6.3E-02
8FT_TEST	86106	1216762	0.04	71	15991	1465463	3945	3945	17	9281	9.8E-05	1.3E-02
Miscible Fluids Blending												
WTP_VSL	809810	1236197	0.00	81	174974	148873	472	4188	4	12958	3.8E-05	6.9E-03
TEST_VSL	71953	179883	0.00	0.0	0.0	0.0	319	319	0	0	0.0E+00	0.0E+00
8FT_TEST	608381	1216762	0.32	71	15991	1465463	3945	3945	120	9281	9.8E-05	1.3E-02
Multiple PJM ZOI												
WTP_VSL	837486	1114791	0.00	68	17417	506650	1772	4764	4	9800	4.9E-05	6.9E-03
TEST_VSL	7804	1234876	0.04	93	2039	827845	120	12562	4	5105	2.8E-04	6.3E-02
8FT_TEST	86106	1216762	0.04	71	15991	1465463	3945	3945	17	9281	9.8E-05	1.3E-02
Heel Concentration by Constituent												
WTP_VSL	244342	1224480	0.00	81	17417	506650	472	5984	4	12958	3.8E-05	6.9E-03
TEST_VSL	12835	97962	0.04	93	2039	73855	2592	3925	1671	3260	2.6E-03	2.6E-03
8FT_TEST	86106	1216762	0.04	71	15991	1465463	3945	3945	17	9281	9.8E-05	1.3E-02

Note that the data for the "WTP_VSL" (WTP PJM equipped vessels) show a wider range for the Nozzle/Particle Reynolds number and the Particle/Nozzle Diameter Ratio than exists for the test data, including the 8ft test. This is a result of low viscosity for a number of WTP PJM equipped vessels. These vessels have viscosity less than 1cP due to heating, the presence of a supernate other than water, or other operational conditions. The lowest viscosity occurs in the RLD-VSL-00007 (0.4cP), but ten other vessels have viscosities less than 0.8cP. Similarity for those conditions would be dependent on the extension of the 8ft test to include lower viscosity testing conditions.

Observations for Fluid Velocity

- The min/max values of the validation datasets span the ranges for the plant with the exception of the particle/nozzle diameter ratio.
    - The minimum particle/nozzle diameter for the plant is approximately one half the minimum value for the validation dataset.
    - Because small particles are readily-suspended and become, in effect, part of the carrier fluid, this difference does not constitute a gap in the V&V dataset.
- There does not appear to be a significant gap between plant vessel and test vessel parameters for fluid velocity when 8 ft vessel tests are included.

Observations for Suction Line Concentration and Heel Concentration

- The maximum plant vessel jet Reynolds number is approximately a factor of two larger than the maximum value for the test vessel data.
    - The maximum jet Reynolds number for plant vessel conditions with dynamic viscosity $\geq$ 1 cP is approximately equal to the maximum value for the test vessels.
- Test vessel data bound the minimum value for plant vessel jet Reynolds number.
- Maximum values for the densimetric particle Reynolds number are approximately 100 for both the test and plant vessels.
    - The maximum value of the densimetric particle Reynolds number is 114, if low dynamic viscosity conditions (< 1 cP) are included and 81 if only conditions with dynamic viscosity $\geq$ 1 cP are considered.
- The minimum value for the particle Reynolds number at plant scale is 0.01 which is approximately a factor of 4 smaller than the test vessel data.
    - Because particles with small densimetric particle Reynolds number are readily suspended, this difference does not constitute a gap in the V&V dataset.
- Test vessel ranges for densimetric particle Froude number and non-dimensional drive time span the range for plant vessels.
- The maximum value for the nozzle particle Reynolds number is at plant scale (~13,000) is approximately 1.7 times greater than the maximum value for the test vessels (~8000), when low dynamic viscosity conditions (< 1 cP) are included.
    - The maximum values for the nozzle particle Reynolds number for both plant scale and test vessels are approximately 8000, if low dynamic viscosity conditions (< 1 cP) are not included.
- The minimum value for the nozzle particle Reynolds number is bounded by the test vessel data.
- The maximum value for the particle diameter to nozzle diameter ratio in the test vessels bounds the maximum value for the plant.
- The minimum value for the particle diameter to nozzle diameter ratio in the plant is a factor of approximately 2.6 smaller than the minimum value for the test vessel data.
    - Because small particles are readily suspended, this difference does not constitute a gap in the V&V dataset.

Observations for Miscible Liquids Blending

- The maximum plant vessel jet Reynolds number is approximately a factor of two larger than the maximum value for the test vessel data.
    - The maximum jet Reynolds number for plant vessel conditions with dynamic viscosity $\geq$ 1 cP is approximately equal to the maximum value for the test vessels.
- Test vessel data bound the minimum value for plant vessel jet Reynolds number.

- The maximum value for the densimetric particle Reynolds number at plant scale is 114, if low dynamic viscosity conditions are included, and 81, if low dynamic viscosity conditions are not included. The maximum value for the densimetric particle Reynolds number in the test vessels is 71, similar to the value in the plant for vessels with dynamic viscosity $\geq$ 1 cP.
- Minimum values for the densimetric particle Reynolds number at plant and vessel scales are both 0, i.e. no solids.
- Test vessel data span the range for densimetric particle Froude number for the plant.
- The maximum values for dimensionless drive time for both plant and test vessels are approximately 4000.
- Test vessel data bound the minimum value for dimensionless drive time for the plant vessels.
- The maximum value for the nozzle particle Reynolds number is at plant scale (~13,000) is approximately 1.7 times greater than the maximum value for the test vessels (~8000), when low dynamic viscosity conditions (< 1 cP) are included.
    - The maximum values for the nozzle particle Reynolds number for both plant scale and test vessels are approximately 8000, if low dynamic viscosity conditions (< 1 cP) are not included.
- The minimum value for the nozzle particle Reynolds number is bounded by the test vessel data.
- The maximum value for the particle diameter to nozzle diameter ratio in the test vessels bounds the maximum value for the plant.
- The minimum value for the particle diameter to nozzle diameter ratio in the plant is a factor of approximately 2.6 smaller than the minimum value for the test vessel data.
    - Because small particles are readily suspended, this difference does not constitute a gap in the V&V dataset.
- Note that a gap related to the lack of sparging in the CFD model and in the V&V dataset has been identified for HLP-27, HLP-28, and UFP-2.

Observations for Multiple-PJM ZOI

- Test vessel data span the range of jet Reynolds number for the plant vessels.
- Test vessel data bound the maximum value for the densimetric particle Reynolds number.
- The minimum value for the densimetric particle Reynolds number at plant scale (0.4) is larger than the minimum value at plant scale (<0.1).
    - Because small particles are readily suspended, this difference does not constitute a gap in the V&V dataset.
- Test vessel data span the range of densimetric particle Froude number and non-dimensional drive time for the plant.
- The maximum value for the nozzle particle Reynolds number is at plant scale (~9,800) is approximately 1.3 times greater than the maximum value for the test vessels (~8000), when low dynamic viscosity conditions (< 1 cP) are included.
    - The maximum values for the nozzle particle Reynolds number for both plant scale and test vessels are approximately 8000, if low dynamic viscosity conditions (< 1 cP) are not included.
- The minimum value for the nozzle particle Reynolds number is bounded by the test vessel data.
- The maximum value for the particle diameter to nozzle diameter ratio in the test vessels bounds the maximum value for the plant.
- The minimum value for the particle diameter to nozzle diameter ratio in the plant is a factor of approximately 2 smaller than the minimum value for the test vessel data.
    - Because small particles are readily suspended, this difference does not constitute a gap in the V&V dataset.

These data indicate that addition of the 8 ft vessel tests sufficiently close the gaps between the datasets available for V&V of CFD and plant conditions relative to the dynamic range of CFD. The extended test vessel dataset is sufficient for V&V of CFD for vessel confirmation.

5 Conclusion

Based on the gap analysis, alternatives are presented for each validation variable on how to proceed with V&V of CFD. They include:

1. Perform no additional testing basing model error and uncertainty at plant scale and plant conditions on validation data from existing tests,
2. Perform no additional testing basing model error and uncertainty at plant scale and plant conditions on comparison error and validation uncertainty from a small-scale V&V dataset extended using a multivariate approach, and
3. Perform additional testing, as necessary, to enable assessment of model error and uncertainty at plant scale and plant conditions based on the extended V&V dataset.

5.1 Data Gap Summary

The data gap analysis found that existing experimental data for multiple PJM ZOI are sufficient for V&V of CFD for design confirmation. Should additional testing be conducted, ZOI information should be collected.

A global gap in suction line performance at plant scale is identified.

A global gap for miscible liquids blending in HLP-27, HLP-28, and UFP-2 is identified related to spargers not being modeled in CFD and sparging not being represented in the V&V dataset.

The gap analysis found that gaps exist between existing experimental data for velocity near the vessel wall and a sufficient dataset for V&V of CFD for vessel design confirmation.

- Use of existing data is not recommended because of the expectation for high values for model error and uncertainty.
- Opportunistic collection of near wall velocity data from additional 8 ft vessel tests is recommended.

The gap analysis found gaps between existing experimental data for miscible liquids blending.

- Use of existing data is not recommended because of the expectation for high values for model error and uncertainty.
- A recommendation for collection of appropriate data from 8 ft vessel testing is advised.

The gap analysis found gaps between existing experimental data for concentration at the suction line inlet and heel concentration.

- The sole recommendation is to collect additional data in a larger scale vessel. 8 ft vessel testing is recommended.

The gap analysis shows that with the inclusion of specific 8 ft vessel tests, the gaps between plant vessel parameters and the available data for V&V of CFD are significantly closed.

- The ranges for the dimensional parameters significantly overlap.
- The ranges for relevant dimensionless parameters significantly overlap.
- The dynamic range of parameters for CFD is spanned.

The gap analysis concludes that with the addition of 8 ft vessel test data, the data available for V&V of CFD for WTP PJM equipped vessel design confirmation will be sufficient for each of the validation variables with the exception of miscible liquids blending in HLP-27, HLP-28, and UFP-2.

5.2 Extension of Validation Model Errors and Uncertainties

Although the dynamic range of CFD is spanned by test data, when 8 ft vessel testing is included, plant scale geometries for the largest vessels are not represented in the V&V dataset. However, full-scale pulse tube operation and the effects of pulse tube arrays are represented in the V&V dataset. If assessed model errors and uncertainties for the validation data are similar, these values can be extended to plant scale with confidence. If a significant difference between model errors and uncertainties is observed, a multivariate approach, like Hills method, will be assessed to extend these values to plant scale.

- Hills' Method of Model-Based Weights, J.R. Hamilton and R.G. Hills (2010a) and J.R. Hamilton and R.G. Hills (2010b) , is a multivariate approach that has been tailored for use with the kind of data set that is currently available for V&V of CFD.
    - The method allows validation variables to be different from the application variable, as long as the significant dependencies are shared.
    - The method allows use of validation experiments different from the application experiment.
- The principle drawback of Hills method relative to V&V of CFD for confirmation of WTP PJM equipped vessel design is that community experience with the method is very limited, so proceeding with the Hills' approach would imply acceptance of an indefinable level of risk.

5.3 Suggested Possible Configurations for the 8ft Vessel Test

The following table summarizes the suggested 8ft vessel testing configurations used in Section 4 to narrow the gap between the WTP PJM equipped vessel and the existing test vessels. The detailed list of specific tests and associated measurement quantities/locations will be included in the RTD (Test Plan) that will be issued by the Project Testing Team.

Test Parameter	Units	8ft Vessel Tests							
		#1	#2	#3	#4	#5	#6	#7	#8
Fluid									
Viscosity	[cP]	1	1	1	8	1	1	1	1
Density	[kg/m^3]	998	998	998	1130	998	998	998	998
Mass	[kg]	5723	5723	5723	6480	5723	5723	5723	5723
Vessel									
Diameter	[in]	96	96	96	96	96	96	96	96
Nozzle Diameter	[in]	4	2	2	2	2	4	2	2
Inner pitch ring radius	[in]	48	48	24	24	36	48	48	24
Suction Line diameter	[in]	3	0.75	0.75	0.75	0.75	-	-	-
Suction line inlet height	[in]	3	1.5	1.5	1.5	1.5	-	-	-
Suction line radial offset	[in]	12	6	6	6	6	-	-	-
Nozzle Height	[in]	6	3	3	3	6	6	3	3

Test Parameter		Units	8ft Vessel Tests							
			#1	#2	#3	#4	#5	#6	#7	#8
Pulse Tube Count		[ ]	1	1	4	4	6	1	1	4
PJM Configuration		[ ]	Single	Single	Standard	Standard	Chandelier	Single	Single	Standard
Head Shape		[ ]	F&D	F&D	F&D	F&D	F&D	F&D	F&D	F&D
Operation										
PJM Jet Velocity		[m/s]	12	12	12	12	12	12	12	12
Drive time		[s]	33.4	16.7	16.7	16.7	16.7	33.4	16.7	16.7
Cycle time		[s]	194.97	97.5	97.5	97.5	97.5	194.97	97.5	97.5
Suction line flow rate		[m^3/s]	9.2E-3	2.3E-3	2.3E-3	2.3E-3	2.3E-3	-	-	-
Fill Height		[in]	58	58	58	58	58	58	58	58
Solids			**Representative Simulant**							
Mass Total		[kg]	635.9	635.9	635.9	635.9	635.9	635.9	635.9	635.9
Particle #1	Diameter	[μm]	10	10	10	10	10	10	10	10
	Density	[kg/m^3]	11200	11200	11200	11200	11200	11200	11200	11200
	Mass	[kg]	25	25	25	25	25	25	25	25
Particle #2	Diameter	[μm]	21	21	21	21	21	21	21	21
	Density	[kg/m^3]	2650	2650	2650	2650	2650	2650	2650	2650
	Mass	[kg]	477	477	477	477	477	477	477	477
Particle #3	Diameter	[μm]	81.6	81.6	81.6	81.6	81.6	81.6	81.6	81.6
	Density	[kg/m^3]	2420	2420	2420	2420	2420	2420	2420	2420
	Mass	[kg]	95	95	95	95	95	95	95	95
Particle #4	Diameter	[μm]	312	312	312	312	312	312	312	312
	Density	[kg/m^3]	2650	2650	2650	2650	2650	2650	2650	2650
	Mass	[kg]	19	19	19	19	19	19	19	19
Particle #5	Diameter	[μm]	775	775	775	775	775	775	775	775
	Density	[kg/m^3]	2900	2900	2900	2900	2900	2900	2900	2900
	Mass	[kg]	19	19	19	19	19	19	19	19

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Waste Tank Size Determination for the Hanford River Protection Project Cold Test, Training, and Mockup Facility

Y. Onishi, Yasuo ; B.E. Wells, Beric E.; Kuhn, William L. Publication Date2001 Mar 30 OSTI IdentifierOSTI ID: 965715 Report Number(s)PNNL-13448

Appendix A Experimental Data Set Result

Appendix A

Experimental Data Set Result

A.1 Data Set Availability

As discussed in Section 3.1, the available experimental datasets were reduced based on the validation variables. Determination of the data for use in the test run cases (with FLUENT) require some additional filtering and are based on several considerations as outlined in Section 1.1. The following sections in this Appendix describe the tests and available measurements in detail, supporting further selection of data for comparison to the test run cases.

A.2 PNNL

Over the course of the last eight years, PNNL has produced a large number of technical reports regarding the fluid dynamics of the WTP PJM-mixed vessels. Only three of these reports are considered to be relevant to the gap analysis; WTP-RPT-077, WTP-RPT-081, and WTP-RPT-182.

A.2.1 Phase 1 Testing - (WTP-RPT-182)

A.2.1.1 General Description

Three mixing-test campaigns involving over 900 test cases were conducted in the 2007-2008 time-frame in three different vessels using non-cohesive simulants. The vessels used were a 15(14 7/16)-inch (2:1 elliptical bottom head), a 34-inch (spherical bottom head) and a 70 inch diameter vessel (a 2:1 elliptical or a 100-to-6 flanged & dished bottom head). Schematics of these three vessels are given, respectively, in Figure 6-1, Figure 6-2 and Figure 6-3. Vessels were configured with four, eight or twelve operating PJMs. One of the primary goals was to use data generated from this large number of experiments to develop predictive models for two measures of mixing performance in vessels; cloud height and U_{cs}. Of the over 900 tests, a small subset reported particle concentration at locations representative of where a suction line would be located. The results of this work are described in the technical report WTP-RPT-182.

Figure 6-1 Schematic of the 39" -Tall, 15" -Diameter Vessel Fitted with 12 PJMs

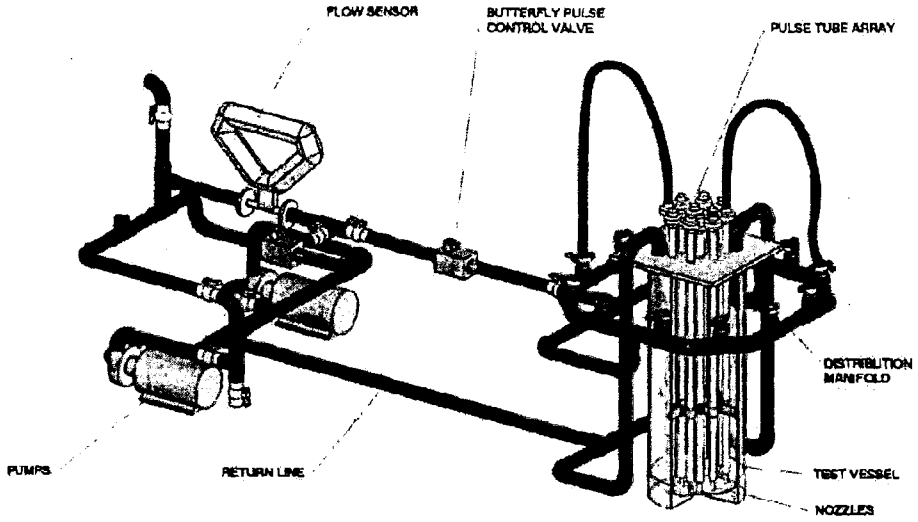


Figure 6-2 Schematic of the 84" -Tall, 34" -Diameter Vessel

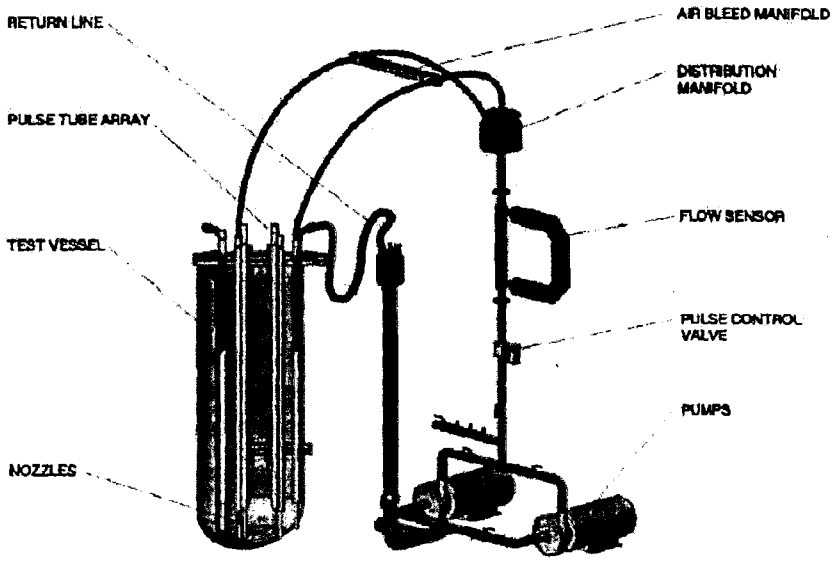
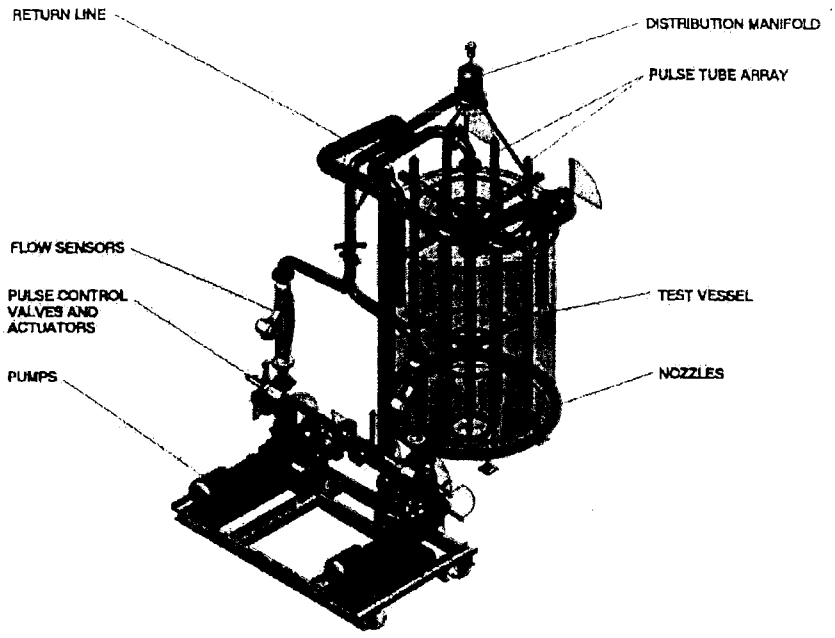


Figure 6-3 Schematic of the 92"-tall (F&D Head) and 99"-tall (2:1 Elliptical Head), 70" -Diameter Vessel with Eight PJMs



A.2.1.2 Validation Variables Measured

The Table 6-1 lists those validation variable that were recorded during the test. Although other measurements may have been taken, only those that are directly related to the validation variables established in Section 1.3, are presented here.

Table 6-1 Validation Variable Availability (WTP-RPT-182)

Primary Validation Variables	**Test Sequence (Name)**
Fluid Velocity for Heat Transfer	None
Concentration at the Suction Line Inlet [a]	Approximately 66 data sets using an ultrasonic probe.
Miscible Fluid Blending	None
Multiple-PJM ZOI	Measured [b]: 2007 test sequence (July and Fall) Visual record of ZOI pattern (July: B1/B2/B5 and B6; Fall: B1/B2)
	Video [c]: 2008 test sequence (57 of 66 tests)
Bulk Concentration in the Heel	None
Secondary Validation Variables	
Cloud Height (Hc)	Many data sets
Critical Velocity for Suspension (Ucs)	Many data sets
Single-Jet ZOI	None
Rate-of-ZOI [d]	2008 test sequence (57 of 66 tests)

Notes:

a. Both average and peak values are available for this test sequence. Data available for the 2008 test series.
b. The 'measured' values refer to the bottom clearing patterns recorded for the 2007 test runs for the mid-scale, spherical head, test configurations. The actual value may be interpreted by these sketches.

c. The 'Video' tests refer to video taken during the 2008 tests of the bottom head clearing. Values may be interpreted by the associated video documentation.
d. The Rate-of-ZOI values may be interpreted by the associated video documentation of the listed tests. There is no associated uncertainty with this evaluation.

A.2.1.3 Geometric, Operational, and Physical Test Configuration

Table 6-2 and Table 6-3 summarize the physical test characteristics as well as the operational configuration and associated simulant properties for those tests selected based on available validation variable defined in Section 1.4.

