The Consortium for Risk Evaluation with Stakeholder Participation III

Consortium Universities: ***Vanderbilt University****, Howard University, Oregon State University, Robert Wood Johnson Medical School, Rutgers University, University of Arizona, University of Pittsburgh*

C R E S P

July 1, 2010

Ms. Shirley Olinger, Manager
U.S. Department of Energy
Office of River Protection
P.O. Box 450 MSIN: H6-60
2440 Stevens Center Place
Richland, WA 99354

RE: CRESP Review Team Letter Report 7 – PJM Vessels

Dear Ms. Olinger:

The CRESP Review Team[1] for issues related to the Waste Treatment Plant (WTP) has been asked to provide on-going support to the Department of Energy (DOE) Office of River Protection (ORP) through review of the technical resolution by DOE and its contractors of several of the External Flowsheet Review Team (EFRT) major issues. This letter report addresses the EFRT issue M-3 Pulse Jet Mixer (PJM) performance, stated as

> "Issues were identified related to mixing system designs that will result in insufficient mixing and/or extended mixing times. These issues include a design basis that discounts the effects of large particles and of rapidly settling Newtonian slurries. There is also insufficient testing of the selected designs." *Comprehensive Review of the Hanford Waste Treatment Plant Flowsheet and Throughput*, CCN 132846, Page v. (See CCN 132846 for a complete presentation of the issue.)"

The scope of this review is to evaluate responses to the EFRT M-3 and related pulse jet mixing concerns with respect to closure of M-3, remaining uncertainties and risks, and recommendations for future actions to reduce uncertainties and risks.

The M-3 closure criteria have been defined by Bechtel National, Inc. (BNI) and ORP as (24590-WTP-PL-ENG-06-0013, Rev 003):

1. PJM vessel mixing requirements are currently documented in 24590-WTP-ES-PET-08-002 (*Determination of Mixing Requirements for Pulse-Jet-Mixed Vessels in the Waste Treatment Plant*). The PJM vessel mixing requirements are updated following completion of the PJM technology

[1] Richard V. Calabrese served as an advisor to the CRESP team during his term as an IPA to DOE-FE.

testing and analysis program required to support closure of EFRT Issue M-3, Inadequate PJM Mixing.

2. An M-3 PJM Vessel Mixing Assessment is completed to demonstrate that all PJM mixed vessels are confirmation ready[2] when evaluated against their mixing requirements. This criterion may be closed incrementally by TSG [Technical Steering Group] approval of closure packages for subgroups of PJM mixed vessels. A final determination for all PJM mixed vessels, and its technical basis is documented in an M-3 PJM Vessel Mixing Assessment (24590-WTP-RPT-ENG-08-021) that is concurred in by the WTP Design Authority and Director of the DOE/ORP WTP Engineering Division. Coincident with the completion of the PJM Vessel Mixing Assessment any residual risks are identified and tracked in accordance with WTP risk management procedures.

3. PJM mixed vessel design and/or operational improvement options, where required, to ensuring a confirmation ready design, are identified and evaluated in engineering studies. The engineering studies shall provide specific recommendations for design and/or operational improvement options and be approved by the WTP Design Authority. A trend[3], if required, is approved to implement the recommended design change(s).

4. WTP Contract changes are identified, where required, to support the PJM mixed vessel assessments and the basis for EFRT Issue M-3 closure. Intent to implement these proposed contract changes is formally transmitted by the DOE Contracting Officer, and tracked for implementation in the project action tracking system.

5. The methods (models, correlations, hand calculations, etc) to be used to confirm the PJM mixed vessel designs, and any additional activities (benchmarking reports, testing, etc) to support design confirmation, are defined by the Design Authority. A trend is approved for work that is not currently identified in the WTP Baseline.

To carry out its review, the CRESP review team has been participating in briefings and discussions with DOE, contractor and DNFSB personnel; and reviewing extensive documentation regarding PJM performance. Appendix A provides a list of documents reviewed. The CRESP review team often has been reviewing documents as they were being

---

[2] Quoted from 24590-WTP-RPT-ENG-10-001, Rev 0, p. 5: "Confirmation Ready" is defined as follows: For Criterion 2, if the vessel assessment concludes that no design changes are required for a vessel to meet its specific requirements, the vessel is considered "confirmation ready" and may continue in the design confirmation process. If vessel design changes were recommended (based on the Engineering Studies in Criterion 3) to assure the vessel meets its specific requirements in Criterion 2, the approval of the Engineering Studies and recommended design changes by the WTP Design Authority will satisfy the "Confirmation Ready" definition. The recommended design changes will be implemented via the design change process.

[3] A "trend" is programmatic cost, schedule and technical definition of future work required to complete the indicated additional project scope.

developed and final documents were not available in many cases at the time of the writing of this letter report. Review of the complete set of engineering documents and vessel assessment packages was beyond the scope of this evaluation; rather the team focused on reviewing key considerations common to many if not all of the vessels and specific assessments for vessels HLP-22 and HLP-27 as indicative of the closure packages for vessels processing Newtonian and non-Newtonian slurries, respectively. Review of WTP contract changes, conformance of documents to contract requirements, and trends defining future BNI work was beyond the scope of this CRESP review. Also, several thousand pages of additional documents were provided to the CRESP review team on June 16, 2010 by DNFSB staff and could not be reviewed in detail for consideration because of the late delivery of so much new information. Rather, this CRESP review focused on the technical basis, uncertainties and risks for the design and operation of the PJM mixed vessels.

The review team believes that most significant concerns are in the areas of (i) performance and flexibility in PJM and vessel operations, (ii) up-scaling PJM performance from small-scale tests to full-scale vessels, (iii) criticality assessment, and (iv) design confirmation. These concerns are addressed in the sections of this report that follow. Additional sections address the vessel assessment packages for HLP-22 and HLP-27.

Performance and Flexibility in PJM and Vessel Operations

Uncertainty will remain about PJM performance until extensive experience has been gained through testing of full-scale or near full-scale prototypic PJM vessels and actual operation of the WTP. The current absence of full-scale or near full-scale testing presents a large risk for the WTP program. A second large source of uncertainty that will impact WTP performance are the characteristics of the actual waste feed to WTP. Current estimates of the characteristics of the WTP waste feed reflect contributions to the wastes from many prior defense materials production processes and waste tank management strategies; actual waste characterization has been based on very limited samples, especially regarding particle and rheological properties. Therefore large batch-to-batch variability can be anticipated in WTP waste feed. A feed qualification program is planned to provide characterization of each feed batch prior to processing, but currently is under development. A robust feed qualification program that includes characterization to verify conformance with the full set of waste properties assumptions included in the design and operating basis will be essential to successful WTP operations.

Recommendation 1. ***Near full-scale[4] vessel testing facilities and simulation capabilities should be available for design confirmation and during the full life cycle of WTP operations.***

Performance testing of actual WTP vessels and/or near full-scale testing of representative prototypic vessel configurations should be an essential part of the design confirmation. This scale of testing is necessary to verify the operating characteristics of each vessel, including scale up from small-scale test data, sampling accuracy, and bubbler performance (see additional comments that follow). However, based on the uncertainty regarding the feed

[4] While a full-scale testing and test bed would be the best approach to minimize risks, we recognize that this may not be achievable. We consider "near full-scale" to 1/8 scale or larger on a volumetric basis.

characteristics, operation of PJM mixed vessels should be considered an on-going learning process during the full life cycle of WTP. Use of a non-radioactive test facility, along with adequately validated computational capabilities (e.g., computational fluid dynamics (CFD) and process analysis simulations), will reduce the risk of operational failures and provide an opportunity for optimization that should enhance WTP efficiency and thereby accelerate waste processing. While the most effective use of CFD simulation will be preliminary evaluation of scenarios to define the most promising operating and experimental conditions to be confirmed through testing, the test facilities should also be used to gather data for comparison with simulation results (e.g., flow field velocities, observation capabilities). During WTP operations, the test facility and the simulations can be used in concert to optimize processing of each feed batch. Availability of the recommended facilities would also assist with training operators, testing inspection techniques and evaluating strategies for vessel bottom inspection and recovery from unanticipated upset conditions.

Recommendation 2. ***PJM vessel designs should retain as much flexibility as possible to process the expected range of feed compositions and to mitigate off-design and upset conditions.***

A "defense in depth" strategy has been developed that provides for (i) conservativeness in PJM vessel design, (ii) controls on feed characteristics to WTP, (iii) the ability to inspect vessels for accumulation of solids, and (iv) multiple mitigation methods for off-specification operations or upset conditions. Each of these components of the defense in depth strategy is important and needs to be matured through the design process and validated as part of design confirmation. Flexibility in PJM operation (e.g., increased operating velocities, larger jet pulse pump pairs) should be maintained to the greatest extent practical unless the accuracy of the scaling can be quantified using larger scale testing and accounted for in the design margin.

Recommendation 3. ***The cumulative design margin as a result of design assumptions should be quantitatively assessed against the individual batches of the planned feed vector (e.g., with respect to zone of influence (ZOI), mixing energy/power, actual anticipated settling velocities).***

Conservativeness in PJM vessel design has been claimed by BNI through the revision of waste acceptance criteria to limit the maximum acceptable particle size and solids content, selection of reasonably bounding simulants for small-scale testing of Newtonian vessels, reductions in the maximum allowable solids loadings to individual PJM vessels, provision of PJM sizes and numbers greater than minimum estimated requirement, and ability to vary the firing strategy of individual and collections of PJMs. Conservativeness in design also has been claimed by BNI with respect to the scale-up from small prototypic vessel testing (i.e., 24590-PTF-PET-10-0001, Rev 0, page C-1, 43.2 inch diameter test vessels) to full-scale WTP vessels; however, the basis for scale-up has significant remaining uncertainty and the actual conservativeness of the scale-up basis could not be verified (see discussion of scale-up below).

Recommendation 4. ***A tracking system should be instituted for design assumptions that impose requirements on the feed qualification program[5].***

Vessel designs rely on assumptions of waste feed characteristics, including overall particle size distributions, settling velocities, physical and chemical properties of individual particles (e.g., plutonium particles), and rheology that will vary with processing steps. The engineers responsible for the design may not be available during WTP commissioning and operations. Thus, a tracking system is necessary to insure that important assumptions are not lost and feed characteristics are adequately measured during feed qualification.

Recommendation 5. ***Functional performance specifications need to be developed for inspecting and accessing vessel bottoms.***

The ability to inspect the bottom of vessels for solids accumulation after draw down of vessel contents is an important part of the defense in depth strategy. Access ports have been proposed as part of the inspection capability and as a potential insertion point for mitigation devices (e.g., water lances); however, functional performance specifications have not been developed for vessel access and inspection. CRESP unresolved concerns include (i) whether the access ports will permit an adequate field of view of the interior vessel bottom for inspection and mitigation, (ii) whether there will be indicators on the vessel bottoms that will permit measurement of depths of residual solids, and, (iii) whether the planned ports and vessel conditions will be compatible with devices that can be used for visual observation and/or determining if unexpected accumulation of specific radionuclides is occurring.