Table 6-2 Design Parameter Summary - Test Configuration (WTP-RPT-182)

Test Name	Vessel Diameter	Relative Cross-Sectional Area	PJM Nozzle Diameter	PJM Nozzle Offset Ratio	PJM Nozzle Velocity	PJM Pulse Tube Duty Cycle	Relative PJM Inner Pitch Ring Radius
	D_T	$D_T^2/N_{PJM}/D_0^2$	D_0	H_0/D_0	U_0	$DC = t_d/(t_d+t_r)$	Δ/D_0
	[in]	[ ]	[in]	[ ]	[m/s]	[ ]	[ ]
C.01	14.4	1094	0.126	1.04	2.8	33%	18.9
C.02	14.4	1094	0.126	1.04	4.2	33%	18.9
C.03	14.4	1094	0.126	1.04	7.2	18%	18.9
C.04	14.4	1094	0.126	1.04	5.8	33%	18.9
C.05	14.4	1094	0.126	1.04	3.9	67%	18.9
C.06	14.4	1094	0.126	1.04	7.2	19%	18.9
C.07	14.4	1094	0.126	1.04	6.5	33%	18.9
C.08	14.4	1094	0.126	1.04	3	N/A	18.9
C.09	14.4	1094	0.126	1.04	8	34%	18.9
C.10	14.4	1094	0.126	1.04	6.2	34%	18.9
C.11	14.4	1094	0.126	1.04	5.2	34%	18.9
C.12	14.4	1094	0.126	1.04	11.8	33%	18.9
C.13	14.4	1094	0.126	1.04	7.6	33%	18.9
C.14	14.4	1094	0.126	1.04	4.2	33%	18.9
C.15	14.4	1094	0.126	1.04	8.6	34%	18.9
C.16	14.4	1094	0.126	1.04	3.5	33%	18.9
C.17	14.4	1094	0.126	1.04	6.8	33%	18.9
C.18	14.4	714	0.191	1.04	4.8	33%	12.5
C.19	14.4	714	0.191	1.04	4.6	33%	12.5
C.20	14.4	714	0.191	1.04	4.4	33%	12.5
C.21	14.4	363	0.268	1.04	2.9	33%	8.9
C.22	14.4	295	0.297	1.04	1.9	34%	8.0
C.23	14.4	295	0.297	1.04	1.9	33%	8.0
C.24	14.4	591	0.297	1.04	2.5	34%	8.0
C.25	33.9	1084	0.297	1.50	4.5	34%	18.8
C.26	33.9	1084	0.297	1.50	3.7	34%	18.8

Test Name	Vessel Diameter	Relative Cross-Sectional Area	PJM Nozzle Diameter	PJM Nozzle Offset Ratio	PJM Nozzle Velocity	PJM Pulse Tube Duty Cycle	Relative PJM Inner Pitch Ring Radius
	D_T	$D_T^2/N_{PJM}/D_0^2$	D_0	H_0/D_0	U_0	$DC = t_d/(t_d+t_r)$	Δ/D_0
	[in]	[ ]	[in]	[ ]	[m/s]	[ ]	[ ]
C.27	33.9	1084	0.297	1.50	5.1	34%	18.8
C.28	33.9	1084	0.297	1.50	6.2	19%	18.8
C.29	33.9	680	0.375	1.50	5.6	33%	14.9
C.30	33.9	680	0.375	1.50	10	34%	14.9
C.31	33.9	680	0.375	1.50	8.6	34%	14.9
C.32	70.0	1087	0.613	1.50	6.7	33%	18.8
C.33	70.0	1087	0.613	1.50	5.8	33%	18.8
C.34	70.0	1087	0.613	1.50	4.4	34%	18.8
C.35	70.0	1087	0.613	1.50	6.6	34%	18.8
C.36	70.0	1087	0.613	1.50	5.8	33%	18.8
C.37	70.0	1087	0.613	1.50	7.1	34%	18.8
C.38	70.0	1087	0.613	1.50	7.1	34%	18.8
C.39	70.0	1087	0.613	1.50	7.1	34%	18.8
C.40	70.0	1087	0.613	1.50	9.6	19%	18.8
C.41	70.0	1630	0.613	1.50	9.8	19%	18.8
C.42	70.0	1630	0.613	1.50	9.9	19%	18.8
C.43	70.0	1087	0.613	1.50	7.3	34%	18.8
C.44	70.0	1087	0.613	1.50	4.8	67%	18.8
C.45	70.0	1087	0.613	1.50	6.6	33%	18.8
C.46	70.0	1087	0.613	1.50	4.6	34%	18.8
C.47	70.0	1087	0.613	1.50	6	34%	18.8
C.48	70.0	1087	0.613	1.50	11.2	19%	18.8
C.49	70.0	1087	0.613	1.50	11.2	19%	18.8
C.50	70.0	1087	0.613	1.50	11.2	19%	18.8
C.51	70.0	1087	0.613	1.50	7.8	33%	18.8
C.52	70.0	1087	0.613	1.50	7.8	33%	18.8
C.53	70.0	1087	0.613	1.50	7.8	33%	18.8
C.54	70.0	1087	0.613	1.50	6.8	33%	18.8
C.55	70.0	1087	0.613	1.50	8.5	34%	18.8
C.56	70.0	1087	0.613	1.50	8.5	34%	18.8
C.57	70.0	1087	0.613	1.50	8.5	34%	18.8
C.58	70.0	1087	0.613	1.50	8.4	34%	18.8
C.59	70.0	1087	0.613	1.50	12	33%	18.8
C.60	70.0	1087	0.613	1.50	12	33%	18.8
C.61	70.0	1087	0.613	1.50	12	33%	18.8
C.62	70.0	1087	0.613	1.50	7.1	33%	18.8
C.63	70.0	1087	0.613	1.50	7.1	33%	18.8

Test Name	Vessel Diameter	Relative Cross-Sectional Area	PJM Nozzle Diameter	PJM Nozzle Offset Ratio	PJM Nozzle Velocity	PJM Pulse Tube Duty Cycle	Relative PJM Inner Pitch Ring Radius
	D_T	$D_T^2/N_{PJM}/D_0^2$	D_0	H_0/D_0	U_0	$DC = t_d/(t_d+t_r)$	Δ/D_0
	[in]	[ ]	[in]	[ ]	[m/s]	[ ]	[ ]
C.64	70.0	1087	0.613	1.50	7.1	33%	18.8
C.65	70.0	482	0.92	1.50	6.8	34%	12.6
C.66	70.0	482	0.92	1.50	6.4	33%	12.6
Minimum	14.4	295	0.126	1.04	1.9	18.4%	8.02
Maximum	70.0	1630	0.92	1.5	12	66.7%	18.91

Table 6-3 Simulant/Particle Parameter Summary - Test Configuration (WTP-RPT-182)

Test Name	Supernate Viscosity	Supernate Density	Total Solids Loading	Particle Diameter	Particle Density
	μ_l	ρ_l	Wt%	d_p	ρ_p
	[kg/m·s]	[kg/m^3]	[ ]	[μm]	[kg/m^3]
C.01	0.0010	999.4	0.16	69	2480
C.02	0.0009	998.6	0.53	69	2480
C.03	0.0009	999.8	1.59	69	2480
C.04	0.0009	999.3	1.57	69	2480
C.05	0.0010	999.9	1.58	69	2480
C.06	0.0008	998.2	4.69	69	2480
C.07	0.0008	998.3	4.66	69	2480
C.08	0.0009	998.1	4.70	69	2480
C.09	0.0008	998.3	4.69	69	2480
C.10	0.0009	999.1	6.20	69	2480
C.11	0.0009	999.3	0.28	76	4180
C.12	0.0008	996.9	2.62	76	4180
C.13	0.0009	998.8	0.88	76	4180
C.14	0.0009	998.8	0.16	166	2460
C.15	0.0008	998.3	1.56	166	2460
C.16	0.0008	998.1	0.53	44	2500
C.17	0.0007	996.6	0.27	164	4170
C.18	0.0008	998.0	1.46	69	2480
C.19	0.0008	998.2	1.53	69	2480
C.20	0.0008	998.0	1.53	69	2480
C.21	0.0009	998.9	1.50	69	2480
C.22	0.0008	997.3	1.46	69	2480
C.23	0.0008	997.7	1.48	69	2480
C.24	0.0008	998.1	1.48	69	2480

Test Name	Supernate Viscosity	Supernate Density	Total Solids Loading	Particle Diameter	Particle Density
	μ_l	ρ_l	Wt%	d_p	ρ_p
	[kg/m·s]	[kg/m^3]	[ ]	[μm]	[kg/m^3]
C.25	0.0010	998.0	0.20	166	2460
C.26	0.0010	998.7	0.19	166	2460
C.27	0.0010	998.2	0.64	69	2480
C.28	0.0010	998.5	0.64	69	2480
C.29	0.0011	999.9	0.32	76	4180
C.30	0.0010	998.3	3.06	76	4180
C.31	0.0010	998.6	1.04	76	4180
C.32	0.0009	994.1	0.32	166	2460
C.33	0.0009	994.2	0.32	166	2460
C.34	0.0010	994.6	0.33	69	2480
C.35	0.0009	994.6	2.08	69	2480
C.36	0.0009	994.3	1.05	69	2480
C.37	0.0010	994.9	2.96	69	2480
C.38	0.0010	994.9	2.96	69	2480
C.39	0.0010	994.9	2.96	69	2480
C.40	0.0009	994.4	2.89	69	2480
C.41	0.0009	994.9	2.89	69	2480
C.42	0.0009	994.7	2.95	69	2480
C.43	0.0009	994.3	2.91	69	2480
C.44	0.0009	994.3	2.96	69	2480
C.45	0.0009	994.5	2.96	69	2480
C.46	0.0010	994.6	0.31	69	2480
C.47	0.0010	994.8	1.00	69	2480
C.48	0.0009	994.8	2.84	69	2480
C.49	0.0009	994.8	2.84	69	2480
C.50	0.0009	994.8	2.84	69	2480
C.51	0.0010	995.0	2.84	69	2480
C.52	0.0010	995.0	2.84	69	2480
C.53	0.0010	995.0	2.84	69	2480
C.54	0.0008	993.6	3.01	69	2480
C.55	0.0008	994.0	3.01	69	2480
C.56	0.0008	994.0	3.01	69	2480
C.57	0.0008	994.0	3.01	69	2480
C.58	0.0010	994.9	0.53	76	4180
C.59	0.0009	994.4	1.69	76	4180
C.60	0.0009	994.4	1.69	76	4180
C.61	0.0009	994.4	1.69	76	4180

Test Name	Supernate Viscosity	Supernate Density	Total Solids Loading	Particle Diameter	Particle Density
	μ_l	ρ_l	Wt%	d_p	ρ_p
	[kg/m·s]	[kg/m^3]	[ ]	[μm]	[kg/m^3]
C.62	0.0010	995.2	0.31	166	2460
C.63	0.0010	995.2	0.31	166	2460
C.64	0.0010	995.2	0.31	166	2460
C.65	0.0009	994.4	2.79	69	2480
C.66	0.0009	994.3	2.79	69	2480
Minimum	0.0007	993.6	0.16	44	2460
Maximum	0.0011	999.9	6.20	166	4180

A.2.1.4 Dimensionless Parameters - Test Configuration

In addition to the descriptive characteristics for each test given in the previous section, the test conditions may also be summarized using dimensionless parameters. These parameters are defined and described in Section 4.4, and are representative of the physics of interest for the WTP PJM vessels.

Table 6-4 Dimensionless Parameter Summary (WTP-RPT-182)

Test Name	Jet Reynolds Number	Particle Reynolds Number	Particle Froude Number	Dimensionless Drive Time
	Re_0	Re_p	Fr_p	T_d
C.01	9365	2.28	7818	6382
C.02	15730	2.56	17566	6487
C.03	24640	2.34	51730	6621
C.04	20320	2.39	33540	6570
C.05	13044	2.28	15181	6505
C.06	27570	2.62	51591	6687
C.07	25420	2.67	42057	6602
C.08	11236	2.56	8955	N/A
C.09	30633	2.62	63707	6729
C.10	22211	2.45	38310	6638
C.11	18218	4.05	11394	6534
C.12	50132	4.92	58488	6773
C.13	27855	4.24	24323	6670
C.14	15730	9.48	7405	6392
C.15	34366	10.12	31016	6662
C.16	13986	1.40	18859	6383
C.17	29485	15.90	9026	6552
C.18	29076	2.73	22921	2899
C.19	27864	2.73	21057	2936
C.20	27776	2.85	19260	5614

Test Name	Jet Reynolds Number	Particle Reynolds Number	Particle Froude Number	Dimensionless Drive Time
	Re_0	Re_p	Fr_p	T_d
C.21	22608	2.50	8379	1068
C.22	19027	2.91	3587	493
C.23	18266	2.79	3590	961
C.24	23046	2.67	6219	1889
C.25	34624	8.27	8489	6452
C.26	28469	8.26	5746	6433
C.27	39241	2.23	25885	6450
C.28	48878	2.29	38273	6491
C.29	49298	3.42	13225	4902
C.30	99540	3.87	42085	5269
C.31	83548	3.78	31137	5157
C.32	116774	9.11	18694	6488
C.33	98858	8.90	14011	12562
C.34	71595	2.29	19151	6399
C.35	109884	2.35	43089	6402
C.36	96565	2.35	33258	6356
C.37	112753	2.24	49892	6456
C.38	112753	2.24	49892	6456
C.39	112753	2.24	49892	6456
C.40	159831	2.35	91131	6487
C.41	167037	2.40	95047	6540
C.42	164826	2.35	96969	6452
C.43	121538	2.35	52690	6491
C.44	79915	2.35	22780	6408
C.45	109884	2.35	43083	12481
C.46	71338	2.19	20933	6331
C.47	93049	2.18	35622	6408
C.48	186469	2.35	124119	6618
C.49	186469	2.35	124119	6618
C.50	186469	2.35	124119	6618
C.51	123869	2.24	60220	6479
C.52	123869	2.24	60220	6479
C.53	123869	2.24	60220	6479
C.54	123906	2.57	45666	6400
C.55	154882	2.57	71393	6509
C.56	154882	2.57	71393	6509
C.57	154882	2.57	71393	6509
C.58	136681	3.88	29563	6502
C.59	204535	4.07	60289	6571
C.60	204535	4.07	60289	6571

Test Name	Jet Reynolds Number	Particle Reynolds Number	Particle Froude Number	Dimensionless Drive Time
	Re_0	Re_p	Fr_p	T_d
C.61	204535	4.07	60289	6571
C.62	110108	8.09	21031	6488
C.63	110108	8.09	21031	6488
C.64	110108	8.09	21031	6488
C.65	181977	2.51	45723	2886
C.66	171273	2.51	40499	5606
Minimum	9365	1.4	3587	493
Maximum	204535	15.9	124119	12562

Note(s):
a. Test C.08 does not have a specified drive time, it is continuously operated with a gravity refill.

A.2.1.5 Measurement Values per Validation Variable

As listed in Section A.2.1.2, measurements for several validation variables were made for the PNNL (WTP-RPT-182) test. The value of the measurements taken are reported below.

A.2.1.5.1 Cloud Height and Average Concentration Measurement Data

The Cloud Height data for PNNL was extracted from available reports and spreadsheets from the report (WTP-RPT-182.pdf, Table B.5). The reported values were visually measured and a summary is provided in Table 6-5.

A set of 6 probes, positioned at various points within the test vessel, was used to take concentration measurements. The concentration measurements are gathered from a series of runs provided in the recorded test data.

Although there are several concentration samples taken for each probe and at various times during the PJM cycle, the mean concentration is used in this analysis. As an example, the calculation of the mean concentration for a selected few tests are determined by the mean concentration over a single PJM cycle and then taken over a number PJM cycles, as follows:

- Test C30 uses 5 total PJM cycles,
- Test C32 uses 2 PJM cycles,
- Test C48 (0.1D Sensor) uses 4 PJM cycles, and
- Test C48 (0.02D Sensor) uses 5 PJM cycles

The results of averaging this data is in Table 6-5 and represents a small portion of the overall available data.

Table 6-5 Summary of PJM-Cycle Averaged Concentration Measurements (WTP-RPT-182)

Test Configuration	Particle Density	Cycle Average	Concentration	Cloud Height
	[kg/m^3]	% Volume	[kg/m^3]	[in]
C30				
0.07D Sensor	4180	14.370	600.666	10.5

Test Configuration	Particle Density [kg/m^3]	Cycle Average % Volume	Concentration [kg/m^3]	Cloud Height [in]
0.1D Sensor	4180	12.547	524.465	
0.15D Sensor	4180	11.006	460.051	
C32				
0.05D Sensor	2460	0.6225 [a]	15.3135	25.5
C48				
0.1D Sensor	2480	3.304	81.9392	23.5
0.2D Sensor	2480	3.033	75.2184	

A.2.1.5.2 ZOI Measurement Data

Although there are ZOI measurements for the 2007 tests, only the 2009 tests are considered for this evaluation. The 2009 tests do not report actual measurements, but may be evaluated by the existing video footage. The use of this footage for ZOI is to be determined based on the footage clarity on a case-by-case basis. The specific cases for use with ZOI evaluations have not yet been identified.

A.2.1.6 Uncertainty Summary

Table 6-6 Input and Data Uncertainty Values (WTP-RPT-182)

Quantity	Uncertainty
Input Uncertainty	
ρ_L	±0.006 g/cm^3
ρ_P	±0.02 g/cm^3
d_p	10%
μ_L	T=±2°C
U_{jet}	±0.9 /±0.5 / ±0.3 m/s
$mass_p$	±0.0004 /±0.0008 / ±0.0006 vol. fraction
$mass_L$	±0.3 /±0.3 / ±0.5 inches height
d_n	±0.02 mm
Data (Systematic) Uncertainty	
Cloud Height	±13 /±13 / ±25 mm
Ucs	±0.9 /±0.5 / ±0.4 m/s

Note:
a. The uncertainty values shown in this table are either bounding, or are shown based on vessel size, 15*in* / 34*in*/ 70*in*, respectively

A.2.2 Large-Tank Test Stand (LTTS) Building 336 Vessel (WTP-RPT-081)

A.2.2.1 General Description

A total of 82 test cases were run using the 12.75 foot diameter (3.87 meters) vessel housed in the 336 building. This non-transparent vessel houses four PJMs, as shown in Figure 6-4, each with four-inch diameter (ID) nozzles and a typical drive-average velocity of approximately ten meters per second. The average pitch-ring circle radius for this vessel may be determined from Figure 6-5 and is approximately 12.15 nozzle diameters. Twenty single-phase tests were run with water as the fluid and the remaining 62 included either 10 or 35 micron glass beads at either 5 or 20 weight percent. PSD data is also available within the technical report [WTP-RPT-081]. Velocity sampling is done by attaching five probes to a vertical support pipe shown in Figure 6-6.

Note that concentration measurements at the suction line were taken only from test #8.

Figure 6-4 External View of the Four PJM LTTS "336" Vessel

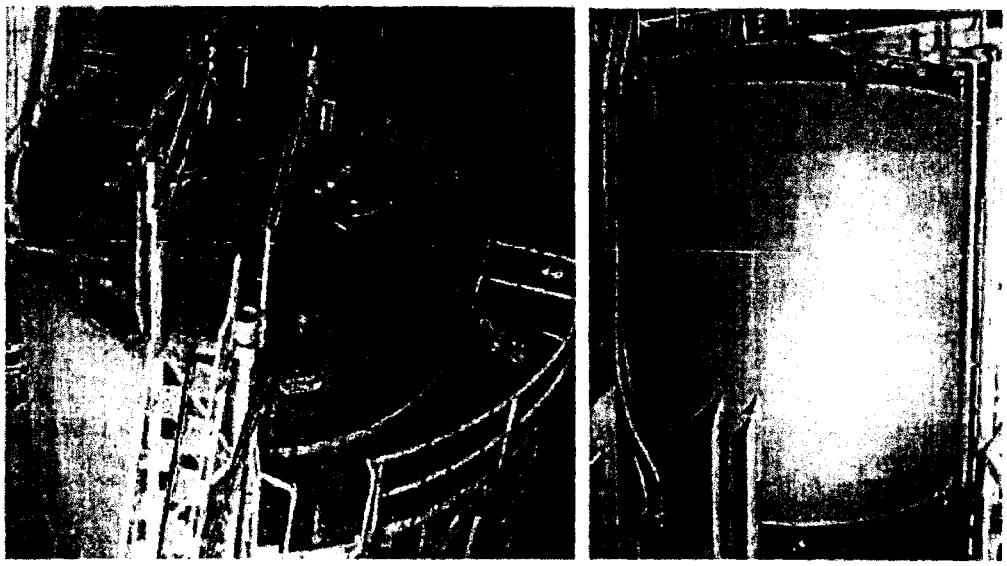


Figure 6-5 Plan View of the Four PJM LTTS "336" Vessels

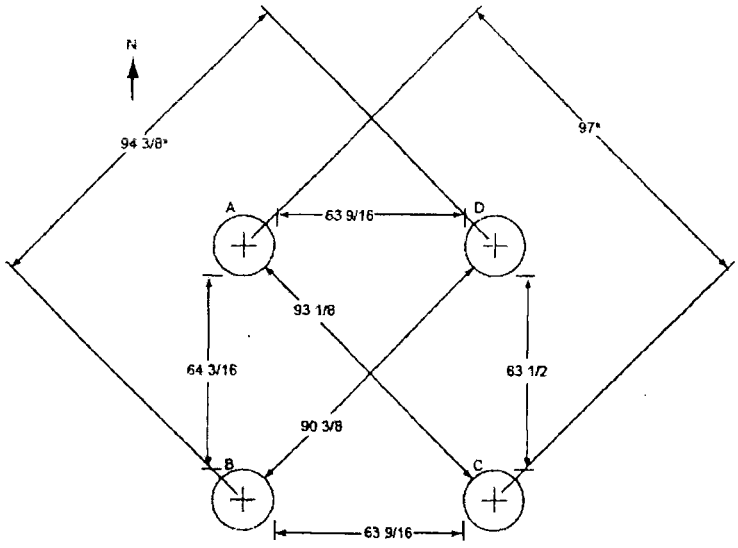
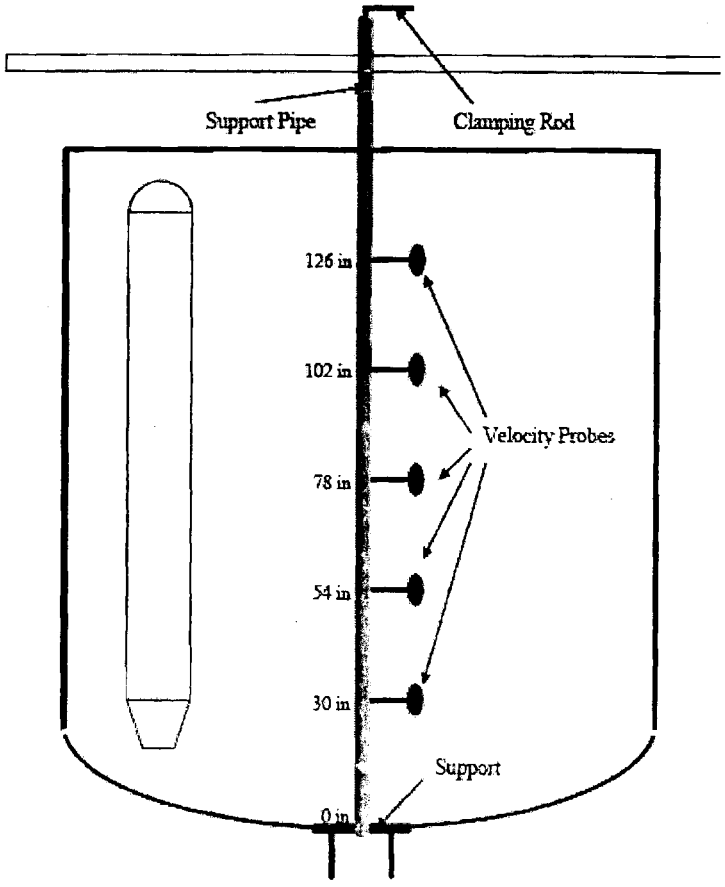


Figure 6-6 Schematic of the Velocity Probe Support Used in the LTTS "336" Vessel



The location of the velocity probes are provided in Table 6-7, Table 6-8, and Table 6-9.

Table 6-7 Velocity Probe Locations for "Hydrodynamic" Cases

Test Number	# of PJM Cycles	Velocity Probe Location			Comments
		Angle (deg.)	Rad. (in.)	Elev. (in.)	
021108A	13.13	0°	12	30,54,78,102,126	See Note b
021108B	27.62	0°	12	30,54,78,102,126	See Note b
021108C	55.33	30°	12	30,54,78,102,126	See Note b
021108D	53.33	60°	12	30,54,78,102,126	See Note b
021108E	57.53	90°	12	30,54,78,102,126	See Note b
021108F	30.11	120°	12	30,54,78,102,126	See Note b
021108G	29.33	150°	12	30,54,78,102,126	See Note b
021108I	29.44	180°	12	30,54,78,102,126	See Note b
021108J	20.33	210°	12	30,54,78,102,126	See Note c
021108K	30.67	240°	12	30,54,78,102,126	
021108L	38.56	270°	12	30,54,78,102,126	See Note d
021108M	32.67	300°	12	30,54,78,102,126	
021108N	29.44	330°	12	30,54,78,102,126	
021108O	32.44	0°	12	30,54,78,102,126	
021108P	66.11	45°	12	30,54,78,102,126	
021108Q	28.67	135°	12	30,54,78,102,126	
021108R	28.40	225°	12	30,54,78,102,126	
021108S	29.18	315°	12	30,54,78,102,126	
021108T	29.78	0°	0	30.48 [a]	
021108U	28.89	180°	24	30.48 [a]	

Notes:

a. From Bottom Center. Additional 4 locations spaced at increasing intervals equal to 24 in.
b. Velocity probe No. 1 data invalid, wire was broken.
c. Velocity probe wire was repaired, data valid from here on.
d. Data for columns S through AG missing.

Table 6-8 Velocity Probe Locations for "Test #1" Cases

Test Number	# of PJM Cycles	Velocity Probe Location			Comments
		Angle (deg.)	Rad. (in.)	Elev. [a] (in.)	
021115B	69.689	0°	0	30.48	Note b
021115C	30.556	0°	0	30.48	Note c
021115D	25.244	180°	24	30.48	
021115E	27.356	180°	24	30.48	
021115F	28.422	135°	24	30.48	
021115G	29.133	135°	17	30.08	
021115H	29.489	135°	17	30.08	
021115I	30.2	135°	17	30.08	
021115J	29.133	0°	0	30.48	

Test Number	# of PJM Cycles	Velocity Probe Location			Comments
		Angle (deg.)	Rad. (in.)	Elev.[a] (in.)	
Notes: a. From Bottom Center. Additional 4 locations spaced at increasing intervals equal to 24 in. b. Mobilization transient, All 4 PJMs operating, initial Conditions: Tank contents settled for 1 day. S.G. = 1.18 c. Periodic Condition reached from previous mobilization transient					

Table 6-9 Velocity and Density Probe Locations for "Test #8" Cases

Test Number	# of PJM Cycles	Velocity Probe Location		Density Sample @r=69"	Density Sample @r=36"	Density Sample @r=0"	Comments
		Angle (deg.)	Rad. (in.)	Elev. (in.)	Elev. (in.)	Elev. (in.)	
Test #8							
021212A	28.4	0°	0	126	54	N/A	Note a
021212B	215.9	180°	24	126	54	36	
021212C	24.6	0°	0	126	54	N/A	Note b
021212D	25.9	180°	24	54	90	12	$\sigma_\rho = 0.003$
021212E	27.3	180°	24	24	108	3	$\sigma_\rho = 0.008$
021212F	25.6	180°	24	72	9	24	$\sigma_\rho = 0.001$
021212G	25.6	180°	24	90	24	54	
021212H	25.3	180°	24	136	36	90	
021212I	26.0	0°	0	126	54	N/A	Note c
Notes: a. PJMs started 12:00:10, mobilization transient, all 4 PJMs operating. Initial Conditions: tank contents settled for 2 days b. Periodic condition, all PJMs operating c. Closure							

Other datasets with density sampling at 3" are 021121D (20%, 10μm), 021204D, N (5%, 35 μm) and 021210B (5%, 35 μm). Dataset 021204E (5%, 35 μm) measures density at 6" while both 021121E,P (20%, 10μm) and 021204G (5%, 35 μm) measure it at 9". These are all used for the suction line concentration data.

A.2.2.2 Validation Variables Measured

The following table lists those validation variable that were recorded during the test. Although other measurements may have been taken, only those that are directly related to the validation variables established in Section 1.3, are presented here.

Table 6-10 Validation Variable Availability (WTP-RPT-081)

Primary Validation Variables	Test Sequence (Name)
Fluid Velocity for Heat Transfer	Twenty tests (021108x). Data sets containing 5% (by weight) solids using 10 micron particles may also be considered candidate data sets for the velocity field. This includes nine data sets (021115B-J) from Test #1.
Concentration at the Suction Line Inlet [a]	Approximately 62 data sets measured fluid density at various locations within the vessel. Test #8 contains three datasets that best fit this validation variable (021212D-F).
Miscible Fluid Blending	None
Multiple-PJM ZOI	None
Bulk Concentration in the Heel	None
Secondary Validation Variables	
Cloud Height (Hc)	None
Critical Velocity for Suspension (Ucs)	None
Single-Jet ZOI	None
Rate-of-ZOI	None

Note:
a. Both average and peak values are available for this test sequence.

A.2.2.3 Geometric, Operational, and Physical Test Configuration

Table 6-11 and Table 6-12 summarize the physical test characteristics as well as the operational configuration and associated simulant properties for those tests selected based on available validation variable results.

Table 6-11 Design Parameter Summary - Test Configuration (WTP-RPT-081)

Test Name	Vessel Diameter	Relative Cross-Sectional Area	PJM Nozzle Diameter	PJM Nozzle Offset Ratio	PJM Nozzle Velocity	PJM Pulse Tube Duty Cycle	Relative PJM Inner Pitch Radius
	D_T	$D_T^2/N_{PJM}/D_0^2$	D_0	H_0/D_0	U_0	$DC = t_d/(t_d+t_r)$	Δ/D_0
	[in]	[ ]	[in]	[ ]	[m/s]	[ ]	[ ]
Hydrodynamic (# 021108A-G, I-U)	153.0	378	3.937	2.38	10.0	22.2%	11.8
Test 1 (021115B-J)	153.0	378	3.937	2.38	10.0	22.2%	11.8
Test 2 (021121A-I)	153.0	378	3.937	2.38	10.0	22.2%	11.8
Test 3 (021121K-P)	153.0	378	3.937	2.38	10.0	22.2%	11.8
Test 4	153.0	378	3.937	2.38	10.0	22.2%	11.8

Test Name	Vessel Diameter	Relative Cross-Sectional Area	PJM Nozzle Diameter	PJM Nozzle Offset Ratio	PJM Nozzle Velocity	PJM Pulse Tube Duty Cycle	Relative PJM Inner Pitch Radius
	D_T	$D_T^2/N_{PJM}/D_0^2$	D_0	H_0/D_0	U_0	$DC = t_d/(t_d+t_r)$	Δ/D_0
	[in]	[ ]	[in]	[ ]	[m/s]	[ ]	[ ]
(021122A)							
Test 5 (021204A-J)	153.0	378	3.937	2.38	10.0	22.2%	11.8
Test 6 (021204N, P-R)	153.0	378	3.937	2.38	10.0	22.2%	11.8
Test 7 (021210A-C)	153.0	378	3.937	2.38	10.0	22.2%	11.8
Test 8 (021212A-I)	153.0	378	3.937	2.38	10.0	22.2%	11.8
Test 9 (021212J-N)	153.0	378	3.937	2.38	10.0	22.2%	11.8
Test 10 (021216A-E, H-I)	153.0	378	3.937	2.38	10.0	22.2%	11.8
Minimum	153.0	378	3.937	2.381	10.0	22.2%	11.8
Maximum	153.0	378	3.937	2.381	10.0	22.2%	11.8

Table 6-12 Simulant/Particle Parameter Summary - Test Configuration (WTP-RPT-081)

Test Name	Supernate Viscosity	Supernate Density	Total Solids Loading	Particle Diameter	Particle Density
	μ_l	ρ_l	Wt%	d_p	ρ_p
	[kg/m·s]	[kg/m^3]	[ ]	[μm]	[kg/m^3]
Hydrodynamic (# 021108A-G, I-U)	0.001	998	N/A	10	2490
Test 1 (021115B-J)	0.001	998	5	10	2490
Test 2 (021121A-I)	0.001	998	20	10	2490
Test 3 (021121K-P)	0.001	998	20	10	2490
Test 4 (021122A)	0.001	998	20	10	2490
Test 5 (021204A-J)	0.001	998	5	35	2490
Test 6 (021204N, P-R)	0.001	998	5	35	2490
Test 7 (021210A-C)	0.001	998	5	35	2490
Test 8 (021212A-I)	0.001	998	20	35	2490
Test 9 (021212J-N)	0.001	998	20	35	2490
Test 10 (021216A-E, H-I)	0.001	998	20	35	2490
Minimum	0.001	998	5	10	2490
Maximum	0.001	998	20	35	2490

A.2.2.4 Dimensionless Parameters - Test Configuration

In addition to the descriptive characteristics for each test given in the previous section, the test conditions may also be summarized using dimensionless parameters. These parameters are described in Section 4.4, and are representative of the physics of interest for the WTP PJM vessels.

Table 6-13 Dimensionless Parameter Summary (WTP-RPT-081)

Test Name	Jet Reynolds Number	Particle Reynolds Number	Particle Froude Number	Dimensionless Drive Time
	Re_0	Re_p	Fr_p	T_d
Hydrodynamic (# 21108A-G, I-U)	997998	N/A	N/A	1000
Test 1 (021115B-J)	1026940	0.12	715509	1000
Test 2 (021121A-I)	1110772	0.12	820959	1000
Test 3 (021121K-P)	1110772	0.12	820959	1000
Test 4 (021122A)	1110772	0.12	820959	1000
Test 5 (021204A-J)	1026940	0.79	204431	1000
Test 6 (021204N, P-R)	1026940	0.79	204431	1000
Test 7 (021210A-C)	1026940	0.79	204431	1000
Test 8 (021212A-I)	1131730	0.80	242673	1000
Test 9 (021212J-N)	1131730	0.80	242673	1000
Test 10 (021216A-E, H-I)	1131730	0.80	242673	1000
Minimum	997998	0.12	204431	1000
Maximum	1131730	0.80	820959	1000
Note(s):				

A.2.2.5 Measurement Values per Validation Variable

Measurements for several validation variables were made for the PNNL (WTP-RPT-081) test. The values are not reproduced here, but may be found in the supporting test documentation.

A.2.2.6 Uncertainty Summary

Table 6-14 Input and Data Uncertainty Values (WTP-RPT-81)

Quantity	Uncertainty
Input Uncertainty	
ρ_L	± 0.001 g/cm (sensor 1) ± 0.005 g/cm (sensor 2/3)
ρ_p	-
d_p	± 1.0 μm (on the mean diameter, for the 10μm particle) ± 5.0 μm (on the mean diameter, for the 100μm particle)
μ_L	-
U_{jet}	-
$mass_p$	-
$mass_L$	-
d_n	± 0.25 in
Data (Systematic) Uncertainty	
Velocity	± 5mm/s + 1%of each axis
Concentration	± 0.001 g/cm

A.2.3 Advanced Product Evaluation Laboratory (APEL) Vessel (WTP-RPT-077)

A.2.3.1 General Description

The principal objective of the tests reported within WTP-RPT-077 was to determine single-phase fluid density as a function of time at three distinct vertical locations with the vessel during mixing of miscible fluids of different densities. Tests were run in the APEL vessel; a 34"-diameter, 93-inch tall vessel having a single center-mounted PJM with a 2" nozzle and a nozzle h/d of 0.934. The PJM operation had a drive and a suction phase. Five tests were conducted by filling the APEL vessel with 132 gallons of liquid, the majority of which was a 50% by weight solution of sodium thiosulfate pentahydrate (specific gravity ~ 1.31) and the remainder was water (specific gravity ~ 1.00). Density was measured continuously using Coriolis densitometers. Three sampling tubes, located at 10", 22" and 34" elevation relative to the vessel bottom (at the centerline), remove fluid at a rate of 0.05 gallons per minute. The fluid is returned to the same elevation subsequent to being measured for density. Tests were run to vary the PJM power per unit vessel volume. Since the volume of the vessel was always 132 gallons, the cycle average power was proportional to ρU_{jet}^3 times the duty cycle.

Figure 6-7 Schematic of the Single PJM APEL Vessel

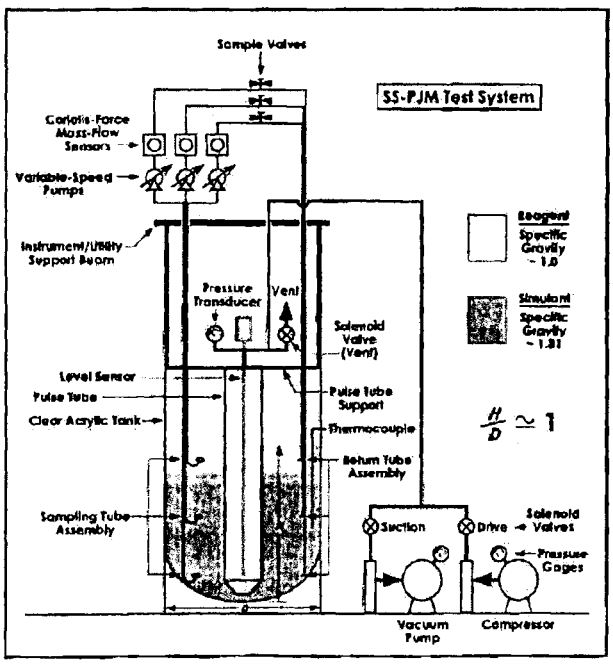
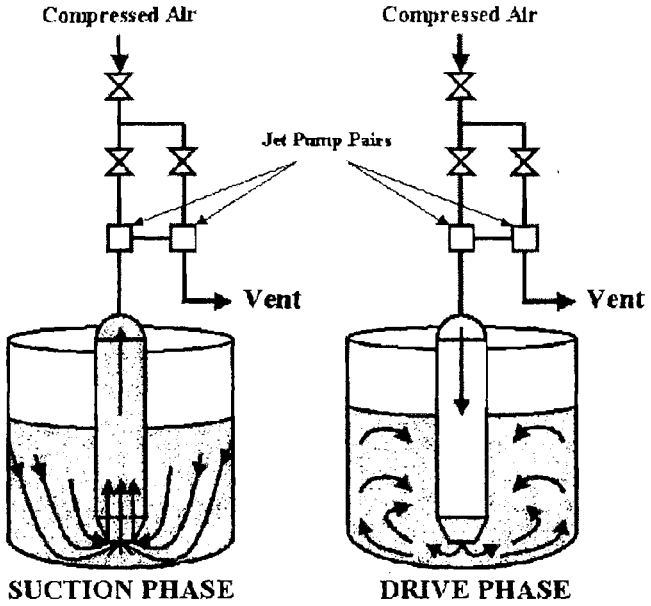


Figure 6-8 Typical Operation of the Single PJM APEL Vessel



A.2.3.2 Validation Variables Measured

Table 6-15 lists those validation variable that were recorded during the test. Although other measurements may have been taken, only those that are directly related to the validation variables established in Section 1.3, are presented here.

Table 6-15 Validation Variable Availability (WTP-RPT-077)

Primary Validation Variables	Test Sequence (Name)
Fluid Velocity for Heat Transfer	None
Concentration at the Suction Line Inlet	None
Miscible Fluid Blending	Five tests with some video footage
Multiple-PJM ZOI	None
Bulk Concentration in the Heel	None
Secondary Validation Variables	
Cloud Height (Hc)	None
Critical Velocity for Suspension (Ucs)	None
Single-Jet ZOI	None
Rate-of-ZOI	None

A.2.3.3 Geometric, Operational, and Physical Test Configuration

Table 6-16 and Table 6-17 summarize the physical test characteristics as well as the operational configuration and associated simulant properties for those tests selected based on available validation variable results.

Table 6-16 Design Parameter Summary - Test Configuration (WTP-RPT-077)

Test Name	Vessel Diameter	Relative Cross-Sectional Area	PJM Nozzle Diameter	PJM Nozzle Offset Ratio	PJM Nozzle Velocity	PJM Pulse Tube Duty Cycle	Relative PJM Inner Pitch Ring Radius
	D_T	$D_T^2/N_{PJM}/D_0^2$	D_0	H_0/D_0	U_0	$DC = t_d/(t_d+t_r)$	Δ/D_0
	[in]	[ ]	[in]	[ ]	[m/s]	[ ]	[ ]
Test 1 (090602R1)	34.0	289	2	0.89	3.24	18.5%	8.5
Test 2 (091002R1)	34.0	289	2	0.89	5.40	12.0%	8.5
Test 3 (091102R1)	34.0	289	2	0.89	5.40	20.0%	8.5
Test 4 (091202R1)	34.0	289	2	0.89	8.10	16.7%	8.5
Test 5 (091302R1)	34.0	289	2	0.89	3.24	18.5%	8.5
Minimum	34.0	289	2.0	0.89	3.2	12.0%	8.5
Maximum	34.0	289	2.0	0.89	8.1	20.0%	8.5

Table 6-17 Simulant/Particle Parameter Summary - Test Configuration (WTP-RPT-077)

Test Name	Supernate Viscosity	Supernate Density	Total Solids Loading	Particle Diameter	Particle Density
	μ_l	ρ_l	Wt%	d_p	ρ_p
	[kg/m·s]	[kg/m^3]	[ ]	[μm]	[kg/m^3]
Test 1 (090602R1)	0.0009	997.8	N/A	N/A	1307
Test 2 (091002R1)	0.0009	997.8	N/A	N/A	1307
Test 3 (091102R1)	0.0014	997.8	N/A	N/A	1307
Test 4 (091202R1)	0.0009	997.8	N/A	N/A	1307
Test 5 (091302R1)	0.0009	997.8	N/A	N/A	1307
Note that the particle here denotes the denser fluid; sodium thiosulfate					

A.2.3.4 Dimensionless Parameters - Test Configuration

In addition to the descriptive characteristics for each test given in the previous section, the test conditions may also be summarized using dimensionless parameters. These parameters are described in Section 4.4, and are representative of the physics of interest for the WTP PJM vessels.

Table 6-18 Dimensionless Parameter Summary (WTP-RPT-077)

Test Name	Jet Reynolds Number	Particle Reynolds Number	Particle Froude Number	Dimensionless Drive Time
	Re_0	Re_p	Fr_p	T_d
Test 1 (090602R1)	71953	N/A	N/A	319
Test 2 (091002R1)	119922	N/A	N/A	319
Test 3 (091102R1)	119922	N/A	N/A	319
Test 4 (091202R1)	179883	N/A	N/A	319
Test 5 (091302R1)	71953	N/A	N/A	319
Minimum	71953	N/A	N/A	319

Test Name	Jet Reynolds Number	Particle Reynolds Number	Particle Froude Number	Dimensionless Drive Time
	Re_0	Re_p	Fr_p	T_d
Maximum	179883	N/A	N/A	319
Note(s):				

A.2.3.5 Measurement Values per Validation Variable

The PNNL test WTP-RPT-077 did not take traditional measurements, but observed mixing behavior. There are no values to report for this test.

A.2.3.6 Uncertainty Summary

Table 6-19 Input and Data Uncertainty Values (WTP-RPT-077)

Quantity	Uncertainty
Input Uncertainty	
ρ_L	-
ρ_p	-
d_p	N/A
μ_L	-
U_{jet}	N/A
$mass_p$	-
$mass_L$	-
d_n	See Note a
Data (Systematic) Uncertainty	
Density	± 0.01 g/cm^3
Note(s): a. Based on micrometer accuracy.	

A.2.4 MCE Phase-2

A.2.4.1 General Description

The testing program was developed specifically to address technical gaps by producing scaled test data to be used by the WTP Mechanical and Process Engineering (M&PE) organization to confirm the design of a set of vessels that process waste with settling solids, or alternatively, identify and test vessel design and operating modifications required to effect required mixing requirements. Required data has been identified, collected, recorded, and reported in accordance with ES nuclear quality assurance (NQA-1) and approved platform operating procedures. Phase 2 experimental data sets consist of 21 test sequences; TS1 through TS21. This testing program is well documented in 24590-WTP-ES-PET-09-001, Rev. 0. All tests were conducted in the Mid Columbia Engineering (MCE) vessel; the "201" vessel (diameter = 43.255 inches). The PJM arrangement used in the vessel had either 8 PJMs to represent FEP-17 or 12 PJMs to represent HLP-22. The PJMs were set into two concentric rings for the 8 and 12 PJM configurations. For the 8 PJM configuration, the inner ring of PJMs (as measured from the center of the nozzle) is a radial distance of 10.8*in*, with the outer ring at 14.4*in*. The 12 PJM configuration uses an inner PJM radial distance of 6.8*in*, with the outer ring at 15.3*in*. Each configuration was run with scaled-down versions of both four- and five-inch nozzles.

Testing involved 15 basic test configurations, each of which included multiple variants of parameters such as pulse jet mixer discharge velocity, frequency of PJM firing, modifications of the vessel internal configurations to test potential mixing improvements, and tests characterizing simulant behavior for dispersal configurations and viscosity. There are in total 90 variants within the 15 basic test configurations.

None of the performance-enhancing design modifications considered in the test sequences are included in the V&V effort. These include pyramidal hydraulic diverters, draft tubes, bubblers and angled nozzles. Hence, the following test sequences will not be considered:
TS7FV1A, TS7FV1B, TS7FV1C, TS7FV1D, TS7FV1E, TS7FV3A, TS7FV3B, TS7FV3C, TS7FV3D, TS7FV5A, TS7FV5B, TS7FV5C, TS7FV5D, TS7FV5E, TS13FV2A, TS13V2B, TS13FV4A, TS13FV4B, TS13FV5A, TS13FV5B, TS18A, and TS18B.

A.2.4.2 Validation Variables Measured

Table 6-20 lists those validation variable that were recorded during the test. Although other measurements may have been taken, only those that are directly related to the validation variables established in Section 1.3, are presented here.