Recommendation 6. ***Sensitivity analysis should be carried out for WTP throughput as a function of heel removal needs and operating strategies.***

The current evaluation of the heel removal strategy provides confidence that a flowsheet is workable for removal of residual solids, but only considers the case of retention in the heel of the greater than 99^{th} percentile particle. However, unplanned retention of larger fractions of particles is possible, and more targeted use of the heel removal strategy may become part of a criticality safety control if heel clean out becomes necessary after processing batches with higher contents of fissile material. Thus, the sensitivity of the overall WTP performance to alternative heel removal scenarios should be evaluated.

Recommendation 7. ***Systems level assessments of tank waste processing should consider alternative processing strategies for the most challenging tank wastes as part of the defense in depth strategy.***

Current WTP operational planning and design bases assume that all of the tank wastes will be processed through the WTP Pretreatment facility. However, additional pretreatment capabilities within the tank farms currently are being considered. The ability to manage the most challenging tank wastes (e.g., because of particle size or composition) should be evaluated as part of the overall waste processing strategy, thereby reducing uncertainty and risks associated with wastes being processed using the pretreatment system currently under design and construction.

---

[5]Design assumptions that impact vessel operations are captured in the Phase 2 System Descriptions currently under development and finalized during design confirmation.

Up-scaling PJM and Vessel Performance From Small-scale Tests to Full-scale Vessels

Another justification for full-scale or near full-scale testing is the uncertainty associated with the basis for scaling the performance of PJMs and integrated PJM vessel performance.[6] WTP represents a first of a kind application for PJM mixing in large volume vessels containing rheologically complex slurries with high concentrations of heterogeneous solids. The integrated PJM vessel systems, including PJM mixing, slurry recirculation and pump-out, solid particle size, shape and density distributions, and PJM configurations, involve multiple physical processes that typically scale on different bases, ranging from processes that scale on a linear basis, volumetric basis, power per volume basis, momentum basis, and some important factors that cannot be scaled at all (e.g., particle characteristics and gravity). Scale up from small-scale tests, although often well known for some phenomena, is not precisely understood for such a complex integrated system. The current scale-up of PJM performance is largely built on the model by Poreh, et al (1967) for predicting the ZOI for PJMs and the low order assessment model (LOAM) for pumpout; more extensive discussion of both of these models is provided in Appendices B and C, respectively. Significant uncertainty and lack of clarity regarding conservativeness in the PJM vessel designs result from the basis for using the Poreh and LOAM models along with underlying assumptions (CCN: 217414). Experience from the chemical process industry, which is analogous to WTP processing, indicates that each step of scale up of novel and complex processes should not exceed a factor of 10 on a volumetric basis.[7] This is in contrast to the current planned scale up from small-scale testing to actual WTP vessels which spans a factor of approximately 1000 or more on a volumetric basis. Thus for representative WTP vessels at least one step of full-scale or near full-scale testing is recommended (see Recommendation 1).

Recommendation 8. ***Integrated vessel performance under design basis event (DBE) conditions should be verified using actual vessels or a near full-scale cold test platform. Individual PJM ZOI scale up and restart after a DBE should be verified at or near full scale for a range of simulants that reflect the range of properties expected to be encountered during waste processing.***

Essential functions that should be verified include PJM zone of influence for mobilizing settled solids during a DBE, restart after a DBE, solids suspension for removal during vessel emptying, process sampling strategy and uncertainty, and bubbler performance. Testing of all vessel configurations is not necessary, but a sufficient set of vessel configurations should be evaluated to provide confidence in the scaling from small-scale tests to full-scale performance.

---

[6] Integrated PJM vessel performance includes vessel configuration and multiple vessel components (e.g., complex internal geometry, suction withdrawal, bubblers, etc.).

[7] This is common practice for high value added pharmaceutical products; effectively treated tank wastes certainly should be considered a high value product. Furthermore, (i) the life cycle of WTP probably exceeds that of nearly any industrial facility, and (ii) any industrial facility that might last as long as WTP will be updated and modified on a continuing basis, however significant modifications to WTP will be extremely difficult if not impossible once radioactive waste processing begins.

Criticality Assessment

A fundamental premise for current criticality assessments is the assumption that comingling of neutron absorbers and fissile materials prevents criticality. This enables processing of batches with several kilograms of ^{239}Pu since the abundance of absorber isotopes in close proximity to fissile material prevents criticality. The assumption of comingling is in turn based on (i) the initial solid phase chemistry resulting from co-precipitation of plutonium with neutron absorbers (e.g., iron, aluminum), (ii) processing chemistry does not cause re-speciation of the solid phases resulting in formation of plutonium solids without co-precipitated neutron absorbers, and (iii) differential settling of plutonium particles does not result in the physical segregation of plutonium from credited neutron absorbers that are not an intrinsic part of the plutonium solid phase. Each of these assumptions will require verification during waste batch qualification (see Appendix D for additional discussion). While plutonium in most of the waste tanks resulted from co-precipitation of plutonium with neutron absorbing isotopes, this is not the case for wastes from the Plutonium Finishing Plant that are contained in tanks SY-102 and TX-118. Differential settling of particles with different particle sizes and densities is well known, but not necessarily significant for criticality control; however, criticality is a remaining risk because of the limited waste characterization.[8] The need for sample characterization to verify that adverse plutonium segregation will not occur has been acknowledged (CCN 217642), albeit internally conflicted by distinguishing between "gravity segregation" and "differential settling".[9] For non-Newtonian fluids, settling would need to be assessed under scaled prototypic conditions because of the effects of turbulence on settling velocities. One approach to resolving this issue is to determine how much segregation and/or differential settling must occur before a criticality threshold with an appropriate safety margin would be approached.

A second key assumption is that essentially all plutonium is removed during heel removal and cleanout for each batch. Added assurance that this assumption is valid can be provided by maintaining an inventory of input and output of fissile materials for each batch to confirm that no significant accumulation of plutonium is occurring as multiple batches are processed. Such accounting would be a form of the "material unaccounted for" method. At present the amount of plutonium contained in each batch is to be estimated by the tank farm operations. A similar analysis should be performed on the material from each batch that is sent to vitrification. The difference then becomes a measure of the unaccounted for plutonium and

---

[8] Changes in the particle size distribution expected to occur during leaching would clearly result in stratified sediment during a design basis event. Estimation of the extent of stratification during sedimentation for the range of particle sizes, densities and geometries anticipated to be present in the waste, as well as complex fluid rheologies present during waste processing, is not well understood. For example, representing a high aspect ratio plutonium particle as a sphere with an equivalent volume for determining settling velocity is not a generally accepted approach in the recent literature.

[9] CCN 217642 states: "Further sample analyses are needed to confirm that any potential for gravity segregation of Pu and absorber metals is very limited. Further confirmation of the bounding Pu particles being PuO_2 forms at 10 μm spherical and 11.4 g/cc density is also needed. There is also a need for further sample analysis to confirm that there is no appreciable discrete Pu-rich crystal growth in HTF waste. However, there are no further mixing tests, beyond those already described that are needed to demonstrate that "differential settling does not result in local concentration of fissile material during processing of batches."

should be below a maximum value determined by criticality assessment for possible accumulation locations.

A third key assumption in the current criticality control strategy is that the inventory of plutonium, other fissile materials and neutron absorbers within a vessel is known, based on *samples obtained from that vessel*, with samples being representative of the entire vessel contents (i.e., a well mixed vessel) to within 5 percent accuracy. The solids content in PJM mixed vessels will be inherently stratified, with time varying particle size distributions at any given location, because of the cyclic nature of PJM operation. Knowledge of the contents in a vessel will be highly uncertain if based on sampling from the contents within that vessel; the currently specified sample representativeness to 5 percent accuracy is not achievable. The accuracy and reproducibility of this approach cannot be *a priori* estimated with reasonable confidence, will be dependent on the size and density of the particles being sampled, and will most likely be on the order of 20 percent or greater for larger/denser particles that may stratify. Small-scale testing completed to date to evaluate the "no solids accumulation" design requirement has indicated that a greater concentration of fast settling solids than the average concentration of the entire vessel contents is removed during the initial stages of slurry transfer from the vessel. Thus, the characteristics of solids transferred from a vessel to the next vessel will vary over time as batch transfers occur. As a result of these considerations, a more accurate way to obtain an inventory of the contents within a vessel at any given time may be based on time weighted sampling (and characterization) of the slurries from the transfer line into the vessel and out of the vessel of interest and use of a mass balance approach. However, even with this approach, accuracy to within 5% is highly unlikely.

***Recommendation 9.* Assessments of potential particle segregation during sedimentation should consider estimates based on considerations beyond the equivalent volume sphere.**

Non-spherical particles sediment at different rates depending upon their orientation,[10] Reynolds number and non-Newtonian fluid effects.[11] A more comprehensive way than the equivalent volume sphere[12, 13] to describe particles of complex shapes is through the "sphericity" approach in which the ratio of the surface area of a sphere that has the same volume as the real particle to the actual surface area of the particle is used.[14, 15] It provides the means to consider the amount of drag a real particle might experience relative to that for a sphere. This can be used with the Reynolds number to predict the particle drag coefficient.[14] The non-uniformity of particle sizes gives rise to larger particles experiencing

[10] K. Cho, Y. I. Cho and N. A. Park, Hydrodynamics of a vertically falling thin cylinder in non-Newtonian fluids, J. Non-Newtonian Fluid Mechanics, 45, 105-145 (1992).

[11] Liu, Y. J. and D. D. Joseph, "Sedimentation of particles in polymer solutions", J. Fluid Mechanics, 255, 565-595 (1993).

[12] W. E. Dietrich, Settling Velocity of Natural Particles, Water Resources Research, 18, 1615-1626 (1982).

[13] P. D. Komar and C. E. Reimers, Grain Shape Effects on Settling Rates, Journal of Geology, 86, 193-209 (1978).

[14] R. P. Chhabra, Bubbles, Drops and Particles in Non-Newtonian Fluids, 2nd Edition, Taylor and Francis (2007)

[15] C. Chang and R. L. Powell, Hydrodynamic Transport Properties of Concentrated Suspensions, *AIChE J.*, 48, 2475-2479 (2002).

an effective non-Newtonian medium that is described by a yield stress (see Appendix F). Other non-Newtonian properties, such as normal stress[16] and shear thinning viscosity [11] have not been modeled for WTP wastes but are important for particle dynamics. It is also important to consider effects of particle concentration. Most experimental studies of non-spherical particle settling focus on individual particles, but at higher concentrations, suspensions of non-spherical experience hindered settling.[17] For a Bingham fluid it may be possible for multiple particles to overcome a yield stress whereas individual or isolated particles cannot.[18]

<u>Recommendation 10.</u>* *The Preliminary Criticality Safety Evaluation Report (CSER, WTP-CSER-ENS-08-001, Rev 0b) ***needs to be revised and include workable and validated methods for criticality controls.***

The revised CSER should include (i) specification of the chemistry that must be maintained throughout each process step along with the method(s) to be used to verify the chemistry to assure that adequate co-mingling of fissile isotopes with neutron absorbers is maintained, (ii) validation of waste sampling and characterization strategies to insure that specified accuracies are achievable, and (iii) evaluation of all potential scenarios of fissile material accumulation and segregation of fissile isotopes from neutron absorbers (e.g., differential settling) including uncertainty assessment. Specific procedures for processing high plutonium batches (such as from SY-102 and TX-118), such as using alternative pretreatment in the tank farms or targeted use of heel dilution or chemical cleanout procedures after processing a specified amount of fissile material (rather than only based on retention of the greater than 99th percentile settling particle), may be ways to provide additional criticality controls.

<u>Recommendation 11.</u>* *Sampling strategies for PJM vessels need to be demonstrated with characterization of sampling uncertainty.

Sampling accuracy for fast settling solids should be demonstrated to meet the specification required under the revised CSER. The sampling strategy for process control, other than criticality controls (e.g., for leaching), may be different than for fast settling solids because the constituents of interest may be more readily mixed. Thus, sampling strategies need to be linked to required use and accuracy of the resulting characterization and verified accordingly.

<u>Design Confirmation</u>

Design confirmation for vessels containing Newtonian slurries is planned to rely primarily on computation fluid dynamics (CFD) simulations. CFD verification and validation (V&V) is required prior to use of CFD for design confirmation. The current plan for CFD V&V (24590-WTP-PL-ENG-03-010, Rev 7) has been developed for a wide range of CFD

---

[16] Leal, L. G., The slow motion of slender rod-like particles in a second-order fluid, J. Fluid Mech. 69, pp 305-337 (1975).

[17] M. A. Turney, M. K. Cheung, M. J. McCarthy and R. L. Powell. Hindered Settling of Rod-Like Particles Measured with Magnetic Resonance Imaging. *AIChE J*. 41, 251-257(1995).

[18] J. P. Singh and M. M. Denn, Interacting Two-Dimensional Bubbles and Droplets in a Yield Stress Fluid, *Physics of Fluids*, 20, 040901 1-11 (2008). Note that this phenomenon should apply to cases of both sedimentation and bubble rise in Bingham fluids.

applications for WTP, only one of which is modeling the performance of PJM vessels. CFD V&V will be based on comparison of simulations with published data for test cases available from the peer-reviewed literature (called "default test cases"). CFD V&V will also include comparison of simulations with experimental results from new testing using selected small- and intermediate-scale PJM configurations (called "assessment cases"); a more detailed discussion of CFD V&V is provided in Appendix E. The specific aspects of WTP PJM vessel performance that will be described by performance criteria and the quantitative metrics for design confirmation have not been documented. Although initial qualitative comparisons of simulation results to experimental observations have been promising, to date CFD has not been demonstrated to be able to quantitatively scale PJM vessel performance nor reasonably predict the solids distributions observed during small-scale testing with different prototypic PJM vessel configurations. Additional large-scale experiments are also being planned as part of design confirmation but planning for such large-scale testing has only just begun and test plans for design confirmation were not available for review.

Currently, CFD simulations are not planned for PJM vessels containing non-Newtonian slurries because of the challenges associated with applying CFD to solids-containing non-Newtonian fluids. However, use of CFD for non-Newtonian cases is discussed in the V&V plan and also has been suggested in the recent Savannah River review of PJM vessels containing non-Newtonian slurries.

***<u>Recommendation 12.</u>* Design confirmation for PJM vessels should not be based only on CFD simulations but also should include full-scale or near full-scale experimental demonstration of critical performance aspects of PJM vessels containing Newtonian and non-Newtonian slurries.**

Critical performance aspects include (i) PJM zone of influence under expected normal operating conditions, (ii) absence of significant solids accumulation in the vessels, (iii) sampling capability able to obtain samples that are representative of the vessel contents or slurries being transferred to the specified accuracy, (iv) bubbler performance within acceptable tolerances, and (v) mobilization of the maximum anticipated depth of settled solids during a design basis event.

***<u>Recommendation 13.</u>* A separate, focused CFD V&V plan should be developed for PJM vessel performance and should include validation using the results of near full-scale or full-scale experiments.**

The current V&V plan is too broad and complex as a result of covering a wide range of CFD applications for WTP. Consequently, it is likely that completion of the current CFD V&V plan will take much longer than a focused effort on PJM vessel needs and may therefore delay design confirmation. The specific aspects of PJM vessel performance that will be simulated as part of design confirmation, along with quantitative metrics and required accuracy of CFD simulations, need to be specified. The resulting specifications for design confirmation using CFD should form the foundation of the V&V assessment cases, and include demonstration of the ability of CFD to scale up individual phenomena (i.e., single PJM performance) and integrated vessel performance. Assessment cases for CFD V&V to be applied to PJM vessels should also include comparisons with experimental data from small-scale prototypic systems obtained to date as well as experimental data from testing representative near-full scale prototypic systems. The V&V plan, including design of the supporting experiments, and results of the V&V process should be independently reviewed by DOE because of the importance placed on CFD in the design confirmation process.

HLP-22 Vessel Assessment Package (Newtonian Slurries)

The mixing performance criteria currently designated for HLP-22 (24590-WTP-RPT-ENG-10-001) are:

Criterion 2. Blend - 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.

Criterion 5. Sample - Mix Slurry - Criticality - The PJM mixing system shall mix the slurry to ensure that a representative sample can be obtained.

Criterion 6. Sample - Mix Slurry - Hydrogen Generation Rate (HGR) Estimation - The PJM mixing system shall mix the slurry to ensure that a representative sample can be obtained.

Criterion 7. Sample - Mix Slurry - Process Control - The PJM mixing system shall mix the slurry to ensure the process control requirements are met and a representative sample can be obtained.

Criterion 8. Store - Release Gas - The PJM mixing system shall disturb the settled solids to release gas.

Criterion 10. Store - Limit Solids Accumulation - The PJM vessels systems shall be designed, considering the mixing and transfer systems, such that solids will not accumulate from batch to batch and limit the bulk density and solids weight percent to less than or equal to the limits established for the calculation *Unit Dose Factors for Use in Updated MAR Accident Analysis* (24590-WTP-Z0C-W14T-00020). This requirement will also ensure that no accumulation of particulate occurs and will protect the criticality safety requirements associated with potential accumulation of PuO_2 particles. This requirement also supports processing of material in the WTP.

Criterion 2.

Scaling of mixing for the purposes of blending liquids is based on power per volume ("0.33" scaling factor) which is the common basis for scaling industrial mixing.

Criterion 5, 6 and 7.
All three of these criteria relate to the ability to obtain representative samples for criticality control, process control and process safety. The greatest risk in achieving adequately representative samples is for criticality control because of the potential presence of fissile isotopes in fast settling particles. This risk is discussed above in the section on Criticality Assessment.

Criteria 8 and 10.
The most significant risk related to hydrogen release under a DBE and preventing accumulation of solids is the uncertainty associated with the basis of scale up from small-scale testing to full-scale WTP vessels. Improvements in system performance have been demonstrated in small-scale testing through increased numbers and improved configuration of PJMs within the vessel. In addition, a backup plan is being developed based on a heel clean out strategy and inclusion of a vessel bottom inspection capability. CRESP strongly recommends either full-scale or near full-scale testing of prototypic WTP vessel configurations to reduce this uncertainty (see multiple recommendations above).

HLP-27 Vessel Assessment Package (Non-Newtonian Slurries)[19]

The primary mixing performance criteria currently designated for HLP 27 (24590-WTP-RPT-ENG-10-001) are:

> Criterion 2. Transfer Slurry - Prevent Plugging - The PJM mixing system and pump suction shall be capable of maintaining the fluid properties to meet the pump suction requirements.
>
> Criterion 8. Store - Release Gas - The PJM mixing system shall disturb the settled solids to release gas.
>
> Criterion 9. Store - De minimis Solid Volume - Note: Applies to the initial assessment for Groups 1A and 1B only. For Group 2 and 3 vessels, this function/requirement is replaced with 10, Limit Solids Accumulation.

Criterion 2
The issue of fully suspending solids and ensuring that there are no regions of accumulation are discussed in Appendix F. The principal issue beyond that is particle segregation either during normal operation or during a DBE (see discussion on criticality controls above). Consideration has been given to the effect of the size of the fraction of larger particles and its effect on clearing in the test vessels. However, particle sizes, densities and shapes do not scale. As a result, the findings to date may not be representative of the full scale system. This provides additional need for near full size testing. In this case, simulants might be considered that would also reflect more comprehensively the heterogeneity of the slurries to be encountered during WTP operation.

[19] The revised version of 24590-WTP-RPT-ENG-10-001 (provided to DOE on June 24, 2010), was not available early enough to be considered by the CRESP review team as part of the review for this letter report.

Extreme caution needs to be exercised if CFD is used to assess how well this criterion is met for vessels containing non-Newtonian slurries such as HLP-27. The current state of the art for CFD limits the ability to model a sufficiently complex mixture of particles that would provide quantitative insights into the functioning of this vessel.

Criterion 8

The issue of bubble release has been addressed in some detail in 24590-WTP-RPT-PET-10-007. This shows that there is a good understanding of the mechanisms associated with bubble release. There are two concerns. On page 6 of that document it is stated that it is assumed that no solids accumulation occurs over time during normal operations. This point has been raised in other parts of this letter. Additional testing is needed to ensure that there is no accumulation of solids during normal operations (see Recommendation 12).

It is also assumed that during a DBE, the solids settle "instantaneously". This is certainly not the case but rather a conservative assumption. However, the solids will settle over time, depending upon the yield stress that is established once continuous mixing stops and the particles will settle preferentially according to their size, shape and density distributions.

Following on page 6 of 24590-WTP-RPT-PET-10-007, it is assumed that after settling has occurred during a DBE, "The top layer is a gas-saturated Newtonian layer, where gases generated in the liquid layer are assumed to be released into the headspace and swept away by the headspace purge/exhaust. 'Any gas found in the liquid waste is considered transient and is not considered as trapped or retained gas'". This neglects the possibility that gas can be trapped on small particles (micron to sub micron) that remain in suspension during a DBE. It is possible that bubbles can attach to particle surfaces and even create enough buoyancy to maintain the particles in suspension.

Criterion 9 (10)

There is considerable concern that the basis for scale-up has not been validated with near full-scale testing using a vessel configuration prototypic of WTP vessels, nor over the operating range of any single vessel (See Appendices C and F).

Furthermore, there is considerable concern about the sampling procedure used to monitor the process and the ability to use these samples for process control (HLP-27A).

Summary and Overall Evaluation

Overall, the Review team recognizes the substantial progress that DOE and BNI have made in understanding PJM vessel performance since the CRESP Letter Report 6 (December 2009). Furthermore, WTP represents a first of a kind application of PJM vessels because of the vessel size and waste characteristics. There are several important PJM vessel design uncertainties and definitions of operating requirements that remain to be resolved, including revision of the criticality controls, validation of scale-up relationships for PJM zone of influence, integrated validation of vessel performance, recovery from a DBE, and viable sampling strategies, that result in PJM vessel performance and programmatic risks. The greatest risk is that the actual ZOI during WTP operations is smaller than predicted by the current design basis and therefore solids accumulation may require more frequent cleanout than predicted. Experimental programs that validate scaling relationships for the ZOI and the integrated vessel performance at full-scale or near full-scale systems are needed. While none of these uncertainties fundamentally indicate that WTP will not function provided that there is enough flexibility in PJM operation, resolution of these issues may result in the pretreatment process operating at lower waste throughput rates than currently projected.