Table 6-20 Validation Variable Availability (MCE Phase-2)

Primary Validation Variables	Test Sequence (Name)
Fluid Velocity for Heat Transfer	None
Concentration at the Suction Line Inlet	Loop samples for average concentrations; TS1, TS1B, TS2, TS2E, TS4A, TS4B, TS4C, TSQV7, TS5F (except at 7 m/s), TS6, TS6E, TS7, TS7E, TS9, TS9E, TS10 (4&8 PJM), TS13FV3A, TS13FV3B, TS13FV6A, TS13FV6B
Miscible Fluid Blending	
Multiple-PJM ZOI	Measured [a] : TS2, TS2B, TS2C, TS4A, TS4B, TS4C, TS4QV4, TS4QV5, TS4QV6, TS4QV7, TS5F, TS6, TS6C, TS7, TS7B, TS7C, TS7D, TS7E, TS9A, TS9B, TS9D, TS9E, TS10 (4&8 PJM), TS13FV6A, TS13FV6B, TS19F, TS20F, TS21F
	Video [b]: TS1, TS1A
Bulk Concentration in the Heel	None
Secondary Validation Variables	
Cloud Height (Hc) [c]	Measured [c] : TS1, TS1A, TS4A, TS5F (4.7 m/s only), TS7, TS7D, TS13FV6A
	Video [d] : TS4B,
Critical Velocity for Suspension (Ucs)	TS1B, TS2C, TS2D, TS2E, TS9D, TS9E, TS13FV6B
Single-Jet ZOI	None
Rate-of-ZOI [d]	TS1, TS1A, TS2FV1, TS2FV2, TS2FV3, TS4A, TS4B, TS4C, TS4QV6, TS4QV7, TS5F (4.7 & 9 m/s only), TS7, TS7B, TS7C, TS7D, TS7E, TS9A, TS9B, TS9C,TS9D, TS9E, TS10 (4&8 PJM), TS13FV3A, TS13FV3B, TS13FV6A, TS13FV6B

Notes:

a. The measured values are documented in the individual test reports and are accompanied by sketches (video is included, but may be unclear). These values have an established uncertainty in the measurement, as documented in Table 19 of 24590-WTP-ES-PET-09-001, Rev. 0.
b. The 'video' designation means that values can be interpreted by the associated video documentation of the listed tests. There is no associated uncertainty with this evaluation.
c. The measured values are documented in the individual test reports and are accompanied by sketches (video is included, but may be unclear). These values have an established uncertainty in the measurement, as documented in Table 19 of 24590-WTP-ES-PET-09-001, Rev. 0.
d. The 'video' designation means that values can be interpreted by the associated video documentation of the listed tests. There is no associated uncertainty with this evaluation.
e. The Rate-of-ZOI determination is based on measurements from the video documentation for the listed tests. There is no associated uncertainty with this evaluation.

Note that all tests have associated video, but due to camera angles, the test configuration, and other particulars associated with the test, it may be difficult to distinguish particular characteristics (such as cloud height) clearly. Only those conditions with clearly defined states are listed in the table above for 'observed' measurements.

The MCE Phase-2 tests produced a significant amount of data regarding multiple PJM ZOI and Rate-of-ZOI measurements. The following table provides a more detailed description of the available ZOI data.

A.2.4.3 Geometric, Operational, and Physical Test Configuration

Table 6-21 and Table 6-22 summarize the physical test characteristics as well as the operational configuration and associated simulant properties for those tests selected based on available validation variable results.

Table 6-21 Design Parameter Summary - Test Configuration (MCE Phase-2)

Test Name	Vessel Diameter	Relative Cross-Sectional Area	PJM Nozzle Diameter	PJM Nozzle Offset Ratio	PJM Nozzle Velocity	PJM Pulse Tube Duty Cycle	Relative PJM Inner Pitch Ring Radius
	D_T	$D_T^2/N_{PJM}/D_0^2$	D_0	H_0/D_0	U_0	$DC = t_d/(t_d+t_r)$	Δ/D_0
	[in]	[ ]	[in]	[ ]	[m/s]	[ ]	[ ]
TS1	43.3	545	0.655	1.50	4.7	37.3%	17.3
TS1A	43.3	545	0.655	1.50	8	29.4%	17.3
TS1B	43.3	545	0.655	1.50	9	29.4%	17.3
TS2	43.3	545	0.655	1.50	4.7	29.4%	17.3
TS2B	43.3	545	0.655	1.50	6	29.4%	17.3
TS2C	43.3	545	0.655	1.50	7	29.4%	17.3
TS2D	43.3	545	0.655	1.50	8	29.4%	17.3
TS2E	43.3	545	0.655	1.50	9	29.4%	17.3
TS2FV1	43.3	545	0.655	1.50	4.7	29.4%	17.3
TS2FV2	43.3	545	0.655	1.50	4.7	29.4%	17.3
TS2FV3	43.3	545	0.655	1.50	4.7	29.4%	17.3
TS4A	43.3	545	0.655	1.50	4.7	22.1%	17.3
TS4B	43.3	545	0.655	1.50	5.5	25.2%	17.3
TS4C	43.3	545	0.655	1.50	4.7	29.5%	17.3
TS4QV4	43.3	545	0.655	1.50	5.9	22.1%	17.3
TS4QV5	43.3	545	0.655	1.50	5.9	22.1%	17.3
TS4QV6	43.3	545	0.655	1.50	5.9	22.1%	17.3
TS4QV7	43.3	545	0.655	1.50	5.9	22.1%	17.3
TS5F_4.7 (Full)	43.3	545	0.655	1.50	4.7	29.5%	17.3
TS5F_6	43.3	545	0.655	1.50	6	29.5%	17.3
TS5F_7	43.3	545	0.655	1.50	7	29.5%	17.3
TS5F_8	43.3	545	0.655	1.50	8	29.5%	17.3
TS5F_9	43.3	545	0.655	1.50	9	29.5%	17.3
TS5F_4.7 (Quarter)	43.3	545	0.655	1.50	5.8	22.1%	17.3
TS6	43.3	545	0.655	1.50	4.7	29.5%	17.3
TS6B	43.3	545	0.655	1.50	6	29.5%	17.3
TS6C	43.3	545	0.655	1.50	7	29.5%	17.3
TS6D	43.3	545	0.655	1.50	8	29.5%	17.3
TS6E	43.3	545	0.655	1.50	9	29.5%	17.3
TS7	43.3	545	0.655	1.50	4.7	29.5%	17.3
TS7B	43.3	545	0.655	1.50	6	29.4%	17.3
TS7C	43.3	545	0.655	1.50	7	29.4%	17.3

Test Name	Vessel Diameter	Relative Cross-Sectional Area	PJM Nozzle Diameter	PJM Nozzle Offset Ratio	PJM Nozzle Velocity	PJM Pulse Tube Duty Cycle	Relative PJM Inner Pitch Ring Radius
	D_T	$D_T^2/N_{PJM}/D_0^2$	D_0	H_0/D_0	U_0	$DC = t_d/(t_d+t_r)$	Δ/D_0
	[in]	[ ]	[in]	[ ]	[m/s]	[ ]	[ ]
TS7D	43.3	545	0.655	1.50	8	29.4%	17.3
TS7E	43.3	545	0.655	1.50	9	29.4%	17.3
TS9A	43.3	545	0.655	1.50	4.7	29.5%	17.3
TS9B	43.3	545	0.655	1.50	6	29.4%	17.3
TS9C	43.3	545	0.655	1.50	7	29.4%	17.3
TS9D	43.3	545	0.655	1.50	8	29.4%	17.3
TS9E	43.3	545	0.655	1.50	9	29.4%	17.3
TS10 8PJM	43.3	545	0.655	1.50	4.7	29.5%	17.3
TS10 4PJM	43.3	1090	0.655	1.50	4.7	29.5%	17.3
TS10 8PJM	43.3	545	0.655	1.50	8	29.4%	17.3
TS10 4PJM	43.3	1090	0.655	1.50	8	29.4%	17.3
TS13FV3A	43.3	1085	0.379	1.50	6	23.6%	17.9
TS13FV3B	43.3	1085	0.379	1.50	13	23.6%	17.9
TS13FV6A	43.3	697	0.473	1.50	6	23.8%	14.4
TS13FV6B	43.3	697	0.473	1.50	13	23.8%	14.4
TS14F	43.3	1085	0.379	1.50	5.7	23.7%	17.9
TS19F (5.7 m/s)	43.3	697	0.473	1.50	5.7	23.5%	14.4
TS19F (7 m/s)	43.3	697	0.473	1.50	7	23.5%	14.4
TS19F (9 m/s)	43.3	697	0.473	1.50	9	23.5%	14.4
TS19F (11 m/s)	43.3	697	0.473	1.50	11	23.5%	14.4
TS20F (5.7 m/s)	43.3	697	0.473	1.50	5.7	23.5%	14.4
TS20F (7 m/s)	43.3	697	0.473	1.50	7	23.5%	14.4
TS20F (9 m/s)	43.3	697	0.473	1.50	9	23.5%	14.4
TS20F (11 m/s)	43.3	697	0.473	1.50	11	23.5%	14.4
TS20F (13 m/s)	43.3	697	0.473	1.50	13	23.5%	14.4
TS21F (5.7 m/s)	43.3	697	0.473	1.50	5.7	23.5%	14.4
TS21F (7 m/s)	43.3	697	0.473	1.50	7	23.5%	14.4
TS21F (9 m/s)	43.3	697	0.473	1.50	9	23.5%	14.4
TS21F (11 m/s)	43.3	697	0.473	1.50	11	23.5%	14.4
TS21F (13 m/s)	43.3	697	0.473	1.50	13	23.5%	14.4
Minimum	43.3	363	0.379	1.5	3.7	22.1%	10.4
Maximum	43.3	1090	0.655	1.5	13	37.3%	17.9

Table 6-22 Simulant/Particle Parameter Summary - Test Configuration (MCE Phase-2)

Test Name	Supernate Viscosity	Supernate Density	Total Solids Loading	Particle Diameter	Particle Density
	μ_l	ρ_l	Wt%	d_p	ρ_p
	[kg/m·s]	[kg/m^3]	[ ]	[μm]	[kg/m^3]
TS1	0.001	998	1.82	178	2450
TS1A	0.001	998	1.82	178	2450
TS1B	0.001	998	1.82	178	2450
TS2	0.001	998	1.84	69.3	2480
TS2B	0.001	998	1.84	69.3	2480
TS2C	0.001	998	1.84	69.3	2480
TS2D	0.001	998	1.84	69.3	2480
TS2E	0.001	998	1.84	69.3	2480
TS2FV1	0.001	998	1.23	69.3	2480
TS2FV2	0.001	998	1.23	69.3	2480
TS2FV3	0.001	998	1.84	69.3	2480
TS4A	0.001	998	3.65	69.3	2480
TS4B	0.001	998	3.65	69.3	2480
TS4C	0.001	998	3.65	69.3	2480
TS4QV4	0.001	998	0.133	200	2650
TS4QV5	0.001	998	0.265	200	2650
TS4QV6	0.001	998	0.529	200	2650
TS4QV7	0.001	998	1.32	200	2650
TS5F_4.7 (Full)	0.01	998	3.65	69.3	2480
TS5F_6	0.01	1140.7	3.2	69.3	2480
TS5F_7	0.01	998	3.65	69.3	2480
TS5F_8	0.01	998	3.65	69.3	2480
TS5F_9	0.01	1140.7	3.2	69.3	2480
TS5F_4.7 (Quarter)	0.01	1140.7	3.17	69.3	2480
TS6	0.001	998	0.5	8.6	8900
TS6B	0.001	998	0.5	10	8900
TS6C	0.001	998	0.5	10	8900
TS6D	0.001	998	0.5	10	8900
TS6E	0.001	998	0.5	8.6	8900
TS7	0.001	998	0.5	200	2650
TS7B	0.001	998	0.5	200	2650
TS7C	0.001	998	0.5	200	2650
TS7D	0.001	998	0.5	200	2650
TS7E	0.001	998	0.5	200	2650
TS9A	0.001	998	5.5	See Note d	See Note d
TS9B	0.001	998	5.5	See Note d	See Note d
TS9C	0.001	998	5.5	See Note d	See Note d
TS9D	0.001	998	5.5	See Note d	See Note d
TS9E	0.001	998	5.5	See Note d	See Note d
TS10 8PJM	0.001	998	6.0	See Note e	See Note e

Test Name	Supernate Viscosity	Supernate Density	Total Solids Loading	Particle Diameter	Particle Density
	μ_l	ρ_l	Wt%	d_p	ρ_p
	[kg/m·s]	[kg/m^3]	[ ]	[μm]	[kg/m^3]
TS10 4PJM	0.001	998	6.0	See Note e	See Note e
TS10 8PJM	0.001	998	6.0	See Note e	See Note e
TS10 4PJM	0.001	998	6.0	See Note e	See Note e
TS13FV3A	0.001	998	0.5	200	2650
TS13FV3B	0.001	998	0.5	200	2650
TS13FV6A	0.001	998	0.5	200	2650
TS13FV6B	0.001	998	0.5	200	2650
TS14F	0.001	998	17.7	See Note f	17.7
TS19F (5.7 m/s)	0.001	998	3.8	See Note g	See Note g
TS19F (7 m/s)	0.001	998	3.8	See Note g	See Note g
TS19F (9 m/s)	0.001	998	3.8	See Note g	See Note g
TS19F (11 m/s)	0.001	998	3.8	See Note g	See Note g
TS20F (5.7 m/s)	0.001	998	13.8	See Note h	See Note h
TS20F (7 m/s)	0.001	998	13.8	See Note h	See Note h
TS20F (9 m/s)	0.001	998	13.8	See Note h	See Note h
TS20F (11 m/s)	0.001	998	13.8	See Note h	See Note h
TS20F (13 m/s)	0.001	998	13.8	See Note h	See Note h
TS21F (5.7 m/s)	0.001	998	17.7	See Note f	See Note f
TS21F (7 m/s)	0.001	998	17.7	See Note f	See Note f
TS21F (9 m/s)	0.001	998	17.7	See Note f	See Note f
TS21F (11 m/s)	0.001	998	17.7	See Note f	See Note f
TS21F (13 m/s)	0.001	998	17.7	See Note f	See Note f
Minimum	0.001	998	0.133	7	2420
Maximum	0.01	1140.7	17.7	200	8900

Notes:

a. Available test cases refer to all performed test cases, with the exception of those previously listed.
b. The weight percent shown represents the total simulant weight percent and is for a single simulant unless otherwise noted.
c. Density of fluid increased due to added glycerol to the water mix.
d. Simulant weight percent by component is 0.5%(S) and 5%(C)
e. Simulant weight percent by component is 0.5% (S10), 0.5% (S200), and 5%(C).
f. Pre-mixed simulant of 5% C(1-52), 45% C(6-24), 40% C(24-26) & 10% C(85-24). All percents given are weight percent of pre-mixed simulant. The added spikes, S(10-89) and S(200-24), are combined with the pre-mixed simulant such that the total volume percent is 6.97% (total weight percent is 17.7%).
g. Pre-mixed simulant of 5% C(1-52), 45% C(6-24), 40% C(24-26) & 10% C(85-24). All percents given are weight percent of pre-mixed simulant. The added spikes, S(10-89) and S(200-24), are combined with the pre-mixed simulant such that the total volume percent is 6.97% (total weight percent is 17.7%). This is then diluted to a volume percent of 1.45% (total weight percent is 3.8%).
h. Pre-mixed simulant of 5% C(1-52), 45% C(6-24), 40% C(24-26) & 10% C(85-24). All percents given are weight percent of pre-mixed simulant. The added spikes, S(10-89) and S(200-24), are combined with the pre-mixed simulant such that the total volume percent is 6.97% (total weight percent is 17.7%). This is then diluted to a volume percent of 5.39% (total weight percent is 13.8%).

Detail on the individual simulant properties are shown in Table 6-23.

Table 6-23 Individual Particle Description (MCE Phase-2)

Test Matrix Identifier	Description	Specific Gravity	Nominal Size [b]	d_{95} Size [b]	Carrier Fluid Density	Solids Density	Re_p [c]
		[]	[μm]	[μm]	[kg/m^3]	[kg/m^3]	[N/A]
G(175-24)	glass beads	2.45	178	261	998	2444	9.8
G(70-24)	glass beads	2.48	69.3	82.2	998/1140	2474	2.4/0.223
C(1-52)	iron oxide	5.24	0.6	N/A	998	5228	0.003
C(6-24)	medium gibbsite	2.42	7	33.4	998	2414	0.076
C(24-26)	Ground silica	2.65	24	N/A	998	2644	0.52
C(85-24)	coarse gibbsite	2.42	85	N/A	998	2414	3.2
S(10-89)	bismuth oxide	8.90	10	20	998	8879	0.31
S(200-26)	un-ground silica	2.65	200	530	998	2644	12.5

Notes:
a. Several tests within test sequence TS5 use a 10 centipoise carrier fluid
b. The nominal size corresponds to the d_{50} size of the particles. Some simulants do not have data available for the d_{95} size. Each test configuration does record values, but they vary by test and draw location.
c. The Particle Reynolds number is based on the nominal (d_{50}) size.

A.2.4.4 Dimensionless Parameters - Test Configuration

In addition to the descriptive characteristics for each test given in the previous section, the test conditions may also be summarized using dimensionless parameters. These parameters are described in Section 4.4, and are representative of the physics of interest for the WTP PJM vessels.

Table 6-24 Dimensionless Parameter Summary (MCE Phase-2)

Test Name	Jet Reynolds Number	Particle Reynolds Number	Particle Froude Number	Dimensionless Drive Time
	Re_0	Re_p	Fr_p	T_d
TS1	78038	8.95	8695	344
TS1A	132830	8.95	25192	151
TS1B	149434	8.95	31883	120
TS2	78038	2.20	21881	435
TS2B	99622	2.20	35660	435 [a]
TS2C	116226	2.20	48537	435 [a]
TS2D	132830	2.20	63396	435 [a]
TS2E	149434	2.20	80235	435 [a]
TS2FV1	78038	2.20	21881	435
TS2FV2	78038	2.20	21881	131
TS2FV3	78038	2.20	21881	435
TS4A	78038	2.20	21881	381
TS4B	91320	2.20	29964	378
TS4C	78038	2.20	21881	438
TS4QV4	97962	11.37	10718	381
TS4QV5	97962	11.37	10718	381
TS4QV6	97962	11.37	10718	381

Test Name	Jet Reynolds Number	Particle Reynolds Number	Particle Froude Number	Dimensionless Drive Time
	Re_0	Re_p	Fr_p	T_d
TS4QV7	97962	11.37	10718	381
TS5F_4.7 (Full)	7804	0.22	21881	438
TS5F_6	11387	0.22	45102	438 [a]
TS5F_7	11623	0.22	48537	438 [a]
TS5F_8	13283	0.22	63396	438 [a]
TS5F_9	17080	0.22	101479	438
TS5F_4.7 (Quarter)	11007	0.22	42145	381
TS6	78038	0.22	33069	438
TS6B	99622	0.28	46348	438
TS6C	116226	0.28	63084	438
TS6D	132830	0.28	82396	438
TS6E	149434	0.22	121258	438
TS7	78038	11.37	6802	438
TS7B	99622	11.37	11085	268
TS7C	116226	11.37	15088	200
TS7D	132830	11.37	19706	151
TS7E	149434	11.37	24941	120
TS9A	78038	0.07	225767	120
TS9B	99622	0.07	367931	438
TS9C	116226	0.07	500795	200
TS9D	132830	0.07	654100	151
TS9E	149434	0.07	827845	120
TS10 8PJM	78038	0.09	183763	438
TS10 4PJM	78038	0.09	183763	438
TS10 8PJM	132830	0.09	532407	151
TS10 4PJM	132830	0.09	532407	151
TS13FV3A	57644	11.37	11085	120
TS13FV3B	124896	11.37	52037	736
TS13FV6A	71941	11.37	11085	Note c
TS13FV6B	155872	11.37	52037	Note c
TS14F	54762	N/A	N/A	Note c
TS19F (5.7 m/s)	68344	N/A	N/A	Note c
TS19F (7 m/s)	83931	N/A	N/A	Note c
TS19F (9 m/s)	107912	N/A	N/A	Note c
TS19F (11 m/s)	131892	N/A	N/A	Note c
TS20F (5.7 m/s)	68344	N/A	N/A	Note c
TS20F (7 m/s)	83931	N/A	N/A	Note c
TS20F (9 m/s)	107912	N/A	N/A	Note c
TS20F (11 m/s)	131892	N/A	N/A	Note c
TS20F (13 m/s)	155872	N/A	N/A	Note c

Test Name	Jet Reynolds Number	Particle Reynolds Number	Particle Froude Number	Dimensionless Drive Time
	Re_0	Re_p	Fr_p	T_d
TS21F (5.7 m/s)	68344	N/A	N/A	Note c
TS21F (7 m/s)	83931	N/A	N/A	Note c
TS21F (9 m/s)	107912	N/A	N/A	Note c
TS21F (11 m/s)	131892	N/A	N/A	Note c
TS21F (13 m/s)	155872	N/A	N/A	Note c

Note(s):
a. Locations are duplicates of the baseline condition
b. "N/A" represents locations with various particles and therefore varied results for the Reynolds and Froude numbers.
c. Location did not specify the duty cycle

A.2.4.5 Measurement Values per Validation Variable

Measurements for several validation variables were made for the MCE Phase-2 test. The value of the measurements taken are reported in Table 6-25.