We hope you find these comments and recommendations helpful in your evaluation and we are available to discuss any questions you may have regarding this review.

Sincerely,

David S. Kosson, Ph.D., Review Team Chairman

Richard V. Calabrese, Ph.D.

Willard C. Gekler

Robert L. Powell, Ph.D.

Stanley I. Sandler, Ph.D.

Attachments: Appendices A-F

Cc: R. Gilbert (ORP), L. Holton (ORP), G. Brunson (ORP), D. Knutson (ORP)
E. Collazo (EM-30), M. Gilbertson (EM-40), S. Krahn (EM-60), K. Pica, S. Schneider (EM-31), D. Chung (EM-2)
C. Powers (CRESP)

Appendix A – Documents Reviewed

<u>WTP Reports</u>

24590-PTF-PL-PET-10-0001, Rev 0., *Plan for M3 Test Platform Testing*, March 3, 2010.

24590-WTP-CSER-ENS-08-0001, Rev 0b, *Preliminary Criticality Safety Evaluation Report for the WTP*, August 29, 2009.

24590-WTP-ES-PET-08-002, *Determination of Mixing Requirement for Pulse-Jet-Mixed Vessels in the Waste Treatment Plant*, October 2008.

24590-WTP-ES-PET-09-001, Rev 0, *M3 Platform Test Data Study*, March 4, 2010.

24590-WTP-GPP-MGT-007, *Comment Resolution Form*, June 4, 2010.

24590-WTP-MRR-PET-10-001, Rev 0, *WTP Mission Assessment of the Design and Operating Changes Expected to Resolve PJM Mixing in PT Vessels*, May 25, 2010.

24590-WTP-PL-ENG-03-010, Rev 7, *Fluent Computational Fluid Dynamics V&V Plan*, February 18, 2010.

24590-WTP-PL-ENG-06-0013, Rev 003, *Issue Response Plan for Implementation of External Flowsheet Review Team (EFRT) Recommendations – M3, Inadequate Mixing System Design*, February 13, 2009.

24590-WTP-RPT-ENG-08-021-03, Rev B., *EFRT Issue M3 PJM Vessel Mixing Assessment, Volume 3 – HLP-VSL-00027 A/B, HLP-VSL-00028, UFP-VSL-00002 A/B*, January 22, 2009.

2490-WTP-RPT-ENG-08-021-08, Rev 0, *EFRT Issue M3 PJM Vessel Mixing Assessment, Volume 8 – HLP-22*, June 17, 2010.

24590-WTP-RPT-ENG-10-001, Rev 0, *Integrated Pulse Jet Mixed Vessel Design and Control Strategy*, February 20, 2010.

24590-WTP-RPT-ENS-10-002, Rev 0, *M3 Criticality Safety Test Requirements,* March 3, 2010.

24590-WTP-RPT-ENS-10-002, Rev 1., *M3 Criticality Safety Test Requirements*, May 23, 2010.

24590-WTP-RPT-PET-08-009, Rev 1, CCN 210459, *Functional/Design Requirement for the M3 Test Platform*, July 21, 2009.

24590-WTP-RPT-PET-10-008, Rev 1, *Revised Simulant Design and Basis for FEP-17, FRP-02, HLP-22, and UFP-01 Vessels for EFRT M3 Mixing Studies*, March 4, 2010.

24590-WTP-RPT-PET-10-008, Rev 1, CCN 211535, *Revised Simulant Design and Basis for FEP-17, FRP-02, HLP-22, and UFP-01 Vessels for EFRT M3 Mixing Studies*, May 2010.

24590-WTP-RPT-PET-10-013, Rev A, *Pretreatment Vessel Heel Dilution/Cleanout Study*, January 22, 2009.

24590-WTP-RPT-PET-10-014, Rev 0., *Slurry Property Ranges in Non-Newtonian Pretreatment Vessels at WTP*, June 3, 2010.

HNF-8862 Rev 0, EDT 628492, *Particle Property Analyses of High-Level Waste Tank Sludges*, 2002.

PNNL-17386, WTP-RPT-157, Rev 0., *Characterization and Leach Testing for REDOX Sludge and S-Saltcake Actual Waste Sample Composites*, 2008.

PNNL-18007, WTP-RPT-171, Rev. 0. *Laboratory Demonstration of the Pretreatment Process with Caustic and Oxidative Leaching Using Actual Hanford Tank Waste*, 2009.

PNNL-18327, *Estimate of the Distribution of Solids within Mixed Hanford Double-Shell Tank AZ-101: Implications for AY-102*, April, 2009.

PNWD-3206, Rev 1, WTP-RPT-043, Rev 1., *Filtration, Washing, and Caustic Leaching of Hanford Tank AZ-101 Sludge*, 2003.

SRNL-RP-2010-00898, *Independent Technical Review of the Assessment of Pulse-Jet Mixing Performance in Vessels Containing Non-Newtonian Sludges at the Waste Treatment and Immobilization Plant*, June 15, 2010, draft.

WTP/RPP-MOA-PNNL-00494, CCN 211535, *Recipes for Simulant Strengths*, March 12, 2010.

WTP-RPT-208, Rev. A., *Reconciling Differences in Phase 1 and Phase 2 Test Observations for Waste Treatment Plant Pulse et Mixer Tests with Non-Cohesive Solids*, January 2010.

<u>CCNs</u>

CCN 18279, T*echnology Steering Group-Issue Closure Record – Partial Closure EFRT Issue M-3 (Closure Package Volume 4, Low Solids Containing Vessels), Inadequate Mixing System Design*, March 2010.

CCN 18631, *M3 Test Platform – Prototypic Comparison Supersede CCN 196477*, May 4, 2009.

CCN 196094, *Closure of EFRT M3 Issue Response Plan Criteria 5*, April 30, 2009.

CCN 205978, *M3 Mixing Vessel Assessment Method – HALL ZOI*, April 11, 2010.

CCN 210453, *M3 – Gas Release Report*, February 18, 2010.

CCN 210455, *Scaling of PJM Vessels Containing Settling Solids in Newtonian Slurries*, March 4, 2010.

CCN 210459, *M3 Test Platform Design*, January 14, 2010.

CCN 211535, S*imulant Qualification Data Package for Post Design Basis Event (DBE) Testing*, March 12, 2010.

CCN 211892, *M3 Mixing Requirements – Supersedes 209446*, February 27, 2010.

CCN 214832, *Closure of EFRT M3 Issue Response Plan Criteria 5*, April 26, 2010.

CCN 214950, *Sand Simulant for Evaluation of Vessel Bottom Clearing and Flow Visualization Using Various PJM Firing Patterns Qualification Data Package*, March 8, 2010.

CCN 214953, *HLW Sludge Simulant Qualification Data Package*, March 23, 2010.

CCN 214970, *Analysis Method for Investigation Solids Accumulation*, March 27, 2010.

CCN 216086, *Revised Simulant Qualification Data Package for FRP Testing*, April 1, 2010.

CCN 217414, *Documentation of Low-Order Modeling Components and Assemblies for WTP PJM Vessel Assessment*, April 26, 2010.

CCN 217642, *Potential for Differential Settling to Concentrate Pu*, May 21, 2010.

Other Materials

Alexander, D., *Inadequate Mixing Design of HLW Concentration, Storage, and Blend Vessels Issues and Improvements: Chemical Processing Oversight Report,* 2010.

Bechtel River Protection Project-Waste Treatment Plant, *HLP-VSL-00022 – Feed Receipt Vessel Engineering Study for M3 (Closure Criterion 3)*.

Cao, Z., Pender, G., and Meng, J., Explicit Formulation of the Shields Diagram for Incipient Motion of Sediment", *Journal of Hydraulic Engineering*, 2006.

Cooke, R., *Laminar Flow Settling: The Potential for Unexpected Problems,* 2002.

CRESP Review Plan for External Flowsheet Review Team (EFRT); Issue M3 (Inadequate Mixing) Closure, May 6, 2010.

Daniel, R., *DOE EM Construction Project Review: EFRT M3 PJM Mixing*, May 3-6, 2010.

Dass, M. and Srivastava, R. (2007), "Visual Evaluation of Effective Cleaning Radius in Model Jet-Agitated Tank", Waste Management Conference, February 25-March 1, 2007, Tucson, AZ.

Derksen, J.J., "Solid Particle Mobility in Agitated Bingham Liquids", *Ind. Eng. Chem. Res*, 48, 2266-2274, 2009.

Gilbert, R., *Status: EFRT M3 PJM Mixing*, May 11, 2010.

Gillies, R.G., Sun, R., Sanders, R.S., and Schann, J., "Lowered Expectations: The Impact of Yield Stress on Sand Transport in Laminar, Non-Newtonian Slurry Flows", *The Journal of the Southern African Institute of Mining and Metallurgy*, 107, 351-357, 2007.

Hydro µP sample dispersion unit, www.malvern.com, retrieved on June 16, 2010.

Independent Review of WTP Non-Newtonian PJM Mixing Vessel Assessment, June 8-11, 2010, Draft Agenda.

Kale, R.N. and Patwardhan, A.W., "Solid Suspension in Jet Mixers", *The Canadian Journal of Chemical Engineering*, 83, 816-828, 2005.

M3 Resolution Estimate Summary, spreadsheet, 2010.

Meyer, P.A., "Mixing Sludges & Slurries with Pulsed Jets: Some mixing theory & Test Results, Slurry Retrieval", Pipeline Transport & Plugging & Mixing Workshop, Orlando, FL, January 14-18, 2008.

Non-Newtonian Test Flow Logic, power point slide, 2010.

Non-Newtonian Physical Model Testing Project Overview, document, 2010.

Papp, I., *EFRT Issue M3 PJM Vessel Mixing Assessment, Volume 4-HOP-VSL-00903/904, PWD-VSL-00015/16, TCP-VSL-0001, TLP-VSL-00009 A/B, RLD-VSL-0008*, March 30, 2010.

Poreh, M., Tsuei, Y.G., and Cermak, J.E., "Investigation of a Turbulent Radial Wall Jet", *Journal of Applied Mechanics*, June, 1967.

Poreh, M. and Hefez, E., "Initial Scour and Sediment Motion Due to an Impinging Submerged Jet", International Association for Hydraulic Research, Conference Proceedings: *Twelfth Congress of The International Association for Hydraulic Research, September 11-14,* 1967, vol. 3.

Powell, M.R., Onishi, Y., and Shekarriz, *Research on Jet Mixing of Settled Sludges in Nuclear Waste Tanks at Hanford and Other DOE Sites: A Historical Perspective*, PNNL-11686, October, 1997.

Status Update and Path Forward for Resolution of the External Flowsheet Review Team (EFRT) Issue – M3, Briefing Prepared for Dr. Ines Triay (EM-1_ in Support of Review Planned for May 24, 2010.

WTP Summary Response, Kosson to Gilbert email dated 6/9/10 at 5:19am and Draft DNFSB Slides, June 2010.

Waste Treatment Plant Project, M3 Vessel Closure Package Status, power point slide, 2010.

Waste Treatment Plant Project, *Preliminary M3 Testing Result Status*, May 19, 2010.

Waste Treatment Plant Project, *Overview of PJM Vessels: Identification of Vessels and Key Schedule Dates*, power point slide, 2010.

Waste Treatment Plant Project, *WTP Pretreatment Flow Diagram*, September 9, 2009.

Waste Treatment Plant Project, *EM-1 Status Update and Path Forward for Resolution of the External Flowsheet Review Team (EFRT) Issue – M3*, May 24, 2010.

WTP Research Technology, *Single Velocity Pumpout Sequence*, May 19, 2010.

WTP Research Technology, *Single Velocity Pumpout Sequence*, May 20, 2010.

WTP M3 Vessel Preliminary Test Result Summary, May 19, 2010, spreadsheet.

WTP M3 Vessel Closure Package Status, spreadsheet (multiple; daily through 2010).

Appendix B - Review of Poreh Papers and Applicability to PJM Vessels

The CRESP team has carefully reviewed the following papers:

1. Poreh, M., Tsuei, Y.G., and Cermak, J.E., "Investigation of a Turbulent Radial Wall Jet," J. Appl. Mech., 34, 457-463, (1967).

2. Poreh, M. and Hefez, E., Initial Scour and Sediment Motion Due to an Impinging Submerged Jet, Proc. Proceedings, 12th Congress of the Intl. Assoc. for Hydraulic Res., Volume 3, Sept. 11-14, (1967).

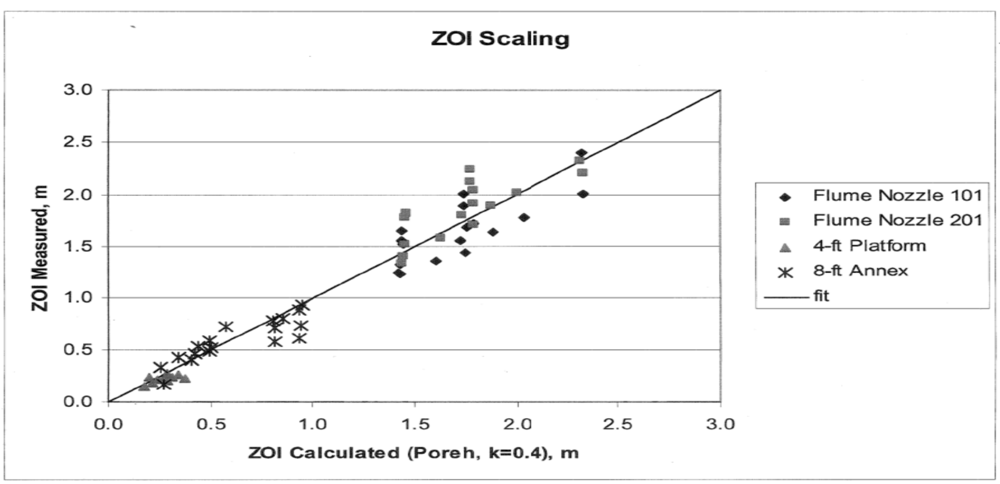
Paper 1 provides the data for the first Multiphase Application Assessment Test Case discussed in the CFD V & V document [24590-WTP-PL-ENG-03-010, Rev 7]. It applies to a pure gas and contains detailed measurements of mean and turbulent velocities, as well as wall shear stress. Please refer to the Appendix E containing the CFD V & V review for more information. Paper 2 is documented as the basis for the proposed 0.18 velocity scaling for bottom clearing of particles. Paper 1 applies to high speed air jets (53 to 113 m/s) emanating from 1 to 3 inch nozzles that impinge at 90º onto a flat plate (floor). The offset distance is considerable. That is, the origin of the jet is located from 8 to 24 jet nozzle diameters above the floor. The range of experimental variables for Paper 2 is not fully stated and is assumed to be the same since it draws heavily from Paper 1. Under these conditions, the vertically directed impinging free jet is fully developed and self similar as it approaches the floor, and the radial wall (floor) jet evolves from this initial condition. In contrast, PJM discharge velocities are moderate (< 12 m/s) and the jet exit/origin is located about 1.5 nozzle diameters above the floor. The impinging jet has very different cross-sectional characteristics that are expected to impact the evolution of the radial wall jet. In addition, the PJM case has liquid rather than gas properties, and contains solids. In developing models for the ZOI, referred to as the radius r_c, scoured clean of sediment by the jet, Paper 2 marries the flow field analysis of Paper 1 with an analysis of erosion based on the Shields diagram. We refer to r_c below as the cleaned radius.

Paper 2, the origin of the 0.18 scaling factor on jet velocity for bottom clearing, is a 40+ year old conference proceedings paper. It is not clear that the proceeding volume was refereed. The arguments leading to models for the cleaned radius are based on speculations that are loosely justified, at best. Two mechanistic models are developed based on different assumptions. These are given in equations (12) and (13) of Paper 2, in which r_c is related to the jet offset from the nozzle exit to the floor b, fluid and sediment particle physical properties and the jet's kinematic momentum flux, K. According to Paper 1: $K = 0.153\,\pi\, D_0^2\, U_0^2$, where D_0 is the jet nozzle diameter and U_0 is the jet exit velocity. Therefore, $K \sim D_0^2\, U_0^2$.

For constant fluid and particle physical properties, Equation (12) reduces to $(r_c/b)^{-2.3} \sim b^2\, K^{-0.85}$. For $K \sim D_0^2\, U_0^2$ we obtain $(r_c/b)^{-2.3} \sim b^2\, D_0^{-1.7}\, U_0^{-1.7}$. There are several ways to interpret this result. Further reduction yields $r_c \sim U_0^{0.74}$. However, during scale-up, b/D_0 and r_c/b must be constant on all scales. With this constraint, algebraic manipulation of this expression leads to the expression $U_0 \sim D_0^{0.18}$, which is the basis of the n = 0.18 scaling assertion. The data of Figure 6 of Paper 2 show that this model only applies at large values of r_c/b. Equation (13) predicts that $(r_c/b)^{-2.3} \sim b^2\, K^{-1.0}$. For this case we obtain $r_c \sim U_0^{0.87}$ and $U_0 \sim D_0^0$, yielding an n = 0 scaling exponent. The data of Figure 7 of Paper 2 show that this equation (13) applies over a broad range including smaller values of r_c/b; which are more likely for the low offset PJMs. Interestingly, Perry Meyer (PNNL), in his email titled "Important Scaling Question", sent to Walt Tamosaitis and Dave Dickey on May 24, 2010, reports that the MCE (Mid Columbia Engineering) Annex ZOI data give an exponent of 0.9; so it is reasonable to ask if he had cast his data in the form $r_c \sim U_0^n$ rather than in the form $U_0 \sim D_0^n$?

If the Poreh analysis is correct, the scaling exponent is more likely to be n = 0 than n = 0.18. Then, the use of n = 0.18 to set the test scale velocity will result in a lower scale test velocity and smaller ZOIs than would be expected at the WTP full scale. However, the mechanistic arguments made in Paper 2 are quite speculative and have not been subject to rigorous peer review. Furthermore, the validity of the Shields diagram, as applied to WTP sediments, has not been verified. It has been said that Poreh conducted experiments on two scales, thereby validating the n = 0.18 scaling exponent. Since there is no evidence of such tests in either Paper 1 or 2, the project should provide additional bases for determining that definitive experiments verify the n = 0.18 scaling exponent.

In Paper 2, Poreh uses the Shields model to calculate the shear stress for particle mobilization which is then combined with the flow field analysis of Paper 1 to obtain a effective clearing radius (ECR), which is considered by BNI to be equal to the ZOI (last paragraph, page 8, CCN: 217414). The accuracy of this correlation with an empirically adjusted constant is shown below for non-cohesive (sand) particulate data (page 9, CCN: 217414). The figure below is Figure 2 of CCN: 217414 and also appears in every other vessel assessment.



On the graph, at large ZOI (greater than 1.5 m) for flume data and for a given set of test data, the Poreh/Shields combined correlations predict, e.g about 1.7 m, while data range from about 1.4 to 2.3 m. At low ZOI (8 ft annex) Poreh/Shields predicts about 0.9 m while data show about 0.6 to 0.9 m and therefore, is not conservative at the smaller scale. So as a rough estimate, we can say that the model correlates the data to within 50%. Contrast this with the statement that follows (from page 9): "Thomson (2010) correlated these data, see Figure 2, and found that the

Poreh/Shields based model matched the regression through the data nearly perfectly, provided a model constant of 0.4 is used rather than 0.542."

There are several things to note. First, the statement "match …data nearly perfectly" is a significant overstatement. Second, there is considerable scatter in the data, and this leads to significant discrepancies and is not always conservative because a mean correlation rather than a confidence interval is used as the basis for subsequent modeling. For example, at a ZOI predicted to be 2.3 m by the correlation, the corresponding experimental results with two different flume nozzles are about (reading from the graph) 2.35, 2.3, 2.2 and 2.0 m. Note that the last result in a 15% over prediction resulting in a 32% over prediction of the area of bottom clearing that was observed in experiments. As a comparison, for vessel HLP-22 in 24590-WTP-RPT-ENG-08-021-08, Rev. 0 the ZOI radius is predicted to be 2.48 m on Page A-36 and 2.85 m on Page A-37.

Further, the correlation appears to result in a systematic under prediction of the ZOI for experimental observations for flume nozzle 101, which is conservative, and a systematic non-conservative over prediction of experimental results for flume nozzle 201; so there are one or more characteristics of the nozzles not captured in the model. Finally, the experimental tests of the correlation are at ZOI values smaller than those expected in HLP-22, so the correlation is being extrapolated beyond where the experimental data were fit.

The ECR (or ZOI) for cohesive solids is calculated using a correlation developed by Guaglitz et al. (2009) who report ECR correlations from measurements for the mobilization of cohesive solids in the form of $ECR = C\,\mathrm{Re}_{Ys}^{1/2}\,D$. Values for C are 0.747, 1.156, 1.67, and 5.78. The *ECR* correlations differ by a factor of up to 8. The constant for the *ECR* correlation, derived from the Poreh and Hefez. (1967) model for the radial wall jet velocity field assuming a 1.5 nozzle offset ratio, lies within this range.

The statement that the correlations differ by a factor of 8, and that the Poreh correlation coefficient for this of 1.1963 (page 11 of CCN: 217414) is within that range, does not provide a high degree of confidence. Clearly, smaller values of C are conservative, and larger values are not. That the Poreh correlation yields larger values than two of the other reported values indicates that it is not the most conservative assumption, especially compared to the value of 0.747. In fact, using a value of 1.1963 rather than 0.747 leads to an area of bottom cleaning that is 2.5 times larger than would be calculated using 0.747. This discrepancy needs to be resolved via larger scale tests.