Table 6-25 Multiple PJM ZOI Results (MCE Phase-2)

Test Sequence	Multiple-PJM ZOI				Rate-of-ZOI	Comments
	Measured Data	Values (a,b) [a] (*in*)		Merged ZOI ?	Video Available?	
		1st PJM	2nd PJM			
TS1	N	N/A	N/A	Y	Y	
TS1A	N	N/A	N/A	Y	Y	Larger area of overlap than TS1
TS2	Y	8, 8	9.5, 10	N/A	N	No disk available
		8.25, 8.5	9.5, 9.5			
		8, 8.5	9.5, 10			
TS2B	Y	6.25, 10.25	9+, 9+	N/A	N	No disk available
		6.5, 10.5	9+, 9+			
		6.5, 10.5	9+, 9+			
TS2C	Y	7, 11+	9+, 9+	N/A	N	No disk available
		7, 11+	9+, 9+			
		7, 11+	9+, 9+			
TS2D	N	N/A	N/A	Y	N	Bottom clearing
TS2FV1	Y	5.75, 9	7, 13	Y	Y	
		5.5, 9	7, 13			
		6, 9	7, 13.25			
TS2FV2	Y	6, 9	9, 9.5	Y	Y	
		6, 9	9, 9			
		6, 9	9, 9.5			
TS2FV3	Y	7, 7	8+, 8+	Y	Y	
		7, 7	8+, 8+			
		7, 7	8+, 8+			
TS4A	Y	7, 8.5	10.5, 10.5	Y	Y	
		7, 9	10.25,10.25			
		7.25, 9	10.25,10.25			
TS4B	Y	7.75, 7.5	9.25, 10.5	Y	Y	

Test Sequence	Multiple-PJM ZOI				Rate-of-ZOI	Comments
	Measured Data	Values (a,b) [a] (*in*)		Merged ZOI ?	Video Available?	
		1st PJM	2nd PJM			
		7.75, 7.75	9.5, 10.25			
		7.5, 8.25	9, 10.25			
TS4C	Y	8, 7	8, 7.5	Y	Y	
		8, 7.5	8.25, 8			
		7.5, 7.5	8.5, 8			
TS4QV4	Y	6, 11	7, 15	Y	Y [b]	Difficult to see ZOI in video
		7, 11	7, 15			
		7, 10.5	7, 15			
TS4QV5	Y	7.5, 10	7, 13	Y	Y [b]	Difficult to see ZOI in video
		7, 10	7, 14.5			
		7.5, 10	7, 14			
TS4QV6	Y	6.25, 10	8, 8	Y	Y [b]	Difficult to see ZOI in video
		6.25, 10	8, 8			
		6.25, 10	8, 8			
TS4QV7	Y	5.5, 8.75	8.75, 8.75	Y	Y [b]	Difficult to see ZOI in video
		5.625, 9	8.75, 8.75			
		5.3125,8.75	8.75, 8.75			
TS5F_4.7	Y	5, 10	6, 6	N/A	Y [b]	Difficult to see ZOI in video
		5, 10	6, 6			
		5, 10	6, 6			
TS5F_6	Y	6, 12+	8+, 8+	N/A	Y [b]	
		6, 12+	8+, 8+			
		6, 12+	8+, 8+			
TS5F_7	Y	12+, 8	8+, 8+	N/A	Y [b]	
		12+, 8	8+, 8+			
		12+, 8	8+, 8+			
TS5F_8	Y	7, 12+	8+, 8+	N/A	Y [b]	
		7, 12+	8+, 8+			
		7, 12+	8+, 8+			
TS5F_9	Y	8.5, 10.25	7.25, 7.25	N/A	Y [b]	Difficult to see ZOI in video
		8.5, 10.5	7.5, 7.5			
		8.5, 10.5	7.5, 7.5			
TS5QF	Y	6.25, 11	7.5, 7.25	N/A	Y [b]	Difficult to see ZOI in video
		6.5, 11	7.5, 7.5			
		6.25, 11	7.5, 7.5			
TS6	Y	7.5, 9	8, 7.75	N/A	Y [b]	Difficult to see ZOI in video
		7.5, 9	7.5, 7.5			
		7.25, 9.25	7.5, 7.625			
TS6B	N	N/A	N/A	N/A	Y [b]	Sketch of overlapping ZOI
TS6C	Y	7.5, 8	7, 11	N/A	Y [b]	Difficult to see ZOI in video
		8, 8	6.5, 10.5			
		8, 8	7, 11			
TS6D	N	N/A	N/A	N/A	Y [b]	Sketch of overlapping ZOI
TS7	Y	5, 8.5	8, 9	Y	Y	Clear ZOI definition in video
		5, 8.5	8.5, 9			
		5.25, 8.25	8.5, 8.75			
TS7B	Y	5, 8	6.5, 7	Y	Y	Clear ZOI definition in video
		5.5, 9	7, 6.5			

Test Sequence	Multiple-PJM ZOI				Rate-of-ZOI	Comments
	Measured Data	Values (a,b) [a] (*in*)		Merged ZOI ?	Video Available?	
		1st PJM	2nd PJM			
		6, 8	7, 6			
TS7C	Y	6.5, 10.5	8.5, 8.5	Y	Y	Resolution poor, but still defined
		6.5, 9	8.5, 8.5			
		7, 9.5	8.5, 8.5			
TS7D	Y	7, 10	10, 11.5	Y	Y	ZOI not as clear, but still defined
		7, 10.5	10, 12			
		8, 11	10, 12			
TS7E	Y	8.5, 9	9, 12	Y	Y	ZOI not as clear, but still defined
		8.25, 9.25	8.5, 12			
		8.5, 9	9, 12			
TS9A	Y	5, 8	8+, 8+	Y	Y	
		5, 8	8+, 8+			
		5, 8	8+, 8+			
TS9B	Y	8.75, 10	6, 10	Y	Y	Clear ZOI definition in video
		8.5, 10	6, 10			
		7.5, 10	6, 10			
TS9D	Y	9+, 9+	12+, 12+	Y	Y	
		9+, 9+	12+, 12+			
		9+, 9+	12+, 12+			
TS9E	Y	9+, 9+	12+, 12+	Y	Y	
		9+, 9+	12+, 12+			
		9+, 9+	12+, 12+			
TS10 (8)	Y	8+, 8+	5, 8	Y	Y	At 4.7m/s
		8+, 8+	5, 8			
		8+, 8+	5, 8			
TS10 (4)	Y	8+, 8+	N/A	N	Y	At 4.7m/s
		8+, 8+				
		8+, 8+				
TS10 (8)	Y	9.5, 10.5	12, 11	Y	Y	At 8m/s
		9.5, 11	12, 10			
		10, 11	12, 11			
TS10 (4)	Y	10.75, 9.75	N/A	N	Y	At 8m/s
		10.5, 11				
		11.25, 10.5				
TS13FV3A	Y	7, 7	5.5, 8	Y	Y	Bottom clears, only one measurement is taken
TS13FV3B	Y	12+, 12+	9+, 9+	Y	Y	
		12+, 12+	9+, 9+			
		12+, 12+	9+, 9+			
TS13FV6A	Y	3, 7.25	6, 6	Y	Y	
		3, 7	6, 6			
		2.75, 7	5.75, 6.5			
TS13FV6B	Y	12+, 12+	9+, 9+	Y	Y	
		12+, 12+	9+, 9+			
		12+, 12+	9+, 9+			
TS14F	Y	3.5, 6	4, 6.25	N/A	Y [b]	Several test states recorded; Cannot read any ZOI from video for TS14F
		3.5, 6	4, 6.25			
		3.5, 6	4, 6.25			
TS19F	Y	4.25, 5.5	6.25, 6.25	N/A	Y [b]	At 4.7m/s

Test Sequence	Multiple-PJM ZOI				Rate-of-ZOI	Comments
	Measured Data	Values (a,b) [a] (*in*)		Merged ZOI ?	Video Available?	
		1st PJM	2nd PJM			
		4.25, 5.5	6.25, 6.25			
		4.5, 5.5	6.25, 6.25			
- 7m/s	Y	5.5, 5	7, 7	N/A	Y [b]	Cannot read any ZOI from video for TS19F
		5.5, 5	7, 6.75			
		5.5, 5.5	6.75, 6.5			
- 9m/s	Y	5.5, 4	7, 6.75	N/A	Y [b]	
		5.5, 4	7, 7			
		5.5, 4	7, 7			
- 11m/s	Y	7, 5	7.5, 7	N/A	Y [b]	
		7, 5	8, 7			
		7, 5.5	7.5, 7.5			
- 13m/s	Y	4, 7	7.5, 7	N/A	Y [b]	
		4.5, 7	8, 7			
		4.5, 7	7.5, 7			
TS20F	Y	4.75, 5.5	6.25, 6	N/A	Y [b]	At 4.7m/s
		4.75, 5.5	6.25, 6.25			
		4.75, 5.25	6.25, 6.25			
- 7m/s	Y	5, 6.5	7, 7.5	N/A	Y [b]	Cannot read any ZOI from video for TS20F
		4.75, 6.5	7, 7			
		5, 6.5	7, 7			
- 9m/s	Y	6, 5.5	8, 8	N/A	Y [b]	
		6, 5.5	8, 8.5			
		6, 5.5	8, 8			
- 11m/s	Y	4, 5.5	8.5, 9	N/A	Y [b]	
		4, 5.5	8.5, 9			
		4.5, 5.5	8, 8.5			
- 13m/s	Y	4.5, 5.5	8.5, 9.5	N/A	Y [b]	
		4.25, 5.5	9, 10			
		4.5, 5.5	9, 9.5			
TS21F	Y	3.5, 5	4.5, 5.5	N/A	Y [b]	At 4.7m/s
		3.5, 5	4.5, 6			
		3.5, 5.5	4.75, 6			
- 7m/s	Y	4.5, 6	6, 6.5	N/A	Y [b]	Cannot read any ZOI from video for TS21F
		4, 6	6, 6			
		4, 6	6.5, 6.5			
- 9m/s	Y	4.5, 5.5	7.5, 7.25	N/A	Y [b]	
		4.5, 5.5	7.5, 7.5			
		4.5, 5.5	7.75, 7.25			
- 11m/s	Y	4.25, 5.5	7.5, 7.5	N/A	Y [b]	
		4.5, 5.5	7.5, 7.5			
		4.5, 6	7.5, 8			
- 13m/s	Y	5, 6	8, 8	N/A	Y [b]	
		5, 6	8.5, 8			
		5, 6	8, 7.5			

Notes:

a. The values shown for the ZOI distance are three separate measurements in most cases. PJM 1 is located at the inner PJM ring; PJM 2 is at the outer PJM ring. The value for 'a' measures from the PJM center to the wall, 'b' measures from the PJM to the center of the vessel. The values shown with a '+' indicate that the recorded ZOI regions merge.

Test Sequence	Multiple-PJM ZOI				Rate-of-ZOI	Comments
	Measured Data	Values (a,b) [a] (*in*)		Merged ZOI ?	Video Available?	
		1st PJM	2nd PJM			
b. Video is available, but the ZOI is undefined from the view. Boundaries or rates of ZOI are difficult to observe.						

A.2.4.6 Uncertainty Summary

Table 6-26 Input and Data Uncertainty Values (MCE Phase-2)

Quantity	Uncertainty
Input Uncertainty	
ρ_L	< ± 0.01 gm/cm^3 of reported value (bulk)
ρ_p	< ± 0.1 of volume % or weight % (depending on reported value)
d_p	± 10% for each size bin with an accumulation tabulation error < ± 10% of volume percent
μ_L	± 10% of reported value
U_{jet}	± 0.2 m/s (± 0.5s on drive time, ± 0.5s on time, ± 0.5in on stroke length)
$mass_p$	± 0.03 kg (instrumentation uncertainty)
$mass_L$	± 0.29gal Volume, ± 0.13 in Level
d_n	± 0.0015 in
Data (Systematic) Uncertainty	
ZOI	± 1 inch (as Measured)
Cloud Height	± 6 inches (as Measured)

A.2.5 MCE Pump-down Testing

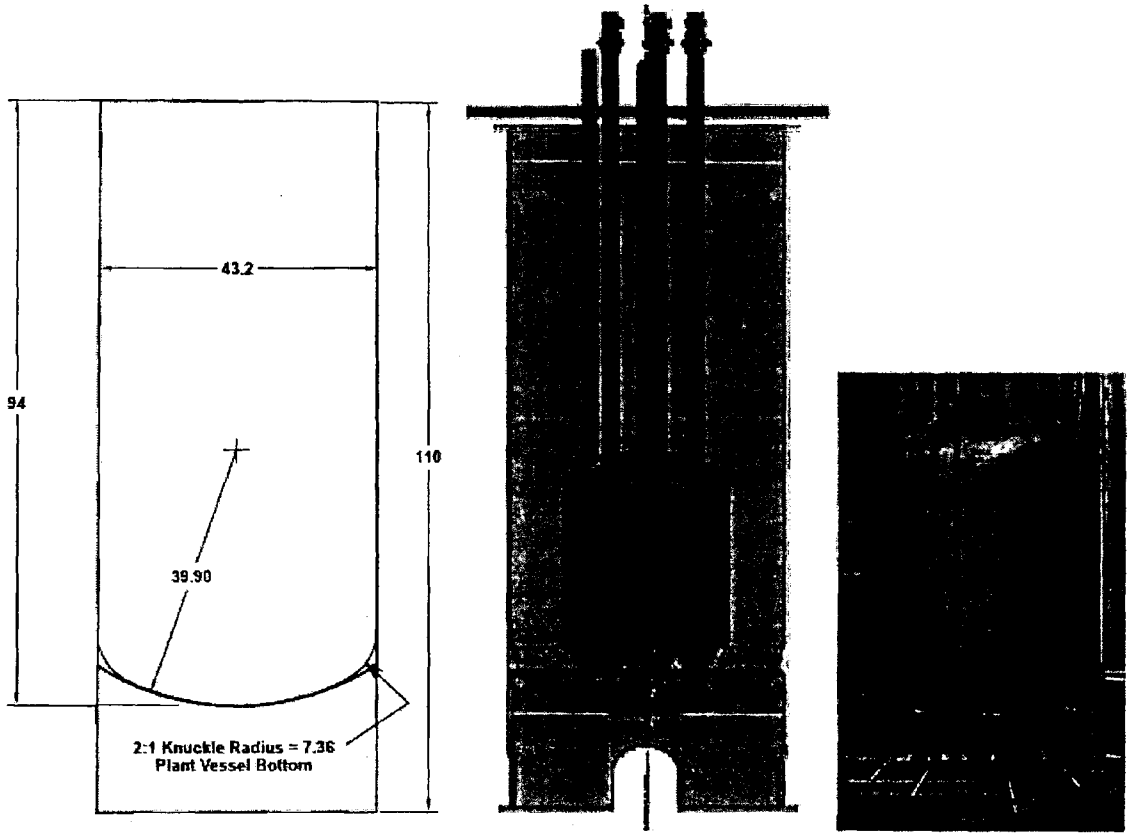
A.2.5.1 General Description

One of the principal objectives of this experimental work was to measure particle concentration in the vessel heel after a full pump-down. Additionally, the vessel was viewed to determine if particles were stagnant or mobilized on the vessel bottom. Slurry density is offered in some cases as a function of space and time. A total of ten tests were reported which conformed to NQA-1 procedures and standards. Mid Columbia Engineering (MCE) vessel draw-down tests were all performed in the "201" vessel (diameter = 43.255 inches) in the 2009-2010 time frame. Based on scaling analyses, test scale configurations were made which represented the (18-PJM) HLP-22, (8-PJM) HLP-27, (8-PJM) FRP-02, (8-PJM) UFP-01 and (8-PJM) FEP-17 vessels. PJM nozzle diameters ranged from 0.307 to 0.766 inches. Only one complete data set is provided for the HLP-22 (CCN 218353), FRP-02 (CCN 218972), UFP-01 (CCN 232595) and FEP-17 (CCN 232596) vessel configurations. Six different complete data sets using the HLP-27 configuration (24590-WTP-RPT-ENG-11-013, Rev. 0) were used to investigate the performance. These HLP-27 tests included a more extensive determination of the heel constituents at the end of draw-down compared to the other vessel configurations.

Several of these are unsuitable for use in the present V&V activity. Three were run while spargers were in operation (UFP-01-NQA-003, HLP-27-LOAM-005 and HLP-27-LOAM-006). CFD simulation of such cases would require a three-phase model where an immiscible fluid model would be used at the free surfaces at the top of the vessel and PJMs while sparger steam would need to be treated as a miscible fluid. Such a complicated three-phase model is too difficult to use in the present circumstances. One data set experienced particle agglomeration during the tests (FRP-02-NQA-002) and another presented a mass discrepancy of 26% at the end of draw-down (HLP-27-LOAM-001). Both of these circumstances render the data unusable. Upon excluding five data sets from consideration, five usable data sets are available for consideration: HLP-22-NQA-007, FEP-17-NQA-004, HLP-27-LOAM-002, HLP-27-LOAM-003 and HLP-27-LOAM-004. HLP-22 and FEP-17 configurations have a suction line which is vertical and exactly coincident with the vessel centerline. This implies that a quarter-symmetry CFD model can be run. All HLP-27 configurations do not permit this degree of symmetry. Heel analysis for each of these vessels falls into one of two categories; HLP-22 and FEP-17 heel analysis consists of the weights of 1) Water, 2) WC and 3) all other solids whileHLP-27 tests report a weight for each constituent.

Vessel draw-down tests typically removed quarter batches at a time over the course of approximately 15-30 PJM cycles. Between quarter batches, the vessels were left in operation for extended periods of time.

Figure 6-9 Dimension of Vessel 201 Used in the Pump-Down Studies (L), a Schematic of Vessel 201 Using a Scaled HLP-27 Configuration (M) and Real Hardware



A.2.5.2 Validation Variables Measured

Table 6-27 lists those validation variable that were recorded during the test. Although other measurements may have been taken, only those that are directly related to the validation variables established in Section 1.3, are presented here.

Table 6-27 Validation Variable Availability (MCE Pump-down)

Primary Validation Variables	
Fluid Velocity for Heat Transfer	None
Concentration at the Suction Line Inlet [a]	All five (Average concentration)
Miscible Fluid Blending	None
Multiple-PJM ZOI	All five
Bulk Concentration in the Heel	All five
Secondary Validation Variables	
Cloud Height (Hc)	None
Critical Velocity for Suspension (Ucs)	None
Single-Jet ZOI	None
Rate-of-ZOI	All five

Notes:
a. Only average concentration values are available for this test sequence.

The test results recorded in 24590-QL-HC1-M00Z-00001-03-00020 , 24590-QL-HC1-M00Z-00001-03-00032 , 24590-QL-HC4-M00Z-00003-04-00002 , 24590-QL-HC4-M00Z-00003-04-00003 and 24590-QL-HC4-M00Z-00003-04-00004 , report ZOI measurements at several conditions of interest. In some instances, there are video recordings associated with these measurements. The specific results for the listed test conditions are shown below.

A.2.5.3 Geometric, Operational, and Physical Test Configuration

Table 6-28 and Table 6-29summarize the physical test characteristics as well as the operational configuration and associated simulant properties for those tests selected based on available validation variable results.

Table 6-28 Design Parameter Summary - Test Configuration (MCE Pump-down)

Test Name	Vessel Diameter	Relative Cross-Sectional Area	PJM Nozzle Diameter	PJM Nozzle Offset Ratio	PJM Nozzle Velocity	PJM Pulse Tube Duty Cycle	Relative PJM Inner Pitch Ring Radius
	D_T	$D_T^2/N_{PJM}/D_0^2$	D_0	H_0/D_0	U_0	$DC = t_d/(t_d+t_r)$	Δ/D_0
	[in]	[ ]	[in]	[ ]	[m/s]	[ ]	[ ]
HLP-22-NQA-007	43.3	640	0.403	1.41	4.97	17.1%	18.9
FEP-17-NQA-004	43.3	545	0.655	1.50	5.90	17.7%	17.2
HLP-27-LOAM-002	43.3	702	0.577	1.50	9.7	16.0%	8.2
HLP-27-LOAM-003	43.3	702	0.577	1.50	6.6	15.6%	8.2
HLP-27-LOAM-004	43.3	702	0.577	1.50	6.2	16.6%	8.2
Minimum	43.3	545	0.403	1.41	4.97	15.6%	8.2
Maximum	43.3	702	0.655	1.50	9.7	17.7%	18.9

Table 6-29 Simulant/Particle Parameter Summary - Test Configuration (MCE Pump-down)

Test Name	Supernate Viscosity	Supernate Density	Total Solids Loading	Particle Diameter	Particle Density
	μ_l	ρ_l	Wt%	d_p	ρ_p
	[kg/(m·s)]	[kg/m^3]	[ ]	[μm]	[kg/m^3]
HLP-22-NQA-007	0.001	998	10	-	-
FEP-17-NQA-004	0.001	998	2	-	-
HLP-27-LOAM-002	0.008	1130	11	-	-
HLP-27-LOAM-003	0.001	998	20	-	-
HLP-27-LOAM-004	0.008	1130	24	-	-
Minimum	0.001	998	2	4.7	2420
Maximum	0.008	1130	24	775.1	11200

Note(s):
a. The particle diameter and density are not shown here since each test uses a mix of different simulants. See the following table for details.
b. The maximum and minimum for the particle diameter and density reflect the max/min for the individual particles.

Details on the particle distribution for each test is found in Table 6-30.

Table 6-30 Particle Distribution (MCE Pump-down)

Simulant Types	Particle Density [kg/m^3]	d_{50} Particle Size [µm]	HLP-22	FEP-17	HLP-27 (2)	HLP-27 (3)	HLP-27 (4)
$Al(OH)_3$ - Gibbsite	2420	81.6	x				
$Al(OH)_3$ - Gibbsite	2420	10.1		x			
WC - Tungsten Carbide	11200	4.7	x	x			
SiO_2 (small)	2650	21.1	x	x			
SiO_2 (large)	2650	312.5	x	x			
Glass Beads	2900	648	x	x			
WC - Tungsten Carbide	11200	8.9				x	x
SiO_2	2650	25.4				x	x
Al_2O_3 - Alumina	3800	140.6			x	x	x
Glass Beads	2900	775.1			x	x	x
Bi_2O_3	8900	12.8				x	x

A.2.5.4 Dimensionless Parameters - Test Configuration

In addition to the descriptive characteristics for each test given in the previous section, the test conditions may also be summarized using dimensionless parameters. These parameters are described in Section 4.4, and are representative of the physics of interest for the WTP PJM vessels.

Table 6-31 Dimensionless Parameter Summary (MCE Pump-down)

Test Name	Jet Reynolds Number	Particle Reynolds Number		Particle Froude Number		Dimensionless Drive Time
	Re_0	Re_p		Fr_p		T_d
		Min	Max	Min	Max	
HLP-22-NQA-007	50772	0.102	71.2	52407	2039	3923
FEP-17-NQA-004	97962	0.102	71.2	73855	2873	2592
HLP-27-LOAM-002	20080	1.134	11.9	28871	7900	3925
HLP-27-LOAM-003	96535	0.265	93.1	13611	3006	3850
HLP-27-LOAM-004	12835	0.035	11.9	13778	3227	3875
Minimum	12835	0.035	11.9	13611	2039	2592
Maximum	97962	1.134	93.1	73855	7900	3925

Note(s):
a. Each pump down test contained a variety of particles in combination. The maximum and minimum values represent this range.

A.2.5.5 Measurement Values per Validation Variable

Measurements for several validation variables were made for the MCE Pump-down test. The value of the measurements taken are reported in Table 6-32.

Table 6-32 Video Recordings Prior to Pump-Down (MCE Pump-down)

Test Description	Jet Velocity at Pump-Down from Full, U_{jet} (*m/s*)	Drive Cycle (*s*)	Total Cycle (*s*)	Comments
HLP-22-NQA-007	4.97 ± 0.2	8.08 ± 0.4	47.3 ± 2.0	Note b
FEP-17-NQA-004	5.9 ± 0.2	7.31 ± 0.4	41.2 ± 2.0	Note a: Video only available for state prior to start of pump-down.
HLP-27-LOAM-002	9.7 ± 0.2	5.93 ± 0.4	37.0 ± 2.0	Note c: The velocity corresponds to the Alt 1 velocity, which is the condition used during pump-down due to as-tested requirements.
HLP-27-LOAM-003	6.6 ± 0.2	8.55 ± 0.4	54.9 ± 2.0	Note d
HLP-27-LOAM-004	6.2 ± 0.2	9.16 ± 0.4	55.2 ± 2.0	Note e

Notes:

a. FEP-17-NQA-004 video results for the quasi-steady state from Step 50 in 24590-QL-HC1-M00Z-00001-03-00020 (associated video: 20100329-0456.5.9M.FB.PO.bttmFull.mov). No video available during pump-down.
b. HLP-22-NQA-007 video results, for the 'B' test sequence, are from Step 12 in 24590-QL-HC1-M00Z-00001-03-00032 (associated video: 20100501-1749.7.92M.FB.PO.bttmFULL.mov). Video for pump-down available for all four conditions, see 24590-QL-HC1-M00Z-00001-03-00032 for details.
c. HLP-27-LOAM-002 video results are for the quasi-steady state from Step 14 in 24590-QL-HC4-M00Z-00003-04-00002 (associated video: 20101119-0435.9.7ms.FB.Alt.1.All_PJMs.No_Spargers-BOTTOM.mov). Video for pump-down available for all four conditions, see 24590-QL-HC4-M00Z-00003-04-00002 for details.
d. HLP-27-LOAM-003 video results are for the quasi-steady state from Step 16 in 24590-QL-HC4-M00Z-00003-04-00003 (associated video: 20101206-2341.6.6ms.FB.PO-BOTTOM.mov). Video for pump-down available for all four conditions, see 24590-QL-HC4-M00Z-00003-04-00003 for details.
e. HLP-27-LOAM-004 video results are for the quasi-steady state from Step 18 in 24590-QL-HC4-M00Z-00003-04-00004 (associated video: 20101208-1253.6.2ms.FB.PO.All_PJMs-BOTTOM.mov). Video for pump-down available for all four conditions, see 24590-QL-HC4-M00Z-00003-04-00004 for details.

Note that the videos are of the quasi-steady state operation of the PJMs using the same jet velocity and PJM firing sequence as during draw-down for the full condition. Additional videos are available for the remaining fill states (3/4, 1/2, and 1/4 full), but are not listed here. Limited videos are also available during the pump-down sequence.