As a result of the concerns expressed above, there is a high degree of uncertainty with respect to the scaling exponent for bottom clearing because of insufficient experimental evidence at the scale of WTP operations. Clarification of the scaling exponent can only be accomplished by conducting experiments at two widely divided scales that span the range from the current small-scale tests to near full-scale for WTP.

Appendix C – Use of Low Order Modeling (LOAM) in WTP Vessel Assessments

This Appendix discusses the use of Low Order Modeling (LOAM) as part of the WTP PJM Vessel Assessment that is described in CCN: 217414 (DOCUMENTATION OF LOW-ORDER MODELING COMPONENTS AND ASSEMBLIES WTP PJM VESSEL ASSESSMENT) and is used to estimate vessel performance and the extent of bottom clearing for HLP-22 (24590-WTP-RPT-ENG-08-021-08, Rev 0) and other vessel assessments. As noted in many of the reports, bottom clearing is an important issue for criticality safety issues, throughput analysis, developing clean out strategies, and cycle timings.

.

As noted on page 5 of CCN: 217414 "The Mechanical & Process Engineering (M&PE) division plans to assess the WTP PJM vessels in multiple ways to establish a preponderance of evidence that the vessels will perform their function within desired tolerances. The methods are industrial scale-up, computational fluid dynamics (CFD), and low-order modeling." Also the following statement appears on page 26 (Summary and Conclusions) of that document:

> "It is recommended
> - that results from the low-order modeling suite presented in this manuscript (CCN: 217414) be interpreted with caution until sufficient data is collected to establish model performance confidence and
> - that results from the low-order modeling suite presented in this manuscript (CCN: 217414) be used as only one source of data to establish preponderance of evidence that a WTP PJM vessel will or will not perform as intended."

In CCN: 217414 (page 5) LOAM is described as a "suite of low order models that parameterize bottom clearing, particle lofting and blending in WTP PJM vessels."

At this time the CRESP review committee has not seen that there are sufficient data collected to validate the overall performance of the model. Nonetheless, LOAM appears to currently be used as the dominant method for estimating the extent of bottom clearing. As stated in CCN: 214970 (ANALYSIS METHOD FOR INVESTIGATING SOLIDS ACCUMULATION), "It (LOAM) is the principal analytical tool used for the assessment of solids accumulation and has been used for M3 closure assessment of previous vessel groups [I: High Iron Batches/High Rheology; II: High Iron Batches/Low Rheology; III: Balance Batches/ High Rheology and IV: Balance Batches/Low Rheology]."

The basic assumptions in LOAM are that:

1) at the initial state all solids are settled on the vessel bottom head. This is a conservative assumption since at the beginning of all processes (except perhaps DBE) some fraction of the particles will be suspended, especially the slowly settling particles will be suspended.

2) as presented in CCN: 217414, LOAM is for particles of a single size and density. On Page 25 it is stated that "If multiple particles are present the governing critical shear stress of mobilizations is assumed to be the largest one. An alternative is to use the value of the most representative particle." The first option is obviously conservative in that it

leads to the highest shear stress, i.e., jet velocity. The result of using the second option is unclear, with respect to (i) how the choice of a representative particle is made (by size? by concentration? by peak in the PSD?), and (ii) whether this will be a conservative estimate since it will lead to a lower critical shear stress. BNI asserts that the first option (use of the highest shear stress) was implemented in the final version of the LOAM that was used in the assessments, however, this was not clear from available documentation.

3) The zone of particles (ZOIR[1]) cleared by a radial wall jet in the presence of solids is estimated using the Poreh et al. (1967) shear stress relation [discussed in Appendix B] coupled with the Shields relations for the critical shear stress for particle mobilization (Cao et al., 2006). It is claimed in CCN: 214970 that "The smallest ZOIR is used to assess the percentage of the vessel bottom cleared." However, what is the smallest ZOIR will depend on the choice made for largest, most dense particles and how these are chosen is not specified in CCN: 217414 or 214970.

   Other comments and concerns about the Poreh/Shields model are discussed in Appendix B.

4) One parameter in the LOAM model is the critical velocity for centerline clearing, U_{CS}, also based on the Poreh correlation. This is tested with laboratory scale data in Table 2 of CCN: 217414. Generally, the agreement is good; however, for 200 micron particles the model generally over predicts the U_{CS}, that is predicting a higher velocity than is needed, which is conservative.

5) Another parameter in the model is the particle suspension height, something that is admittedly uncertain because of observational subjectivity. This part of the model is tested in Table 1 of CCN: 217414. Compared to laboratory test data, the model in all but one case predicts a somewhat lower particle suspension height than observed, which is conservative. However, the largest value compared with experiment is only 24 inches, while the values predicted for FEP-17 range from 43 to 162 inches, and for HLP-22 the working height of a batch (24590-WTP-RPT-ENG-08-021-08, Rev. 0) is 288-62=226 inches, which is almost a factor of ten beyond which the correlation has been tested, which introduces the uncertainty of extrapolating a correlation beyond existing data.

6) The trapped mass in secondary flows is estimated via an area ratio for the secondary flow region, based on the bottom areas that are not cleared. It appears that an effect of this assumption is to allocate a fraction of the particle mass in the tank to constant motion not bottom settling entrapment. Presumably this would occur for the slowest settling particles and is a form of particle segregation.

7) The ECR (or ZOI) for cohesive solids is calculated using the correlation of Gauglitz (WPT-RPT-177, May 2009). As discussed in Appendix B, there is significant uncertainty involved in using this correlation,

[1] ZOIR is an abbreviation for "zone of influence radius" and is used interchangeably in reports with ZOI which is an abbreviation for "zone of influence."

8) Terminal settling velocity is used in the analysis with equations from Perry's Handbook. There equations are for a single particle (page 12 of CCN: 217414). The case is not established that these equations are valid for particles in a slurry. As stated in 24590-WTP-RPT-ENG-08-021-03 page D-11 and elsewhere LOAM assumes zero particle interactions, and thus attempts to estimate the shortest (reasonable) settling time to the suction line inlet. The zero interaction assumption is bounding (conservative) for assessing accumulation.

9) The particle concentration at the suction line inlet is of concern, including for suction line plugging. This is one area where particle stratification is considered, and two models were proposed. One model in 24590-WTP-RPT-ENG-08-021-08, Rev. 0, uses exponential particle stratification based on terminal particle velocity and the other model uses a relation based on the square of the terminal velocity. From page 21:

> The concentration of phase *p* at the suction line inlet is sensitive to particle stratification. Solids with fast settling times are known to stratify within WTP PJM vessels. Easily suspended solids are expected to show negligible stratification. Accounting for stratification is important when assessing solids accumulation. The LOAM is instrumented with two stratification functions, f_{strat}. One varies exponentionally with the particle settling velocity. The other models varies with particle settling velocity squared:
>
> $$f_{strat} = \begin{cases} \exp(C_{strat} u_t) & , C_{strat} = 0 \\ 1 + (C_{strat} u_t)^2 & , C_{strat} = 0 \end{cases} . \qquad (27)$$
>
> The modeling constant, C_{strat}, is tuned to available pump down data. Equation (27) shows that the stratification model is currently turned off in LOAM. Existing experimental data for the solids removal rate during pump down match the LOAM predictions well without additional stratification. The model may be needed, if larger, heavier particles are present.

So a model has been provided to allow for stratification, however since C_{strat} has been set equal to zero in the current application of LOAM, no stratification is assumed. It is unclear whether this is a bounding case or how sensitive results are to these assumptions. Also, in LOAM the use of air spargers is not considered, which would affect mixing and stratification.

10) The rest of the model is basically a straight forward iterative mass balance model incorporating all the assumptions above (and others). The mass balances are based on slabs of volume, each of which is assumed to be of uniform particle concentration, but less concentrated than the slab below, and more concentrated than the slab above. This

can be viewed as a finite difference approximation to a continuous distribution, and as usual in such cases, the finite difference approximation will be closer to the continuous result as the number of slabs increases resulting in decreasing volumes within each slab.

The CRESP team agrees with the conclusions of Peltier (page 27 of CCN: 217414), the author of LOAM, when he says "(a) that results from the low-order modeling suite presented in this manuscript be interpreted with caution until sufficient data is collected to establish model performance confidence and (b) that results from the low-order modeling suite presented in this manuscript be used as only one source of data to establish preponderance of evidence that a WTP PJM vessel will or will not perform as intended."

The model has been assembled by putting together many pieces, some based on experiment, some based on theory, and some based on theory with parameter adjustment. While there is some testing of the individual pieces based on limited experimental data, there is limited validation of the whole model and especially using data from prototypical large scale systems. This is needed, especially at the full scale. However, neither Peltier nor BNI have identified a test plan for this.

One test of the model is on Page D-13, Figure 30 of 24590-WTP-RPT-ENG-08-021-08, Rev. 0, which is a comparison with MCE Drawdown test data. Figure 30 reports the ratio of the initial concentration of solids to the final concentration (note these are concentration ratios, not ratios of total amounts) for a HLW sludge simulant computed from a mass balance based on analyzing the amount of slurry withdrawn and the dry weight of solids accumulated during each 25% draw down. The concentration ratio of the test data varies from 1 (no draw down) to 0.5 at draw down complete, while LOAM predicts 0.7. The agreement is not good here, and also at all intermediate draw down points, but this large error is conservative because LOAM predicts a larger solids concentration remaining in the vessel than is actually the case. Also reported page D-14, Figure 31 of 24590-WTP-RPT-ENG-08-021-08, Rev. 0 is the particle size distribution (PSD) for the full batch, for ¾, ½ and ¼ batch remaining and the heel. As stated on pages D-11 and 12 of 24590-WTP-RPT-ENG-08-021-08, Rev. 0, "This data is indicative of stratification in the vessel. For HLP-VSL-00022 it is apparent that the vessel is stratified during the first half of pump down and then relatively well mixed (demonstrated by coincidence of the ½ batch and ¼ batch distributions." In particular, we see from the PSDs that the largest particles are preferentially withdrawn during the first two stages of the draw down (decreasing contribution to the PSD), though some remain in the heel. LOAM provides no guidance on how the PSD in the tank or in the heel change with draw down.

However, Page D-16, Figure 32 of 24590-WTP-RPT-ENG-08-021-08, Rev. 0 presents a different picture for HLW simulant in Vessel UFP-VSL-00001 in which LOAM predicts a lower solids concentration remaining in the vessel than shown by the test results. This is the opposite of a conservative prediction. Thus, from these two examples in 24590-WTP-RPT-ENG-08-021-08, Rev. 0 we see that even in the case of laboratory scale data there is no clear trend because in one case LOAM over predicts (conservative) and in the other case under predicts (not conservative) the concentrations of remaining solids during draw down. This may have been because LOAM does not include consideration of sparger behavior, which was present in later but not the former example indicated above.