Table 6-33 Detail on Multiple-PJM ZOI Measurements (Pump-down)

Test Sequence	Multiple-PJM ZOI				Rate-of-ZOI	Comments
	Velocity (m/s)	Values (a,b) [b, c] (*in*)		Merged ZOI ?	Video Available?	
		1st PJM	2nd PJM			
FEP-17-NQA-004	5.9	6.5, 8.25	9.25, 8	Y	Y	8-PJMs: Data from Step 50 (Full Batch, Pumpout Velocity)
		6.5, 8.5	9.25, 8			
		6.5, 8.75	9.25, 8			

Test Sequence	Multiple-PJM ZOI				Rate-of-ZOI	Comments
	Velocity (m/s)	Values (a,b) [b, c] (*in*)		Merged ZOI ?	Video Available?	
		1st PJM	2nd PJM			
HLP-22-NQA-007(B)	4.97	4, 4	6, 6	Y	Y	18-PJMs: Data from Step 12 (Full Batch, Pumpout Velocity)
		4, 6	6, 6			
		4, 5.75	6, 6			
HLP-27-LOAM-002	9.7	13.5	4.75,5.5 3.5,10.5	Y	Y	8-PJMs: Data from Step 14 (Full Batch, Alt 1 Velocity) First row for 2nd PJM is North-South, then East-West
		14.5	4.75,5.5 3.5,10.5			
		14	4.75,5.5 3.5,10.5			
HLP-27-LOAM-003	6.6	14.5	8.5, 4.5 5, 10.75	N/A	Y [d]	8-PJMs: Data from Step 18 (Full Batch, Pumpout Velocity)
		14.5	8.5, 4.5 5, 10.75			
		14.5	8.5, 4.5 5, 10.75			
HLP-27-LOAM-004	6.2	11.5	5.5,5.25 4.25,10.5	N/A	Y [d]	8-PJMs: Data from Step 20 (Full Batch, Pumpout Velocity)
		12	5.5,5.25 4.25,10.5			
		11.5	5.5,5.25 4.25,10.5			

Notes:

a. Data from completed Test Procedures from each stated test. All values are provided for the 'Full' condition.

b. The values shown are from Attachment P of 24590-QL-HC1-M00Z-00001-03-00020 and 24590-QL-HC1-M00Z-00001-03-00032 . PJM 1 is located at the inner PJM ring; PJM 2 is at the outer PJM ring. For the inner PJMs, the value for 'a' measures from the PJM center to the wall, 'b' measures from the PJM to the center of the vessel. For the outer PJMS, the 'a' and 'b' values are determined from the PJM center to the vessel wall at a 120deg angle to one another.

c. The values shown are from Attachment P of 24590-QL-HC4-M00Z-00003-04-00002 , 24590-QL-HC4-M00Z-00003-04-00003 and 24590-QL-HC4-M00Z-00003-04-00004 . The HLP-27 tests listed recorded "circular" and "irregular" ZOI values. For the inner PJMs, a diameter for the ZOI is given (1st PJM), while the outer PJMs have four values associated with north, south, east, and west and are reported as radii (2nd PJM).

d. Video is available, but the ZOI is undefined from the view. Boundaries or rates of ZOI are difficult to observe.

Detail on the mass recovery and associated mass discrepancy for the draw down is shown in Table 6-34. These mass discrepancy numbers range from -1.92% to 3.19% of the starting mass.

Table 6-34 Initial, Final, and Discrepant Particle Masses (MCE Pump-down)

Simulant Type (Name)	HLP-22-NQA-007	FEP-17-NQA-004	HLP-27-LOAM-002	HLP-27-LOAM-003	HLP-27-LOAM-004
Simulant [kg]					
$Al(OH)_3$ - Gibbsite	9.16				
$Al(OH)_3$ - Gibbsite		2.70			
WC - Tungsten Carbide	2.44	0.72			

Simulant Type (Name)	HLP-22-NQA-007	FEP-17-NQA-004	HLP-27-LOAM-002	HLP-27-LOAM-003	HLP-27-LOAM-004
SiO_2 (small)	45.82	13.52			
SiO_2 (large)	1.83	0.54			
Glass Beads	1.83	0.54			
WC - Tungsten Carbide				2.22	3.18
SiO_2				86.39	124.05
Al_2O_3 - Alumina			123.90	73.10	104.97
Glass Beads			6.35	4.43	6.36
Bi_2O_3				55.38	79.52
Total Simulant Mass Added	61.1	18.0	130.3	221.5	318.1
Mass Out (Suction Line + Heel)	59.1	17.7	132.7	220.2	317.9
Unaccounted Mass	1.9	0.4	-2.5	1.3	0.3
Unaccounted Mass %	3.19	2.07	-1.92	0.59	0.09

Additional detail on the recovered masses on a per case basis for the pump-down tests.

Table 6-35 Recovered Masses During Pump-Down for HLP-27-LOAM-002

Initial Vessel Level	Final Vessel Level	Fill/ Pumpout quantity (L)	Mass Solids (kg)	% total solids recovered	Beads (kg)	% of Beads recovered	Al2O3 (kg)	% of Al2O3 recovered
Solids Added	Full	946	130.25		6.354		123.9	
Solids recovered per analytical results								
Full	3/4	222	64.62	48.7	1.33	21.6	63.2	50.0
3/4	1/2	193.6	27.16	20.5	0.71	11.5	26.5	20.9
1/2	1/4	205.6	20.36	15.3	0.31	5.0	20.1	15.8
1/4	Heel	210.7	11.33	8.5	0.44	7.2	10.9	8.60
Heel	Heel	114.1	9.28	7.0	3.37	54.7	5.9	4.70
		Total	132.74	100	6.16	100	126.6	100

Table 6-36 Recovered Masses During Pump-Down for HLP-27-LOAM-003

Initial Vessel Level	Final Vessel Level	Fill/ Pumpout quantity [L]	Mass Solids [kg]	% total solids recovered	Beads [kg]	% of Beads recovered	Non-Glass Beads [kg]	% of Non-Glass Beads
Solids Added	Full	946	221.53		4.43		217.1	
Solids recovered per analytical results								
Full	3/4	218	129.17	58.7	0.35	7.5	128.8	59.8
3/4	1/2	193.6	54.4	24.7	0.07	1.4	54.3	25.2
1/2	1/4	205.2	20.97	9.5	0.03	0.6	20.9	9.7
1/4	Heel	210.9	5.9	2.7	0.06	1.3	5.8	2.7
Heel	Heel	118.3	9.75	4.4	4.21	89.2	5.5	2.6
		Total	220.21	100	4.72	100	215.5	100

Table 6-37 Recovered Masses During Pump-Down for HLP-27-LOAM-003 (per Constituent)

Initial Vessel Level	Final Vessel Level	Al_2O_3 Mass Solids	Al_2O_3 % total solids	Bi_2O_3 Mass Solids	Bi_2O_3 % Total Solids	SiO_2 Mass Solids	SiO_2 % Total Solids	WC Mass Solids	WC % Total Solids	Glass Beads Mass Solids	Glass Beads % Total Solids
		[kg]	Recov.	[kg]	Recov.	[kg]	Recov.	[kg]	Recov.	[kg]	Recov.
Solids added	Full	73.1		55.38		86.4		2.22		4.43	
Solids recovered per analytical results											
Full	3/4	51.66	71.3	27.97	52.6	47.98	54.7	1.2	54.1	0.35	7.50
3/4	1/2	11.43	15.8	15.66	29.4	26.59	30.3	0.66	29.6	0.07	1.40
1/2	1/4	3.60	5.0	7.22	13.6	9.87	11.3	0.26	11.5	0.03	0.60
1/4	Heel	1.54	2.1	1.8	3.40	2.44	2.80	0.07	3.30	0.06	1.30
Heel	Heel	4.21	5.8	0.54	1.00	0.76	0.90	0.03	1.50	4.21	89.2
	Total	72.44	100	53.19	100	87.64	100	2.23	100	4.72	100

Table 6-38 Recovered Masses During Pump-Down for HLP-27-LOAM-004

Initial Vessel Level	Final Vessel Level	Fill/ Pumpout quantity [L]	Mass Solids [kg]	% total solids recovered	Beads [kg]	% of Beads recovered	Non-Glass Beads [kg]	% of Non-Glass Beads
Solids Added	Full	946	318.2		6.36		311.8	
Solids recovered per analytical results								
Full	89%	97.5	71.78	22.5	1.31	19.6	70.47	22.6
89%	3/4	124.2	58.51	18.3	0.69	10.4	57.82	18.5
3/4	1/2	197	81.47	25.5	0.77	11.5	80.7	25.8
1/2	1/4	208	50.02	15.7	0.32	4.70	49.7	15.9
1/4	Heel	210.9	36.18	11.3	0.37	5.60	35.81	11.5
Heel	Heel	108.4	21.13	6.60	3.23	48.2	17.9	5.70
	Total		319.1	100	6.69	100	312.41	100

Table 6-39 Recovered Masses During Pump-Down for HLP-27-LOAM-004 (per Constituent)

Initial Vessel Level	Final Vessel Level	Al_2O_3 Mass Solids	Al_2O_3 % total solids	Bi_2O_3 Mass Solids	Bi_2O_3 % Total Solids	SiO_2 Mass Solids	SiO_2 % Total Solids	WC Mass Solids	WC % Total Solids	Glass Beads Mass Solids	Glass Beads % Total Solids
		[kg]	Recov.	[kg]	Recov.	[kg]	Recov.	[kg]	Recov.	[kg]	Recov.
Solids Added	Full	104.97		79.52		124.06		3.18		6.36	
Solids recovered per analytical results											
Full	89%	40	38.4	10.63	13.5	19.38	15.3	0.46	14.5	1.31	19.6
89%	3/4	21.15	20.3	13.45	17.1	22.66	17.9	0.56	17.7	0.69	10.4
3/4	1/2	22.62	21.7	23.24	29.6	34.12	27.0	0.72	22.6	0.77	11.5
1/2	1/4	10.33	9.90	14.61	18.6	24.09	19.1	0.68	21.3	0.32	4.70
1/4	Heel	6.79	6.50	11.02	14.0	17.5	13.8	0.5	15.7	0.37	5.60
Heel	Heel	3.33	3.20	5.67	7.20	8.65	6.80	0.26	8.20	3.23	48.2
	Total	104.21	100	78.62	100	126.4	100	3.18	100	6.69	100

A.2.5.6 Uncertainty Summary

Table 6-40 Input and Data Uncertainty Values (MCE Pump-down)

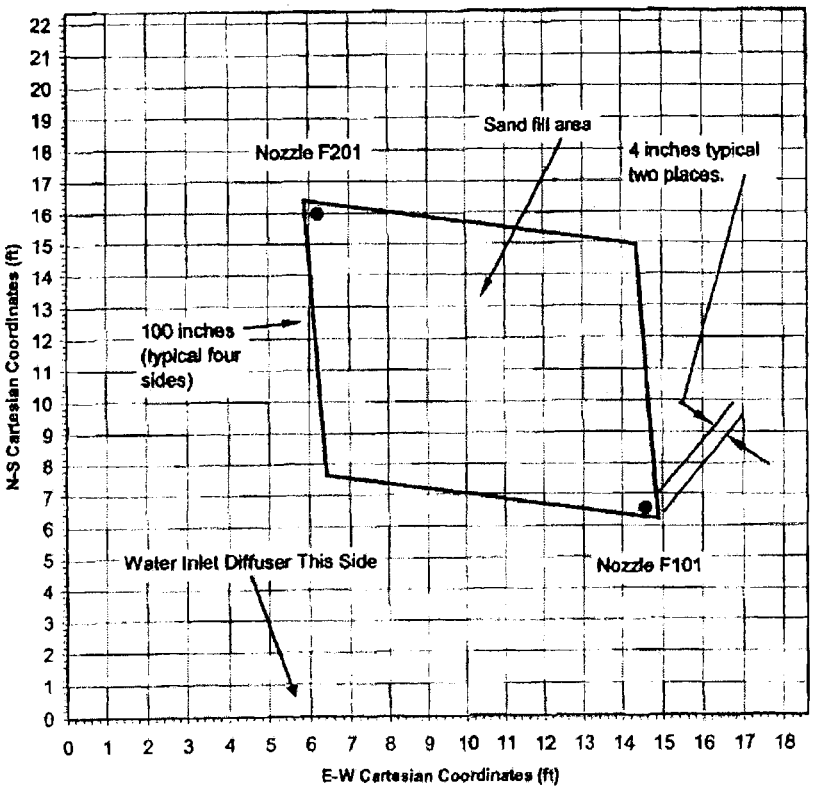
Quantity	Uncertainty
Input Uncertainty	
ρ_L	-
ρ_p	-
d_p	-
μ_L	-
U_{jet}	± 0.20 [m/s] HLP-22,FEP-17
$mass_p$ (per constituent)	± 0.005 [kg] HLP-22,FEP17
$mass_L$ (fill height)	± 0.125 [in] HLP-22 ± 0.200 [in] FEP-17
d_n	-
Data (Systematic) Uncertainty	
ZOI Measurement	± 1.0 [in]
Cloud Height	± 6.0 [in]

A.2.6 WSU Flume

A.2.6.1 General Description

The Washington State University (WSU) flume tests are documented in 24590-WTP-ES-PET- 10-001, Rev. 0 "WSU Radial Flume Test Data Study". Nineteen different experimental runs are described which measure ZOI in a geometrical likeness of HLP-22. The flume is essentially a rectangular box, ~6.81 meters by 5.67, with a fluid level of approximately 1.22 meters, shown in Figure 6-10. Two PJMs are installed nearly diagonally, but not symmetrically, inside the flume with a center-to-center distance of 152 inches or ~37.82 nozzle diameters. This implies a pitch ring circle radius of approximately 18.9 nozzle diameters. Jet nozzles are approximately four inches in diameter and situated six inches off of the flume bottom. Tests are run by three 55-second drive cycles separated by two 180 second dwell periods. If fluid levels should reach the top of the flume, a spillway is located on one side of the flume to control overflow. Drive-average jet velocities range from approximately 6m/s to 12m/s. Sediment layers for each test are either full bottom coverage or sand placed within a diamond-shaped wooden frame for partial bottom coverage. Sediment heights used are 0.35", 1", 3" or 6" but full-coverage tests are only done in the 0.35" cases. Information provided through 24590-WTP-ES-PET- 10-001, Rev. 0 is sufficiently detailed to produce a CFD geometry.

Figure 6-10 Plan View of the WSU Flume



A.2.6.2 Validation Variables Measured

The WSU flume tests were specifically focused on measuring ZOI and nothing else. Once the PJMs were started, visibility into the flume was severely impaired. Therefore, rate-of-ZOI could not be visually recorded.

Table 6-41 Validation Variable Availability (WSU Flume)

Primary Validation Variables	Test Sequence (Name)
Fluid Velocity for Heat Transfer	None
Concentration at the Suction Line Inlet	None
Miscible Fluid Blending	None
Multiple-PJM ZOI	Nineteen cases
Bulk Concentration in the Heel	None
Secondary Validation Variables	
Cloud Height (Hc)	None
Critical Velocity for Suspension (Ucs)	None
Single-Jet ZOI	None
Rate-of-ZOI	None

A.2.6.3 Geometric, Operational, and Physical Test Configuration

Table 6-42 and Table 6-43summarize the physical test characteristics as well as the operational configuration and associated simulant properties for those tests selected based on available validation variable results.

Table 6-42 Design Parameter Summary - Test Configuration (WSU Flume)

Test Name	Vessel Diameter	Relative Cross-Sectional Area	PJM Nozzle Diameter	PJM Nozzle Offset Ratio	PJM Nozzle Velocity	PJM Pulse Tube Duty Cycle	Relative PJM Inner Pitch Ring Radius
	D_T	$D_T^2/N_{PJM}/D_0^2$	D_0	H_0/D_0	U_0	$DC = t_d/(t_d+t_r)$	Δ/D_0
	[in]	[ ]	[in]	[ ]	[m/s]	[ ]	[ ]
F3A-003 (6MS)	138.0	587	4.026	1.50	6.3	23.4%	18.9
F3A-003 (8MS)	138.0	587	4.026	1.50	8.21	23.4%	18.9
F3A-003 (12MS)	138.0	587	4.026	1.50	11.93	23.4%	18.9
F3A-V4	138.0	587	4.026	1.50	6.29	23.4%	18.9
F3A-V5	138.0	587	4.026	1.50	8.36	23.4%	18.9
F3A-V6	138.0	587	4.026	1.50	11.97	23.4%	18.9
F3A-V7	138.0	587	4.026	1.50	6.27	23.4%	18.9
F3A-V8	138.0	587	4.026	1.50	8.28	23.4%	18.9
F3A-V9	138.0	587	4.026	1.50	12.1	23.4%	18.9
F3A-V10	138.0	587	4.026	1.50	6.21	23.4%	18.9
F3A-V11	138.0	587	4.026	1.50	7.98	23.4%	18.9
F3A-V12	138.0	587	4.026	1.50	11.97	23.4%	18.9
F3A-V13	138.0	587	4.026	1.50	6.2	23.4%	18.9
F3A-V14	138.0	587	4.026	1.50	7.32	23.4%	18.9

Test Name	Vessel Diameter	Relative Cross-Sectional Area	PJM Nozzle Diameter	PJM Nozzle Offset Ratio	PJM Nozzle Velocity	PJM Pulse Tube Duty Cycle	Relative PJM Inner Pitch Ring Radius
	D_T	$D_T^2/N_{PJM}/D_0^2$	D_0	H_0/D_0	U_0	$DC = t_d/(t_d+t_r)$	Δ/D_0
	[in]	[ ]	[in]	[ ]	[m/s]	[ ]	[ ]
F3A-V15 Repeat	138.0	587	4.026	1.50	8.31	23.4%	18.9
F3A-V16	138.0	587	4.026	1.50	8.99	23.4%	18.9
F3A-V17	138.0	587	4.026	1.50	10.01	23.4%	18.9
F3A-V18	138.0	587	4.026	1.50	11.45	23.4%	18.9
F3A-V19	138.0	587	4.026	1.50	11.95	23.4%	18.9
Minimum	138.0	587	4.026	1.50	6.2	23.4%	18.9
Maximum	138.0	587	4.026	1.50	12.1	23.4%	18.9

Note(s):
a. The vessel diameter is an approximate value based on the area of the box flume.

Table 6-43 Simulant/Particle Parameter Summary - Test Configuration (WSU Flume)

Test Name	Supernate Viscosity	Supernate Density	Total Solids Loading	Particle Diameter	Particle Density
	μ_l	ρ_l	Wt%	d_p	ρ_p
	[kg/(m·s)]	[kg/m^3]	[ ]	[μm]	[kg/m^3]
F3A-003 (6MS)	0.001	998	1.21	270	2644
F3A-003 (8MS)	0.001	998	1.21	270	2644
F3A-003 (12MS)	0.001	998	1.21	270	2644
F3A-V4	0.001	998	1.21	270	2644
F3A-V5	0.001	998	1.21	270	2644
F3A-V6	0.001	998	3.4	270	2644
F3A-V7	0.001	998	3.4	270	2644
F3A-V8	0.001	998	3.4	270	2644
F3A-V9	0.001	998	9.8	270	2644
F3A-V10	0.001	998	9.8	270	2644
F3A-V11	0.001	998	9.8	270	2644
F3A-V12	0.001	998	18.5	270	2644
F3A-V13	0.001	998	18.5	270	2644
F3A-V14	0.001	998	18.5	270	2644
F3A-V15 Repeat	0.001	998	18.5	270	2644
F3A-V16	0.001	998	18.5	270	2644
F3A-V17	0.001	998	18.5	270	2644
F3A-V18	0.001	998	18.5	270	2644
F3A-V19	0.001	998	18.5	270	2644
Minimum	0.001	998	1.21	270	2644
Maximum	0.001	998	18.5	270	2644

Note(s):
a. The total solids loading is based on an estimated amount of sand added to the diamond pattern in several tests. This is determined from the sand depth and flume area.

A.2.6.4 Dimensionless Parameters - Test Configuration

In addition to the descriptive characteristics for each test given in the previous section, the test conditions may also be summarized using dimensionless parameters. These parameters are described in Section 4.4, and are representative of the physics of interest for the WTP PJM vessels.

For all 19 test cases, the simulant and process fluid are identical: L-60 un-ground silica and water. There is no tolerance specified for the liquid density or viscosity. For the evaluation of the Jet and Particle Reynolds number, the value for water density at 998.6 kg/m^3 and a kinematic viscosity of 1.0×10^{-6} m^2/s is used.

Table 6-44 Dimensionless Parameter Summary (WSU Flume)

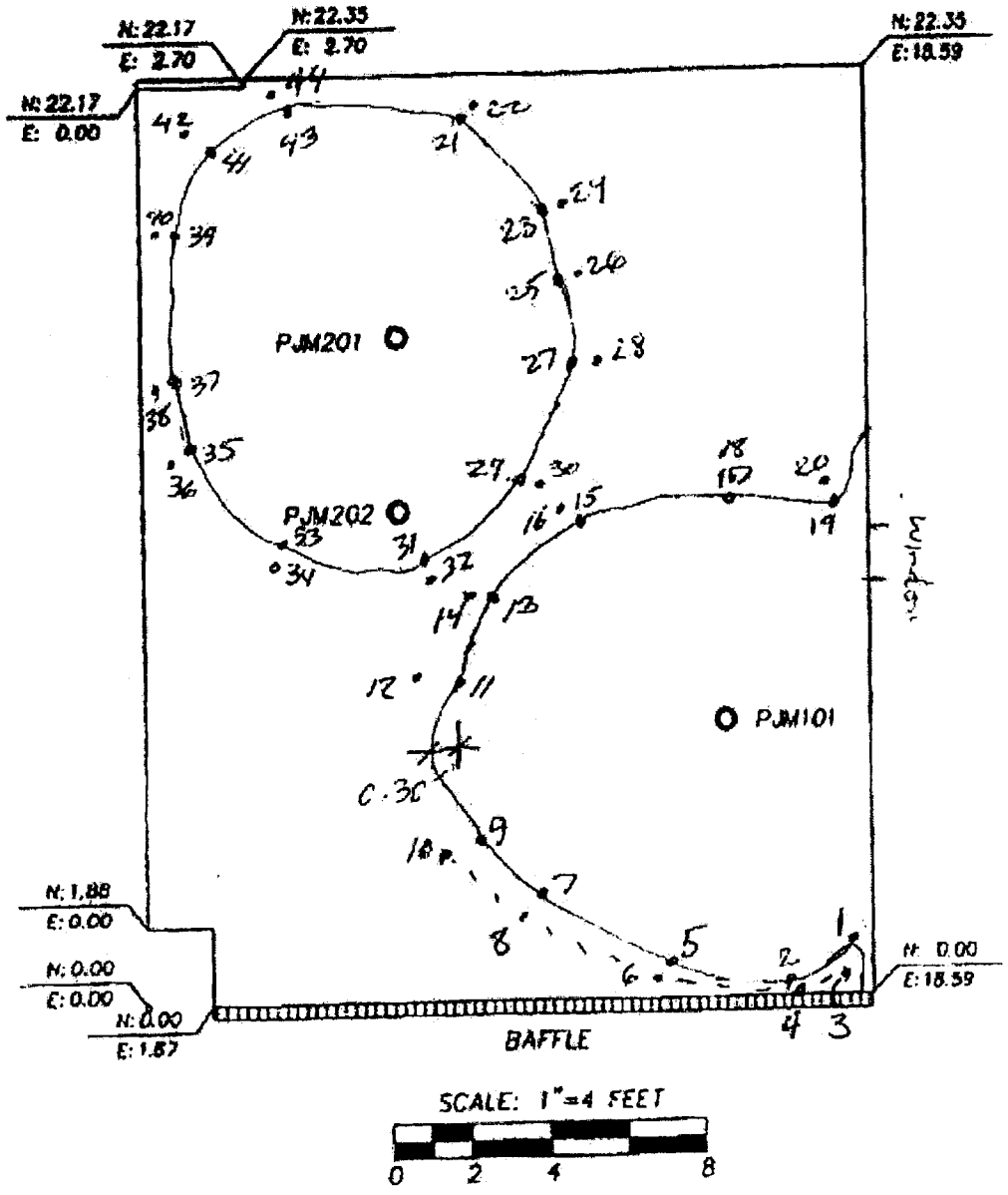
Test Name	Jet Reynolds Number	Particle Reynolds Number	Particle Froude Number	Dimensionless Drive Time
	Re_0	Re_p	Fr_p	T_d
F3A-003 (6MS)	642952	17.81	9086	3388
F3A-003 (8MS)	837879	17.81	15430	4416
F3A-003 (12MS)	1217527	17.81	32580	6416
F3A-V4	641931	17.81	9057	3383
F3A-V5	853187	17.81	15999	4496
F3A-V6	1221609	17.81	32799	6438
F3A-V7	639890	17.81	8999	3372
F3A-V8	845023	17.81	15694	4453
F3A-V9	1234876	17.81	33515	6508
F3A-V10	633767	17.81	8828	3340
F3A-V11	814406	17.81	14577	4292
F3A-V12	1221609	17.81	32799	6438
F3A-V13	632746	17.81	8799	3335
F3A-V14	747049	17.81	12266	3937
F3A-V15 Repeat	848084	17.81	15808	4469
F3A-V16	917482	17.81	18501	4835
F3A-V17	1021579	17.81	22937	5384
F3A-V18	1168540	17.81	30011	6158
F3A-V19	1219568	17.81	32689	6427
Minimum	632746	17.8	8799	3335
Maximum	1234876	17.8	33515	6508

Note(s):

A.2.6.5 Measurement Values per Validation Variable

The WSU Flume tests recorded the ZOI measurements with a visual diagram, rather than a table. An example of the measurement is shown below.