Note also that in Figure 30 Page D-13 of 24590-WTP-RPT-ENG-08-021-08, Rev. 0, the concentration ratio (both from LOAM and the test data) indicates that the concentration ratio considerably flattens out as the draw down continues, which is taken as evidence that initially there is particle segregation (i.e., a higher concentration of particles is being removed from the vessel than the bulk concentration presumably because the denser particles are preferentially present in the bottom zone near the suction point and being withdrawn), while after about half the draw down occurs, the curve is flat from which one can infer that remaining particles in the vessel are well stirred and the concentration of the draw down fluid is similar to that in the tank. This is supported by the PSD analysis discussed above. This suggests that the model captures, to some extent, that there is particle stratification through the particle settling velocities, though apparently not very accurately since the biggest differences between LOAM and the MCE test data are in the middle of the draw down region.

Based on the above evaluation, the CRESP team believes that LOAM may capture some of the important physics of vessel mixing. However, LOAM is a model that has only been tested at very small scale compared the actual vessels to be used in the WTP and therefore has not yet been proven to be reliable. Further, even against limited MCE data, LOAM cannot not be shown to be systematic in its predicted errors, so one cannot be sure, a priori, whether its predictions will be conservative or not. An overall uncertainty analysis has not been provided for LOAM to understand what design margin is needed to provide an overall conservative design.

Because presently LOAM is being used in apparently every vessel design to determine whether it is “confirmation ready”, we question whether Bechtel is relying on LOAM to a greater extent than is justified in the absence of adequate model validation.

Also, we wonder whether, by not using a sensitivity analysis, an opportunity is being missed to use LOAM to define further testing to verify or improve the model. For example, one can argue whether the use of the Poreh model is appropriate or not from theory. However, if the Poreh result for a specific case was used in LOAM together with cases having + and – 20% scale factors, and the results for solids accumulation did not appreciably change, then it could be concluded that refining the Poreh correlation might not be useful. However, if a large sensitivity was found, then considerably more experimental effort in that area would be justified. That is, we are not suggesting that LOAM is correct, but if it even approximately captures the physics, a sensitivity analysis might be useful in deciding where refinements are necessary rather than trying to argue solely on theoretical grounds.

Appendix D – Evaluation of Criticality Safety Reports

Comments on
Criticality Safety Test Requirements, WTP-RPT-ENG-10-002, Rev.1
Preliminary Criticality Safety Evaluation Report (CSER), WTP-CSER-ENS-08-001, Rev 0b

These reports indicate that the approach planned for WTP will assure criticality safety; e.g., on page 1 of the report it is stated that "the operations will be maintained safely subcritical under both normal and credible contingent conditions" and "criticality is considered incredible." This latter conclusion allows the criticality safety management to conclude that application of the double contingency principle is not necessary.

Both of the foregoing statements rest on assumptions which appear at various places in the report. The basis for considering criticality incredible appears to be based on the summary of contingencies in Table 7.1 of the CSER. Note that the credibility or incredibility of contingent condition 7.11.1 is not given. This may be a typographic omission but it is unclear from the CSER that it is incredible. The definition of incredible is not given in detail but appears to have some qualitative definition based on likelihood or frequency of occurrence, which is a common measure in the performance of HAZOP analyses that were used to support the development of potential criticality scenarios in the CSER.

More importantly the CSER relies on the following assumptions:

1. Sampling of the process streams for fissile materials will give representative samples. This means that the sampling of process fluids in tanks is accurate and not subject to error because of variability in the fluid composition greater than expected. Note that all sampling demonstrations to date have been on stimulants and not real process fluids and they have been on small scale units. On page 5 of report WTP-RPT-ENS-10-002 it is stated that "the uncertainty value of 5% (assumed in the CSER) for how representative the sample is of tank contents may not be achievable with the current sampling and mixing vessel design." Yet the CSER relies on the development of criticality safety limits (CSL) that are based on sample analysis. There must be a statement of the realistic limits of sampling and an analysis based on these.

2. Mixing will assure nearly uniform mixtures in vessels. This report correctly notes that M3 test requirements must support this assumption for valid criticality safety analysis. Note that it is unclear that this assumption is supported by testing performed to date. Again on p. 5 of the aforementioned report it is stated that "the PJM mixing system does not provide a homogeneous

waste mix with respect solids that settle rapidly between pulses" and that "solids that are not kept in solution cannot be accurately sampled with the existing design." This conclusion appears to be applicable to both the mixing and sampling designs. Document CCN 211892, M3 Mixing Requirements identifies the current CSER requirements for consistency with released documents, including the CSER. It is expected that the results of M3 testing will be evaluated to provide input for future revisions of the CSER.

Note that Section 3.2.2 of WTP-RPT-ENS-10-001 states that "differential settling is an analytical issue that will be resolved in a future revision to the CSER and is not an M3 testing issue." CRESP recommends that differential settling be treated as a residual risk issue. As discussed in the main body of this report the proposed operational phase feed pre-qualification controls need to address this risk by extensive waste characterization. Differential settling of particles with different particle sizes and densities is well known, but not necessarily significant for criticality control though it is a remaining risk because of the limited waste characterization. This need for waste characterization to verify that adverse plutonium segregation will not occur has been acknowledged in (CCN 217642).

3. The report states that neutron absorbers are credited for subcriticality in both solid and liquid phases because of the coexistence of neutron absorbers (Fe, Cd, Ni, and Mn in the liquid phase and Fe and Ni in solid phase) with the Pu and U fissile isotopes in each phase. This assumption is based on planned process chemistry. Unplanned chemistry is not considered credible. No specific data is offered to show that the Fe and Ni absorbers will always be intimately mixed with solid phase fissile isotopes, particularly Pu isotopes.

Based on the preceding assumptions, the entire approach to criticality control is based on predictable mixing and accurate sampling to maintain fissile material concentrations below CSLs defined by the CSER, including during a DBE. Thus, the mixing must support CSER assumptions and the sampling systems must have very low uncertainty. Evidence has not been provided that both of these criteria have been identified and demonstrated with assurance to be achievable. In view of the concerns cited in WTP-RPTl-ENS-10-001 criticality control may not be plausible with the proposed approach using sampling of well mixed solutions from PJM mixed vessels based on the currently documented sampling strategy.

It may be that another approach to criticality control needs to be considered, namely, limiting the mass of fissile isotopes in each batch and verification that the all these isotopes are passed on to the HLW plant prior to introduction into the PT process. This approach is aimed at maintaining the total mass of fissile isotopes to a value that is less than the minimum critical mass of the most reactive isotope, ^{239}Pu.

Appendix E- Comments on Fluent Computational Fluid Dynamics V & V Plan (24590-WTP-PL-ENG-03-010, Rev 7)

The Fluent Computational Fluid Dynamics V & V Plan (24590-WTP-PL-ENG-03-010, Rev 7) consists of 3 distinct and somewhat disjoint sections:

1. The main document which contains the necessary background and other required information, describes verification and validation (V & V) requirements and discusses the Default Test Cases in some detail.
2. Attachment A which discusses the Multiphase Application Assessment Test Cases.
3. Attachment B which presents the Eulerian Multiphase Model equations.

The following comments do not focus on compliance with ANSI or NQA-1 V&V requirements but rather focus on how the plan will insure accurate and credible simulation of actual WTP operations, particularly with respect to M3 PJM mixing and particle suspension issues.

Main Document: Fifteen different Default Test cases are presented (see Figure 1) which 'bound' the entire spectrum of WTP operations that will be subject to simulation. The spectrum of WTP operations is described in Sections 4.1 to 4.5 and range from thermal analysis of glass pouring facilities; to PJM mixing; to hydrogen in pipes and ancillary vessels; to flow in cooling channels and heat exchangers; to problems involving fluid-structure interactions (FSI). Justification for the selected Default Test Cases of Figure 1 is given in Section 6.2. The order of attack for these cases, and the time line for their completion, is not given. For many of these cases, little attempt is made to relate the default test to a specific WTP simulation that is planned or underway.

The intended use of CFD for design confirmation and beyond is not clearly stated. The CRESP review team is not familiar with the breath of experiences that BNI computational scientists have with WTP operations; so the following comment is based on the impression that their main focus will be on PJM mixed vessels. Perhaps then it is premature to develop such a broad V & V plan. Implementation of the proposed plan, including associated testing, could take considerable time. It will likely be more productive to compartmentalize the plan along the lines of the operations described in Sections 4.1 to 4.5, or better evolved unit operations based on experience and lessons learned. This would also allow a better mapping among default and application assessment test cases, as well as more practical justification for the selected cases. Such compartmentalization would also allow more focus on the most urgent needs requiring V&V CFD. Otherwise, it would be necessary to add attachments equivalent to A and B for each unit operation and Fluent model. Because simulations in support of WTP design confirmation and actual WTP operations will be at the state of the art, a full V & V is not a routine task and time will be needed to analyze and reconcile the differences between experimental testing results and simulations. When pushing the envelope, it is necessary to determine the accuracy/uncertainty in model results and define acceptance criteria on an individual test case basis.

The Default Test Cases presented in Table 1 and described in Section 6.2should be considered from the perspective that many of the proposed simulations in support of WTP design and operations will push the envelope of the current state of the art. Nonetheless, there is no case to test the effect of particle size distribution (PSD). That is, flow in a fluid containing more than one solid phase. While the Eulerian multiphase model can accommodate several particle phases, simulations for a broad PSD are non-trivial. Fluent has very limited non-Newtonian fluid (Test Case 11) capabilities and it has not been established that CFD will be used for non-Newtonian vessel design confirmation, though this is recommended in the SRNL report. The intended use of CFD for non-Newtonian systems should be clarified. The volume of fluid (VOF) model is computationally costly and difficult to accurately implement on complex problems. It is difficult to argue that a prototypic WTP operation with either Newtonian or non-Newtonian fluids can be simulated using VOF alone. For example, can the VOF model be used to predict the location and motion of the free surface in a PJM mixed vessel, as well as particle suspension and fluid velocities? More justification is needed in terms of its intended use. While ANSYS believes that Fluent maps seamlessly with its solids models through Workbench, there is insufficient demonstration of this capability to know this to be the case.

Exactly what WTP scenarios will Fluid-Solid Interaction (FSI) methods be used to simulate - vibration and failure of angled PJM nozzles? The intended use of FSI should be better clarified. With respect to Test Case 7, would it not be better to consider turbulent rather than laminar flow around a circular cylinder? Turbulent flow around a cylinder with a steady approach velocity is a benchmark problem considered by many computational scientists. Charrouf [PhD, University of Maryland, 2006] demonstrated that Fluent could perform as well as any of the currently accepted research codes when a User Defined Function (UDF) was used to implement the Lagrangian Dynamic sub-grid scale model in a Large Eddy Simulation (LES) of this flow. It might be that a Reynolds Averaged Navier Stokes (RANS) simulation of this more applicable case to PJM mixed vessels would not pass the proposed acceptance criteria. It would be better to select Default Test Cases that reflect key aspects of WTP operations and accept a larger margin of error, than to selected less applicable cases that safely meet more simplistic acceptance criteria that are unrealistic for state of the art simulations. A stronger and more justified mapping is needed among the Default Test Cases, the Application Assessment Test Cases and proposed/planned simulations of WTP scenarios.