Figure 6-11 Sketch of ZOI for WSU Flume Test



The values reported for this evaluation are limited to those distances between PJMs (for separated ZOI) and the length of the ZOI overlap (for merged ZOI). The measured values are shown in the following table.

Table 6-45 Multiple PJM ZOI for the MCE Flume Test

Test Sequence	Sand Config.	Sand Depth [in.]	Merged ZOI (Y/N)	ZOI (101) [a] [ft]	ZOI (201) [a] [ft]
F3A-003 (6MS)	Full Flume	0.35	N	5.23	5.84
F3A-003 (8MS)	Full Flume	0.35	Y	5.0	5.0
F3A-003 (12MS)	Full Flume	0.35	Y	11.14	11.14
F3A-V4	Diamond Mold	0.35	N	4.96	5.78
F3A-V5	Diamond Mold	0.35	N	5.35	6.43
F3A-V6	Diamond Mold	0.35	Y	11.7	11.7
F3A-V7	Diamond Mold	1	N	4.32	4.94
F3A-V8	Diamond Mold	1	N	5.38	6.13
F3A-V9	Diamond Mold	1	Y	9.98	9.98
F3A-V10	Diamond Mold	3	N	3.94	4.41
F3A-V11	Diamond Mold	3	N	5.01	5.77
F3A-V12	Diamond Mold	3	Y	6.15	6.15
F3A-V13	Diamond Mold	6	N	4.04	4.34
F3A-V14	Diamond Mold	6	N	4.44	4.98
F3A-V15 Repeat	Diamond Mold	6	N	4.71	5.59
F3A-V16	Diamond Mold	6	N	5.25	6.18
F3A-V17	Diamond Mold	6	N	5.74	6.46
F3A-V18	Diamond Mold	6	Y	8.30	8.30
F3A-V19	Diamond Mold	6	Y	10.45	10.45
			Minimum	3.94	4.41
			Maximum	11.7	11.1

Notes:

a. The values for the un-merged ZOI (Merged ZOI = 'N') conditions are the radial measurements at 0°. The merged ZOI value (Merged ZOI = 'Y') is the peninsula width.

b. The Particle Reynolds number is based on the nominal particle size. The particle size distribution is determined through Microtrac analysis.

c. For those locations that use a diamond mold, the weight percent is calculated based on a fill level of 1.22m and assumed to cover the entire bottom of the flume. The full flume tests also assume a fill level of 1.22m.

A.2.6.6 Uncertainty Summary

Table 6-46 Input and Data Uncertainty Values (WSU Flume)

Quantity	Uncertainty
Input Uncertainty	
ρ_L	N/A
ρ_p	N/A
d_p	N/A
μ_L	N/A
U_{jet}	± 0.50 [m/s]
$mass_p$	N/A
$mass_L$	N/A
d_n	± 0.10 [in]
Data (Systematic) Uncertainty	
ZOI Measurement	± 0.50 [in]

Appendix B WTP Vessel Space

Appendix B

WTP Vessel Dimensional and Non-Dimensional Parameter Space

B.1 WTP PJM Vessel Solids Comparison

The WTP PJM vessels are expected to contain the following particle types and quantities. These values, while summarized here, are only a rough estimate of the expected waste and are not for use in plant operations.

Table 6-47 WTP PJM Vessels Solids Composition Summary

Vessel	Total Solids wt% Min	Total Solids wt% Max	Individual Particle Composition		Particle 1	Particle 2	Particle 3	Particle 4	Particle 5	Particle 6	Particle 7
FEP-VSL-00017	0	2	Diameter	um	11	58	210	310	700	10	-
			Density	kg/m^3	2,900	2,900	2,900	2,900	2,900	11,400	-
			wt% of solids		49.9	25	20	4	1	0.1	-
FRP-VSL-00002	0	3.8	Diameter	um	10	22	25	40	100	-	-
			Density	kg/m^3	11,430	7,734	6,328	3,387	1,802	-	-
			wt% of solids		0.5	65	16.5	15	3	-	-
HLP-VSL-00022	2.9	9.4	Diameter	um	11	58	210	310	700	10	-
			Density	kg/m^3	2,900	2,900	2,900	2,900	2,900	11,400	-
			wt% of solids		49.9	25	20	4	1	0.1	-
HLP-VSL-00027A/B	0.1	19.8	Diameter	um	5	10	42	140	162	300	10
			Density	kg/m^3	4,600	6,000	3,700	3,800	2,900	2,900	11,400
			wt% of solids		12	2	76.9	5	3	1	0.001
HLP-VSL-00028	15.3	19.8	Diameter	um	5	10	42	140	162	300	10
			Density	kg/m^3	4,600	6,000	3,700	3,800	2,900	2,900	11,400
			wt% of solids		12	2	76.9	5	3	1	0.001
HOP-VSL-00903/00904	0.02	1	Diameter	um	3.9	7.8	15.7	26	-	-	-
			Density	kg/m^3	2,710	2,710	2,710	2,710	-	-	-
			wt% of solids		49	31	17	3	-	-	-
PWD-VSL-00015/16	0	5	Diameter	um	11	58	210	310	700	-	-
			Density	kg/m^3	2,900	2,900	2,900	2,900	2,900	-	-
			wt% of solids		50	25	20	4	1	-	-
PWD-VSL-00033	0.1	5	Diameter	um	11	58	210	310	700	-	-
			Density	kg/m^3	2,900	2,900	2,900	2,900	2,900	-	-
			wt% of solids		50	25	20	4	1	-	-
PWD-VSL-00043	0	5	Diameter	um	3.9	7.8	15.7	26	-	-	-
			Density	kg/m^3	2,710	2,710	2,710	2,710	-	-	-
			wt% of solids		49	31	17	3	-	-	-

Vessel	Total Solids wt% Min	Total Solids wt% Max	Individual Particle Composition		Particle 1	Particle 2	Particle 3	Particle 4	Particle 5	Particle 6	Particle 7
PWD-VSL-00044	0	2	Diameter	um	11	58	210	310	700	-	-
			Density	kg/m^3	2,900	2,900	2,900	2,900	2,900	-	-
			wt% of solids		50	25	20	4	1	-	-
RLD-VSL-00007	0	5	Diameter	um	3.9	7.8	15.7	26	-	-	-
			Density	kg/m^3	2,710	2,710	2,710	2,710	-	-	-
			wt% of solids		49	31	17	3	-	-	-
RLD-VSL-00008	0	2	Diameter	um	3.9	7.8	15.7	26	-	-	-
			Density	kg/m^3	2,710	2,710	2,710	2,710	-	-	-
			wt% of solids		49	31	17	3	-	-	-
TCP-VSL-00001	0	1	Diameter	um	3.9	7.8	15.7	26	-	-	-
			Density	kg/m^3	2,710	2,710	2,710	2,710	-	-	-
			wt% of solids		49	31	17	3	-	-	-
TLP-VSL-00009	0	1	Diameter	um	3.9	7.8	15.7	26	-	-	-
			Density	kg/m^3	2,710	2,710	2,710	2,710	-	-	-
			wt% of solids		49	31	17	3	-	-	-
UFP-VSL-00001A/B	2.2	6.2	Diameter	um	11	58	210	310	700	10	-
			Density	kg/m^3	2,900	2,900	2,900	2,900	2,900	11,400	-
			wt% of solids		49.9	25	20	4	1	0.1	-
UFP-VSL-00002A/B	20	20	Diameter	um	5	10	42	140	162	300	10
			Density	kg/m^3	4,000	6,000	3,080	3,200	2,900	2,900	11,400
			wt% of solids		12	2	75.9	5	4	1	0.001

Note(s):

a. CNP-VSL-00003 and CNP-VSL-00004 do not contain any solids.
b. Solids composition of CXP-VSL-00004 and RDP-VSL-00002A/B is not available.
c. Total particle solids composition is from Appendix E PIBOD Results by Vessel in the 24590-WTP-RPT-ENG-08-021-10, Rev 1.
d. Individual particle solids composition is the LOAM input data in the appendices of the EFRT Issue M3 PJM Vessel Mixing Assessment, Volumes 3 - 10.

B.2 WTP Vessel Dimensional Parameter Space

The dimensional space defined by the WTP PJM vessels is based on the parameters defined in Section 1.3. A detailed description of the results on a per vessel basis is shown in the table below.

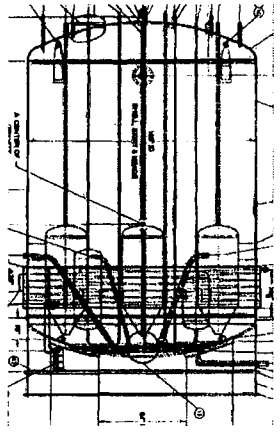
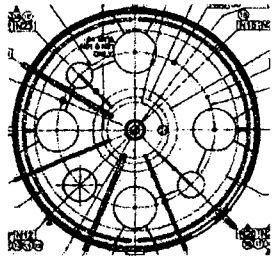
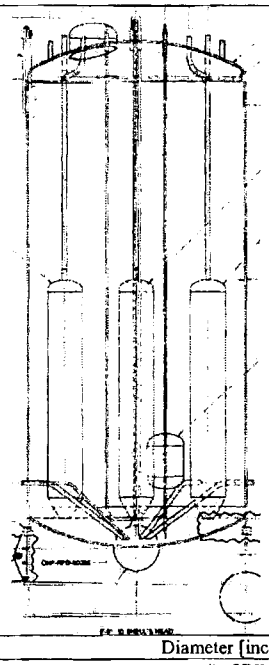
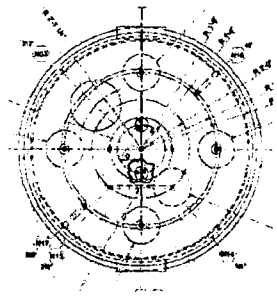
Table 6-48 Design, Simulant, and Particle Details - WTP PJM Vessels

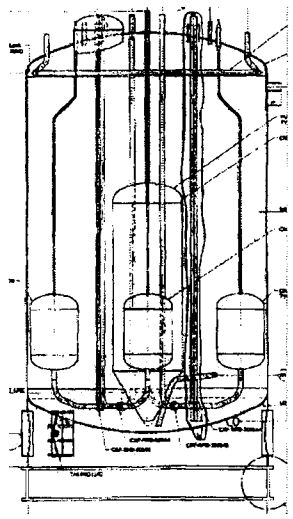
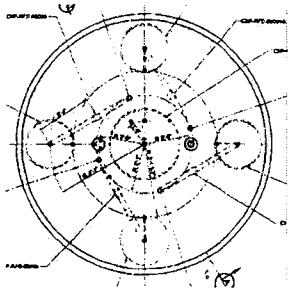
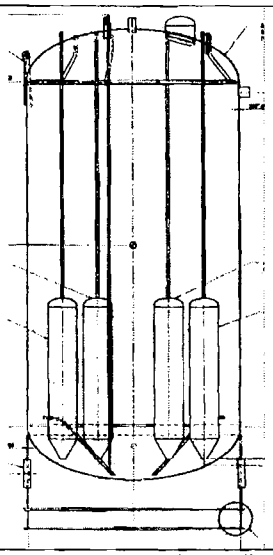
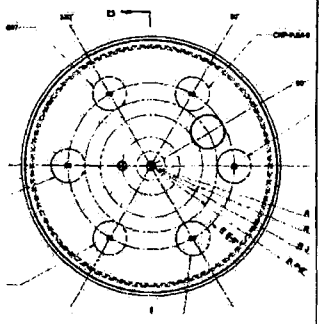
Vessel	Fluid Velocity (heat transfer)	Suction Line Concentration	Miscible Fluid Blending	Multiple PJM ZOI	Heel (conc. by constituent)	Diameter D_T [in]		Nozzle Height H_0 [in]		# of PJMs N_{PJM} [#]		PJM Jet Velocity U_0 [m/s]				Drive Time t_d [s]				Refill Time t_r [s]				Relative Cross Sectional Area/PJM $D_T^2/N_{PJM}/D_0^2$ [ ]		PJM Nozzle Diameter D_0 [in]		PJM Nozzle Offset Ratio H_0/D_0 [ ]		PJM Nozzle Velocity U_0 [m/s]		PJM Pulse Tube Duty Cycle $DC = t_d/(t_d+t_r)$ [ ]	
												Bottom		Top		Bottom		Top		Bottom		Top		Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
CNP-VSL-00003	X					168		6		4		8		12		9		6		n/a		n/a		441	441	4	4	1.5	1.5	8	12	0.17	0.27
CNP-VSL-00004			X			113		6		4		8		12		6		4		n/a		n/a		200	200	4	4	1.5	1.5	8	12	0.17	0.17
CXP-VSL-00004			X			126		6		1		8		12		20		13		n/a		n/a		992	992	4	4	1.5	1.5	8	12	0.17	0.18
FEP-VSL-00017		X		X	X	264		6		8		12		13		22		17		99		137		545	545	4	4	1.5	1.5	12	13.2	0.11	0.18
FRP-VSL-00002		X		X	X	564		6		12		12		14		40		28		157		236		1,657	1,657	4	4	1.5	1.5	12.1	13.9	0.11	0.20
HLP-VSL-00022	X	X		X	X	456		6		18		12		13		35		26		170		231		640	640	4.25	4.25	1.4	1.4	12.1	13.3	0.10	0.17
HLP-VSL-00027A/B	X	X		X	X	300		6		8		11		15		36		20		168		237		703	703	4	4	1.5	1.5	11	15	0.08	0.18
HLP-VSL-00028	X	X	X	X	X	318		6		8		12		15		37		21		177		237		790	790	4	4	1.5	1.5	11.5	15	0.08	0.17
HOP-VSL-00903/00904		X			X	144		6		4		8		11		6		4		17		16		324	324	4	4	1.5	1.5	8	10.5	0.20	0.26
PWD-VSL-00015/16		X	X		X	264		6		8		8		9		24		22		44		44		545	545	4	4	1.5	1.5	8	9	0.33	0.35
PWD-VSL-00033		X			X	288		6		8		8		11		11		7		26		29		648	648	4	4	1.5	1.5	8	11	0.19	0.30
PWD-VSL-00043		X			X	288		6		8		8		11		11		7		26		29		648	648	4	4	1.5	1.5	8	11	0.19	0.30
PWD-VSL-00044		X	X		X	276		6		8		12		15		25		19		168		271		595	595	4	4	1.5	1.5	12	15	0.07	0.13
RDP-VSL-00002A/B		X				144		6		4		8		12		13		9		0		0		324	324	4	4	1.5	1.5	8	12	0.17	0.22
RLD-VSL-00007		X	X		X	156		6		4		8		11		8		7		28		26		380	380	4	4	1.5	1.5	8	10.6	0.21	0.22
RLD-VSL-00008		X	X		X	156		6		4		8		11		9		7		22		28		380	380	4	4	1.5	1.5	8	11	0.20	0.29
TCP-VSL-00001		X			X	318		6		8		8		8		9		76		74		151		156	790	790	4	4	1.5	1.5	8	9	0.32	0.33
TLP-VSL-00009		X	X		X	312		6		8		8		10		23		20		53		56		761	761	4	4	1.5	1.5	8	10	0.26	0.30
UFP-VSL-00001A/B	X	X	X	X	X	240		6		12		12		13		16		12		69		107		266	266	4.25	4.25	1.4	1.4	12	13.2	0.10	0.19
UFP-VSL-00002A/B	X	X	X	X	X	168		6		6		12		16		15		9		77		105		294	294	4	4	1.5	1.5	12	15.7	0.08	0.16
Variables						**Min**	**Max**		**Min**	**Max**		**Min**	**Max**			**Min**	**Max**			**Min**	**Max**			**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**
Fluid Velocity (heat transfer)						168	456	6	4	18		8	16			6	26			69	237			266	790	4	4.25	1.4	1.5	8	15.7	0.08	0.27
Suction Line Concentration						144	564	6	4	18		8	16			4	74			17	271			200	1,657	4	4.25	1.4	1.5	8	15.7	0.07	0.35
Miscible Fluid Blending						113	318	6	4	12		8	16			4	22			22	271			266	992	4	4.25	1.4	1.5	8	15.7	0.07	0.35
Multiple PJM ZOI						168	564	6	4	18		8	16			4	28			69	237			266	1,657	4	4.25	1.4	1.5	8	15.7	0.08	0.20
Heel (conc. by constituent)						144	564	6	4	18		8	16			4	74			17	271			294	1,657	4	4.25	1.5	1.5	8	15.7	0.07	0.35

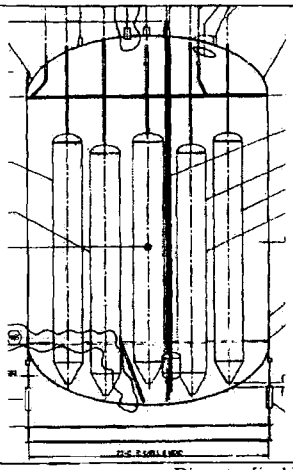
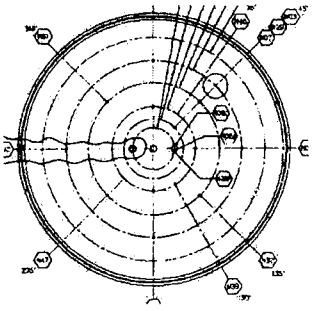
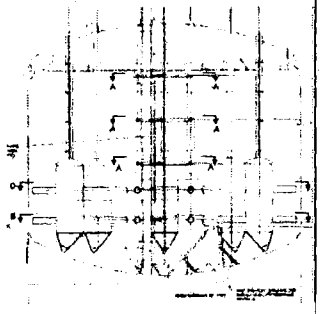
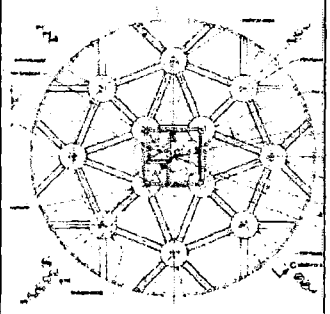
Table 6-49 Design, Simulant, and Particle Details - WTP PJM Vessels, cont.

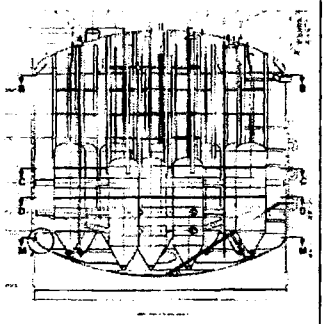
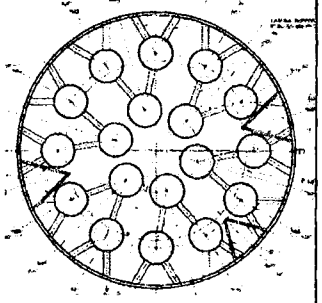
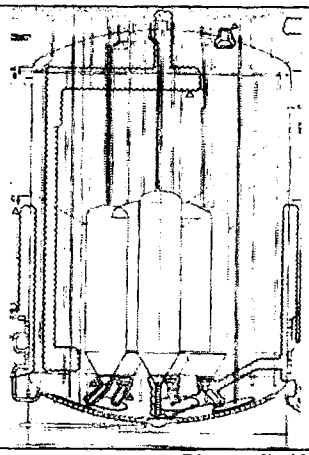
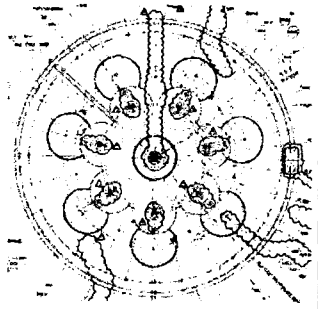
	Relative PJM Inner Pitch Ring Radius		Supernate Viscosity		Supernate Density		Total Solids Loading		Particle Diameter		Particle Density		Jet Reynolds Number		Particle Reynolds Number		Particle Froude Number		Dimensionless Drive Time (Stroubal)	
	D/D_0		ν_l		ρ_l		Wt%		d_p		ρ_p		Re_p		Re_p		Fr_p		T_d	
	[]		[kg/(m·s)]		[kg/m^3]		[]		[μm]		[kg/m^3]		[]		[]		[]		[]	
Vessel	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
CNP-VSL-00003	14.0	14.0	0.0006	0.002	996	1,371	0	0	0	0	0	0	4.05E+05	2.79E+06	n/a	n/a	n/a	n/a	709	709
CNP-VSL-00004	12.3	12.3	0.0006	0.0006	1,012	1,014	0	0	0	0	0	0	1.37E+06	2.06E+06	n/a	n/a	n/a	n/a	472	472
CXP-VSL-00004	15.8	15.8	0.0014	0.0027	1,142	1,232	0	0	0	0	0	0	3.44E+05	1.07E+06	0	0	0.00E+00	0.00E+00	1,575	1,575
FEP-VSL-00017	16.5	16.5	0.0006	0.0012	1,003	1,097	0	2	10	700	2,900	11,400	1.02E+06	2.45E+06	0	325	7.76E+05	2.70E+03	2,598	2,209
FRP-VSL-00002	19.8	19.8	0.0017	0.0046	1,158	1,392	0	3.8	10	100	1,802	11,430	3.10E+05	1.16E+06	0	7	2.68E+06	2.73E+04	4,764	3,831
HLP-VSL-00022	16.5	16.5	0.0014	0.0038	1,129	1,304	2.9	9.4	10	700	2,900	11,400	3.88E+05	1.34E+06	0	150	9.52E+05	3.33E+03	3,923	3,203
HLP-VSL-00027A/B	9.3	9.3	0.0008	0.03	1,004	1,264	0.1	19.8	5	300	2,900	6,000	3.74E+04	2.41E+06	0	50	1.31E+06	2.04E+04	3,898	2,953
HLP-VSL-00028	11.1	11.1	0.0008	0.03	1,004	1,036	15.3	19.8	5	300	2,900	6,000	3.91E+04	1.97E+06	0	46	1.43E+06	1.60E+04	4,188	3,100
HOP-VSL-00903/00904	12.0	12.0	0.0006	0.0006	998	1,001	0.02	1	3.9	26	2,710	2,710	1.35E+06	1.78E+06	0	1	9.75E+05	2.53E+05	472	413
PWD-VSL-00015/16	15.0	15.0	0.0006	0.0009	1,003	1,068	0	5	11	700	2,900	2,900	9.06E+05	1.63E+06	0	135	3.13E+05	6.88E+03	1,890	1,949
PWD-VSL-00033	21.0	21.0	0.0008	0.0009	1,003	1,008	0.1	5	11	700	2,900	2,900	9.06E+05	1.41E+06	0	100	3.13E+05	9.38E+03	866	758
PWD-VSL-00043	21.0	21.0	0.0005	0.0005	1,001	1,006	0	5	3.9	26	2,710	2,710	1.63E+06	2.25E+06	0	1	9.80E+05	2.80E+05	866	758
PWD-VSL-00044	17.3	17.3	0.0006	0.0007	1,001	1,004	0	2	11	700	2,900	2,900	1.74E+06	2.55E+06	0	133	7.04E+05	1.74E+04	2,953	2,805
RDP-VSL-00002A/B	12.0	12.0	0.0008	0.0008	996	998	0	0	0	0	0	0	1.01E+06	1.52E+06	0	0	0.00E+00	0.00E+00	1,024	1,024
RLD-VSL-00007	13.0	13.0	0.0004	0.0004	1,004	1,009	0	5	3.9	26	2,710	2,710	2.04E+06	2.72E+06	0	1	9.85E+05	2.61E+05	630	730
RLD-VSL-00008	13.0	13.0	0.0005	0.0005	996	998	0	2	3.9	26	2,710	2,710	1.62E+06	2.23E+06	0	1	9.73E+05	2.77E+05	709	758
TCP-VSL-00001	18.8	18.8	0.0043	0.0051	1,293	1,373	0	1	3.9	26	2,710	2,710	2.06E+05	2.92E+05	0	0	1.53E+06	3.26E+05	5,984	6,555
TLP-VSL-00009	18.5	18.5	0.0006	0.0006	1,000	1,001	0	1	3.9	26	2,710	2,710	1.35E+06	1.70E+06	0	1	9.78E+05	2.30E+05	1,811	1,969
UFP-VSL-00001A/B	7.1	7.1	0.0014	0.0042	1,214	1,313	2.2	6.2	10	700	2,900	11,400	3.74E+05	1.34E+06	0	151	1.06E+06	3.30E+03	1,779	1,467
UFP-VSL-00002A/B	6.3	6.3	0.0008	0.0079	1,032	1,374	20	20	5	300	2,900	11,400	1.59E+05	2.74E+06	0	76	1.62E+06	1.15E+04	1,772	1,391
Variables	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**
Fluid Velocity (heat transfer)	6.3	16.5	0.0006	0.03	996	1374	0.1	20	5	700	2,900	11,400	3.74E+04	2.79E+06	0	151	3.30E+03	2.04E+04	709	3,203
Suction Line Concentration	6.3	21.0	0.0006	0.03	998	1392	0.02	20	3.9	700	2,710	11,430	3.74E+04	2.74E+06	0	325	3.30E+03	3.26E+05	413	6,555
Miscible Fluid Blending	6.3	18.5	0.0006	0.03	996	1374	0.02	20	3.9	700	2,710	11,400	3.91E+04	2.74E+06	0	151	3.30E+03	2.77E+05	413	3,100
Multiple PJM ZOI	6.3	19.8	0.0004	0.03	996	1392	1	20	3.9	700	2,710	11,430	3.74E+04	2.74E+06	0	325	3.30E+03	2.73E+04	413	3,831
Heel (conc. by constituent)	6.3	21.0	0.0004	0.03	996	1392	1	20	3.9	700	2,710	11,430	3.91E+04	2.74E+06	0	325	1.15E+04	3.26E+05	413	6,555

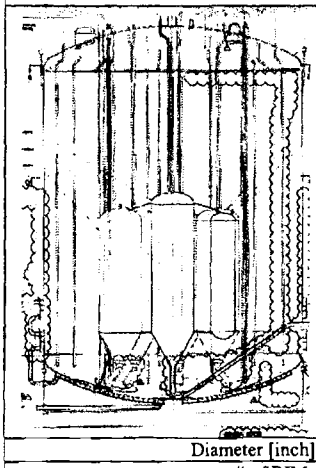
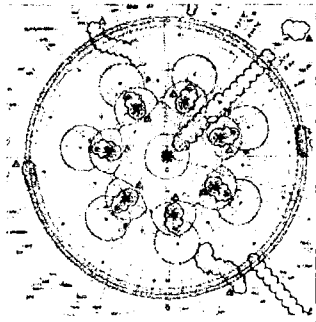
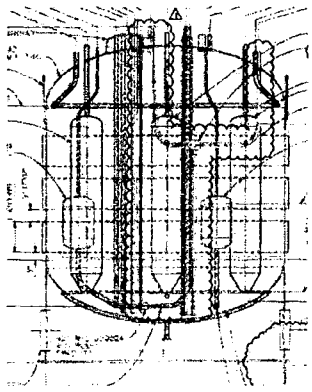
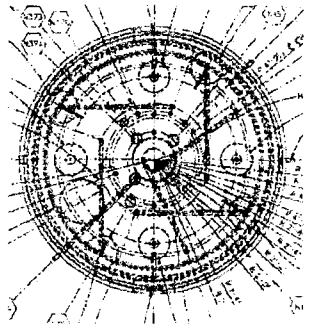
Figure 6-12 WTP Vessels - Plan and Section Views

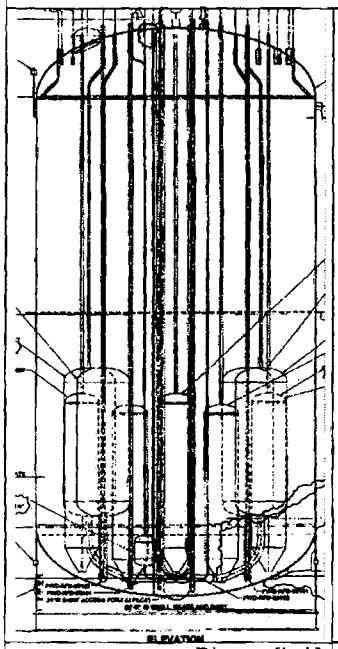
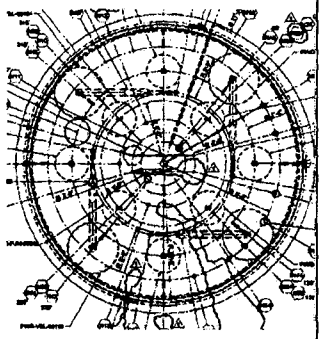
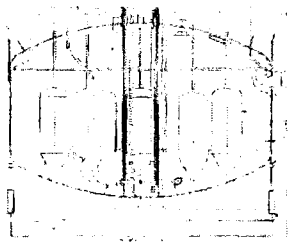
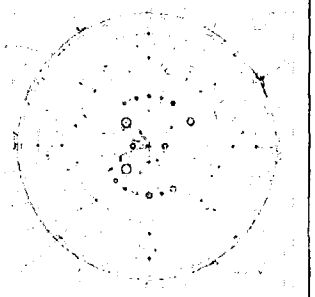
CNP-VSL-00003		CNP-VSL-00004	
			
Diameter [inch]	168	Diameter [inch]	113
# of PJMs	4	# of PJMs	4
24590-QL-POB-MVA0-00002-01-16, Rev F, Drawing - 168 Inch ID, CNP-VSL-00003 Eluate Contingency Storage		24590-PTF-MV-CNP-00002, Rev 0, Equipment Assembly CS Evaporator Recovered Nitric Acid Vessel CNP-VSL-00004	

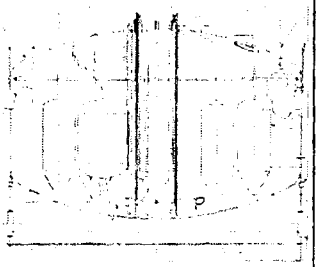
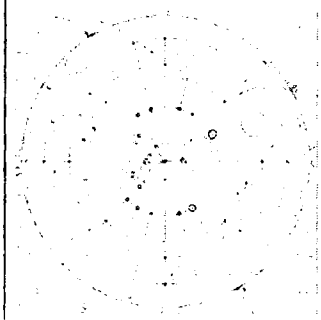
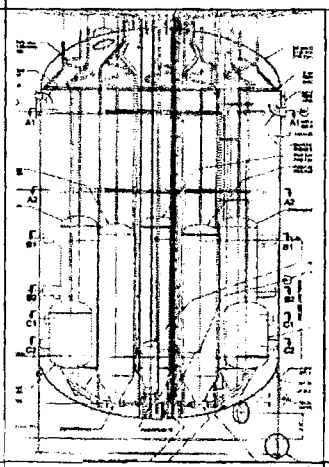
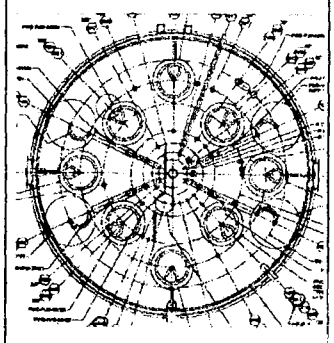
CXP-VSL-00004		CXP-VSL-00026A/B/C	
			
Diameter [inch]	126	Diameter [inch]	180
# of PJMs	1	# of PJMs	6
24590-PTF-MV-CXP-00002, Rev 0, Equipment Assembly Caustic Rinse Collection Vessel CXP-VSL-00004 (Q)		24590-PTF-MV-CXP-P0008, Rev 0, Equipment Assembly Cesium Ion Exchange Treated LAW Collection Vessel CXP-VSL-00026A	

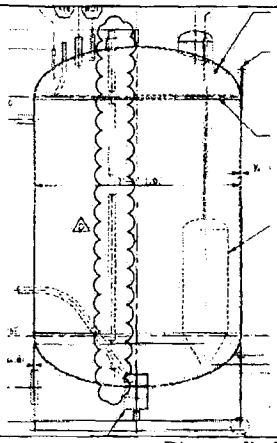
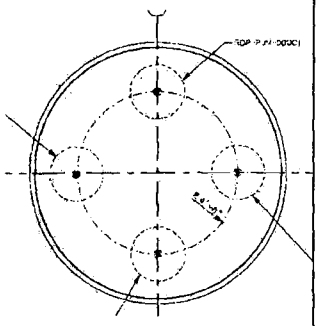
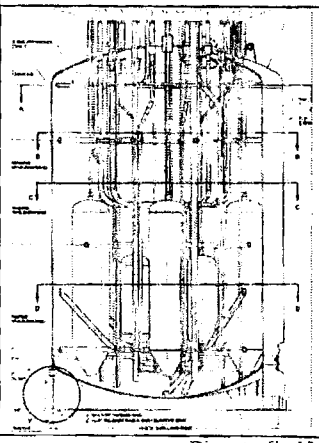
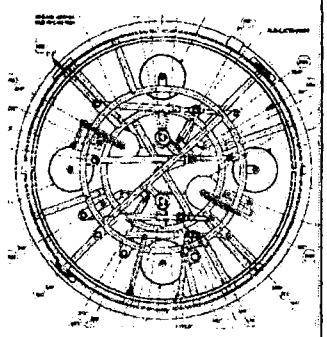
FEP-VSL-00017A/B		FRP-VSL-00002A/B/C/D	
			
Diameter [inch]	264	Diameter [inch]	564
# of PJMs	8	# of PJMs	12
24590-PTF-MV-FEP-00001, Rev 0, Equipment Assembly Waste Feed Evaporator Feed Vessel FEP-VSL-00017A (Q)		24590-PTF-M2-FRP-00005001, Rev B, Internal Modifications Waste Feed Receipt Vessel FRP-VSL-00002A/B/C/D Sheet 1 OF 2	

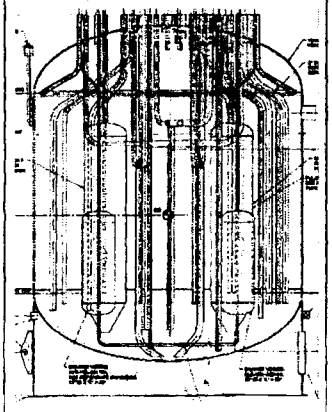
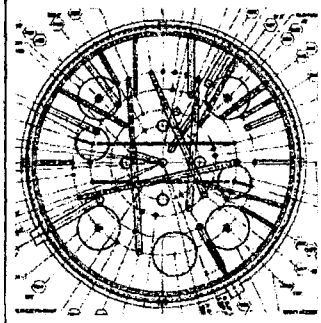
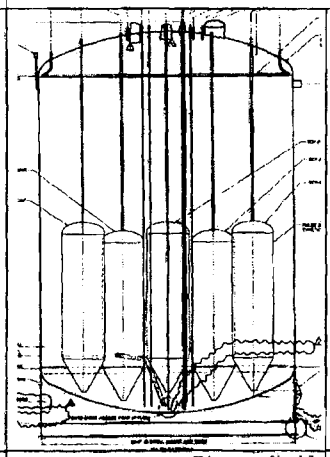
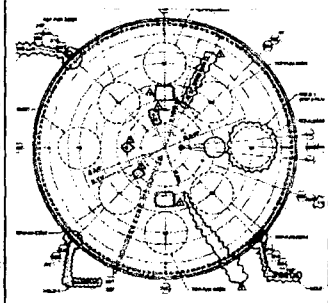
HLP-VSL-00022		HLP-VSL-00027A/B	
			
Diameter [inch]	456	Diameter [inch]	300
# of PJMs	18	# of PJMs	8
24590-PTF-MV-HLP-00003002, Rev_0, HLP-VSL-00022 Mixing Assessment Equipment Changes Plan, Elevation and Section Views Sheet 2 OF 4		24590-PTF-MV-HLP-00009, Rev 1, Equipment Assembly HLW Lag Storage Vessel HLP-VSL-00027A	

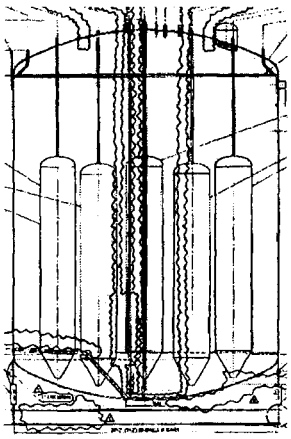
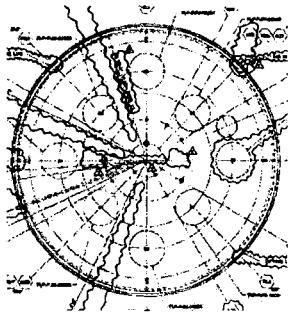
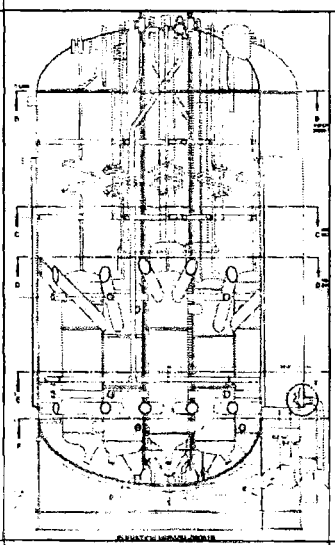
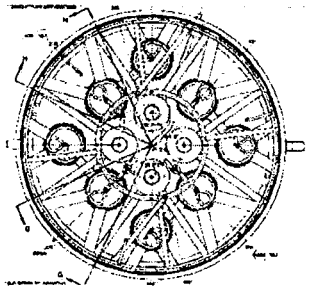
HLP-VSL-00028		HOP-VSL-00903/904	
			
Diameter [inch]	318	Diameter [inch]	144
# of PJMs	8	# of PJMs	4
24590-PTF-MV-HLP-00012, Rev 1, Layout of Internals HLW Feed Blen Vessel HLP-VSL-00028		24590-HLW-MV-HOP-00001, Rev 1, Equipment Assembly SBS Condensate Receiver Vessel HOP-VSL-00903 (Q)	

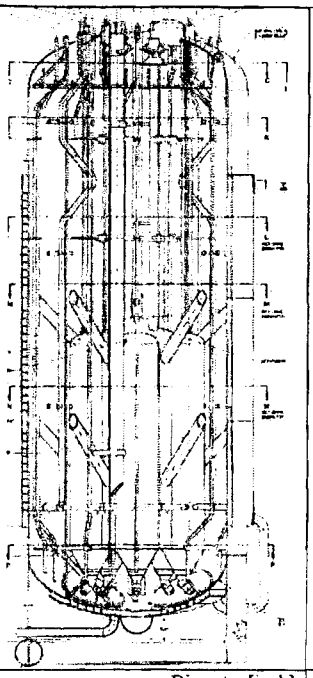
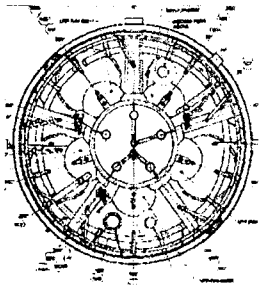
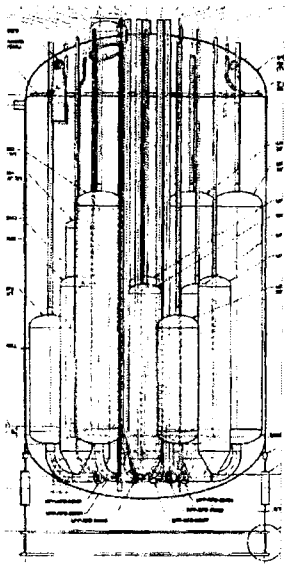
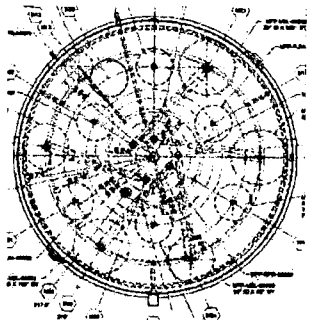
PWD-VSL-00015		PWD-VSL-00033	
			
Diameter [inch]	264	Diameter [inch]	288
# of PJMs	8	# of PJMs	8
24590-PTF-MV-PWD-00007 Rev 1, Equipment Assembly Acidic Alkaline Effluent Vessel PWD-VSL-00015		24590-PTF-MV-PWD-00001002, Rev 0, Equipment Assembly Plan Overflow Vessel PWD-VSL-00033 (Q) Sheet 2 OF 2	

PWD-VSL-00043		PWD-VSL-00044	
			
Diameter [inch]	288	Diameter [inch]	276
# of PJMs	8	# of PJMs	8
24590-PTF-MV-PWD-00003001 Rev 0, Equipment Assembly HLW Effluent Transfer Vessel PWD-VSL-00043 (Q) Sheet 1 OF 2		24590-PTF-MV-PWD-00010001, Rev 0, Equipment Assembly Plant Wash Vessel PWD-VSL-00044 Sheet 1 OF 3	

RDP-VSL-00002A/B/C		RLD-VSL-00007	
			
Diameter [inch]	144	Diameter [inch]	156
# of PJMs	4	# of PJMs	4
24590-PTF-MV-RDP-00001, Rev 0, Equipment Assembly Spent Resin Slurry Vessel RDP-VSL-00002A (Q)		24590-HLW-MV-RLD-00025001, Rev 0, Equipment Assembly Acidic Waste Vessel RLD-VSL-00007	

RLD-VSL-00008		TCP-VSL-00001	
			
Diameter [inch]	156	Diameter [inch]	318
# of PJMs	4	# of PJMs	8
24590-HLW-MV-RLD-00004, Rev 1, Equipment Assembly Plant Wash & Drains Vessel RLD-VSL-00008		24590-PTF-MV-TCP-00002 Rev 0, Equipment Assembly Treated LAW Concentrate Storage Vessel TCP-VSL-00001	

TLP-VSL-00009A		UFP-VSL-00001A	
			
Diameter [inch]	312	Diameter [inch]	240
# of PJMs	8	# of PJMs	12
24590-PTF-MV-TLP-00001, Rev 0, Equipment Assembly LAW SBS Condensate Receipt Vessel TLP-VSL-00009A		24590-PTF-MV-UFP-00027001, Rev 0, UFP-VSL-00001A and UFP-VSL-00001B Mixing Assessment Equipment Changes Plan, Elevation and Section Views 24590-PTF-MV-UFP-00027002, Rev 0, UFP-VSL-00001A and UFP-VSL-00001B Mixing Assessment Equipment Changes Section and Views	

UFP-VSL-00002A/B		UFP-VSL-00062A/B/C	
			
Diameter [inch]	168	Diameter [inch]	180
# of PJMs	6	# of PJMs	6
24590-PTF-MV-UFP-00016, Rev 2, Layout of Internals Ultrafiltration Feed Vessel UFP-VSL-00002A		24590-PTF-MV-UFP-00005 Rev 1, Equipment Assembly Ultrafilter Permeate Vessel UFP-VSL-00062A	

January 29, 2012 - February 04, 2012

January 2012

S	M	T	W	T	F	S
1	**2**	**3**	**4**	**5**	**6**	7
8	**9**	**10**	**11**	**12**	**13**	14
15	**16**	**17**	**18**	**19**	**20**	21
22	**23**	**24**	**25**	**26**	**27**	28
29	**30**	**31**				

February 2012

S	M	T	W	T	F	S
			1	**2**	**3**	4
5	**6**	**7**	**8**	**9**	**10**	11
12	**13**	**14**	**15**	**16**	**17**	18
19	**20**	**21**	**22**	**23**	**24**	**25**
26	**27**	**28**	**29**			

	29 Sun	30 Mon	31 Tue	1 Wed	2 Thu	3 Fri	4 Sat
7 am							
8 00		**Tank Farms Mor**	**TF Plan of the da**	**TF Plan of the da**	**Overview of Ava** CR - 2440STVCN/ Steiling, Jeri L	**Karl to Dr** Kadlec	
9 00		**One-on-One witl**	**meet with Ellen a**				
10 00		**FW: RC** **One-or** CR - 24 Tobias,			**FW: TPD Staff Meeting** CR - 2440STVCN/2200 Tobias, Shannon I		
11 00		**Inspection suppc** CR - 2440STVCN/ Steiling, Jeri L		**SST Retrieval Roundtable Workshop** WSU Campus - Consolidated Information Center Higgins, Kathleen L			
12 pm						**Work Every Friday 8:00am-12:00pm Friday PM off**	
1 00		**One-on-One witl**			**BRIEFING FOR EI** ELLENS OFFICE 28 Piippo, Robert E		
2 00		**One-on-One witl**			**Joe E and Chad H Retirement** ETB 3200 Q Ave Columbia River Room		
3 00		**One-on-One witl**					
4 00			**Pick up Veggies** 2009 Harris Ave Mattlin, Ellen M				
5 00							
6 00							