Attachment A - Multiphase Application Assessment Test Cases: The multiphase application assessment test cases apply mainly to PJM mixed vessels and employ the isothermal, incompressible, single phase and Eulerian multiphase models in Fluent. The four proposed test cases are introduced in Section 6.3 and discussed in Attachment A.

In general, there is little or no discussion of the challenges faced in building an accurate CFD model, as well as the expected margin of error for these cases. Even less attention is given to the challenges of experimentally validating the results. Experimental details are particularly lacking. What are the criteria for the location of the upwash leading edge and/or the cloud height? How will these be accurately and objectively measured? It is stated that four high resolution cameras are available. What is high resolution? There is no mention of lighting, field of view and test bed access. Consider Table 7 - Conditions for Test Set S3a - Rate-of-ZOI (small box flume) and Table 9 - Conditions for Test Set S4a – ZOI (full scale box flume). Most of the tests are for a single particle size, but Table 7 lists two cases and Table 9 lists one case where a bimodal PSD will be simulated (noted as 210μm/2.9sg + 24 μm /2.4sg). The 210 versus 24 μm particles will have very different settling velocities. Will there be two distinct cloud heights? How will they be distinguished?

There is no plan to measure detailed velocity fields and/or particle concentrations. Validation appears to be more along the lines of macroscopic comparisons (uncleared bottom regions, how high the particles penetrate, etc.), where success means that the CFD and experimental results visually look about the same; rather than on hard mesoscale/smaller scale data. Macroscopic comparisons can be misleading. For instance, Robinson [PhD, University of Maryland, 2001] showed that for a Rushton turbine stirred tank, the power number was reasonably well predicted using a k-ε turbulence model. However, energy dissipation rates were severely under predicted close to the impeller and severely over predicted close to the wall. So even though the volume integrated sum matched the power draw, the mixing and fluid processes in critical locations were not accurately predicted. While comparisons on velocity field and particle concentration are difficult, they are possible with careful thought and planning, and are the most convincing test comparisons.

On page 40 of the report it is stated:

> "*If the governing equations solved by FLUENT scale accurately and FLUENT-based models match experiments well at one scale, then extrapolation of CFD success from one scale to another nearby scale may be done with confidence. The challenge may be recast with the following two questions:*
>
> *How well can FLUENT match experiments at any scale?*
> *How faithfully do the governing equations in FLUENT scale?"*

The questions are appropriate, but there is no definition of 'another nearby scale'. Is this the proposed 1,000 or so scale-up in volume from the approximately four foot diameter test platform that is currently being used?

The four proposed Multiphase Application Assessment Test Cases are:

1. Single Phase Impinging Gas Jet Flow
2. Single Phase Upwash Fountain Flow
3. ZOI, Rate of ZOI and Upwash in a Small Box Flume
4. ZOI, Rate of ZOI and Upwash in a Full Scale Box Flume

Case 1 is for a pure gas (air) flow and Case 2 is for a pure water flow; while Cases 3 and 4 are for particles in water. Each of these is referred to below by the indicated case number.

The Case 1 study is based on the data of Poreh, Tsuei & Cermak (1967) for a turbulent radial wall jet resulting from a gas jet impinging at 90º onto a flat plate. These authors provide the data so no accompanying experimental program is required. It is a noble test case given all of the controversy about "Poreh Scaling". However, it should be noted that these data are for very high speed gas jets at large offset distances from the floor. That is, the origin of the gas jet is so far above the flat plate that the impinging jet is fully developed and self similar. This is not the case for the PJMs since their exit nozzle is located close to the floor (about 1.5 nozzle diameters above the tank bottom). Among the proposed V&V acceptance criteria are prediction of the wall shear stress and boundary layer thickness. These parameters (particularly the former) depend on conditions at the wall. Yet there is no discussion of how the wall region will be treated in the CFD. Are wall functions appropriate or will a zonal model (grid to wall) be required?

The statement made on page 47 about the equations on the bottom of page 46 raises concerns: *"The values of α, β and γ are adjustable parameters used to fit the data. In both experiments and CFD, data will be interpreted using these functional forms presented above. However, the values of α, β and γ may differ between CFD and experiment."* This statement should be justified. An accurate simulation should be able to give back the experimentally measured values of α, β and γ within reasonable uncertainty. Poreh et al. also present data for turbulence intensity (their Figure 11) that can be directly converted to turbulent kinetic energy (TKE). Why is TKE not used in the validation? Which turbulence model is being used? One of the important fundamental conclusions stated by Poreh et al. is that eddy viscosity models cannot describe this flow, so this is an appropriate question. Robinson [PhD, University of Maryland, 2001] showed that for a Rushton turbine stirred tank, the Reynolds stress model more severely under predicted turbulence quantities than k-ε turbulence models, so model choice is not easily dismissed. Since the Case 1 validation is for a gas flow, a good test of the model might be to run a separate simulation for an impinging submerged single phase liquid jet, keeping all dimensionless groups the same as for one of the test cases, but inputting liquid physical properties. If scale-up follows the expected rules, the dimensionless results should be the same.

The Case 2 study considers an array of four PJMs located in a tank filled with water. There is only consideration of the drive cycle - not the suction cycle, and the focus is only on the central upwash (as opposed to upwash near the tank walls) region. The experimental program is not well defined, even with respect to vessel size selection. Vertical mean velocities will be measured on a horizontal X pattern on three different horizontal planes near the center of the tank. The dimensions of the X and the velocity measurement method are not given. There is no mention of how the free surface (liquid-gas interface) is treated. Will there be video measurements of the time evolving free surface flow features?

Cases 3 and 4 consider bottom scouring of solid particles and upward cloud penetration of solids in water, in two different sized box flumes. The radius of the time dependent ZOI will be measured for a single PJM centered in the flumes. Concerns about the PSD and camera technique have already been discussed above. Table 6 and 7 give conditions for the steady and time dependent ZOI tests, respectively, for the small flume, while Tables 9 and 10 give similar information on the larger scale. Since the conditions in Tables 6 and 7 are the same, as are 9 and 10, why is it necessary to separate the time dependent tests from those at long time? Can't these be done simultaneously? Furthermore, why will the transient ZOI acceptance criterion be based only on the time to reach 50% of the final ZOI, rather than on the entire ZOI time history? The nozzle offset from the bottom is always set at 1.5 times the nozzle diameter. For most tests, the sediment depth is set at one-half the nozzle diameter, which is one-third the nozzle offset. A few tests are planned with the sediment depth being 33% greater than the nozzle offset. There are no provisions to test PJM performance in settled solid beds that fill the tank to a significant height above the jet nozzle exit, relating to the expected case of a WTP design basis event.

As second set of tests for Cases 3 and 4 involve moving the single PJM off center, towards one of the corners of the flume, so that the floor jet interacts with and climbs up the adjoining corner walls. This is said to mimic the interaction of two or more PJMs in a mixing vessel that results in upwashing as their radial floor jets collide. Refer to Figure 6, page 48 for an illustration (which actually applies to liquid-gas upwash). In that illustration, the maximum mean vertical velocity occurs on the vertical center plane between the colliding jets, and the condition there is one of zero mean velocity gradient or stress. In the Case 3 and 4 tests, the flume walls replace this vertical plane and present a no slip boundary condition to the upwashing fluid. Wall boundary layers, especially those containing solids, are difficult to treat numerically. So, to what extent do these test cases represent realistic WTP scenarios? Again sediment depth is small and the upwash front arrival time is not defined. Are the deposited solids loosely aggregated or are they cohesive with a defined shear strength?

There are no test cases, with or without particles, to assess Fluent's performance during the PJM suction stroke or in extremely complex geometries such as in a PJM mixed vessel. An intensive experimental program has been carried out in the MCE (Mid Columbia Engineering) four foot diameter PJM mixed test vessel. Yet, no test case is proposed to simulate any of these results. This is a major shortcoming of the Multiphase Application Assessment Test Case Plan. The V & V plan should include simulation of a WTP scenario that is experimentally well studied on one scale with provisions to test scale-up to a size consistent with full-scale or near full-scale WTP scenarios.

Attachment B - Eulerian Multiphase Model in Fluent v6.3: While this attachment is focused on the Eulerian model, some broad and somewhat misleading statements are made about the VOF and Mixture multiphase models. Our current understanding is that the VOF model in Fluent v6.3 has limitations in that it is computationally expensive and difficult to apply to more than two phases. The VOF model in Fluent v12.1 is claimed by ANSYS to be much more robust. The Mixture model is more forgiving and is sometimes used in place of VOF for more than two phases. We are uncertain that it can accurately predict non-Newtonian viscosity and fluid behavior.

The presentation of the Eulerian multiphase model is little more than a compendium of the various sub-model components that are available in Fluent or through implementation of UDFs. Section B.10 (Modeled Terms) is thorough in its listing, but we have not been able to verify if it is complete. Unfortunately, for each term there is no discussion of which sub-model is best and/or should be selected for a specific simulation. There is no discussion of the strengths and limitations of the model framework and model sub-components when applied to WTP scenarios. Will the tunable constants in the various modeled be left at their default value, or will they be adjusted to give the best fit to the experimental data. What are the consequences to model deployment for scale-up? What are the most significant challenges and limitations when applying the Eulerian Multiphase Model to PJM mixed vessels? Can Fluent predict scouring of a deep, moderately cohesive sediment layer? Can it predict suspension and settling of heavy particles in a non-Newtonian fluid?

Final Remarks: The document currently does not provide a well documented CFD V & V plan based on user experience. It may be unrealistic at this time to develop a comprehensive V & V plan that can be achieved in the short term. As recommended above, it may be more prudent to compartmentalize the plan and focus now on applications relevant to PJM mixed vessels. Even here, considerable thought is needed on how to design and conduct definitive experiments, choose modeling strategies and set reasonable measures of success for CFD validation. The proposed experimental validation program lacks essential detail to the extent that a separate review of this program is warranted. We cannot comment further without access to more detailed information. With respect to intended uses of CFD, it is noted that it may not be necessary to have a fully V &V'ed code to exploit its use to design an experimental program to demonstrate the adequacy of PJM mixed vessels to meet WTP process requirements.

Appendix F - Non-Newtonian Fluid Issues

Non-Newtonian fluid/slurry properties affect the performance of PJM vessels, UFP-2 A/B, HLP 27 A/B and HLP 28. A recent assessment by a group centered at the Savannah River Site, with additional expertise drawn from the National Laboratories and industry, specifically addressed the "ability to adequately mix high level wastes under a spectrum of mixing conditions including those (HLW) containing fast-settling particles under conditions of low Bingham plastic yield stress and plastic viscosity." This Independent Technical Review (ITR) team consisted of eight members from the fields of chemistry, chemical engineering (5), mechanical engineering and physics[1]. A separate, recent assessment by Alexander[2] addressed similar issues by systematically critiquing previous work to recommending additional analysis and tests as a path forward.

At various points in the process, the slurries that are used in these vessels are considered to be non-Newtonian. These properties mostly derive from the presence of the particles. The principle non-Newtonian property that is considered important for waste processing is the yield stress. More specifically, the slurries are considered as a Bingham fluid which is a material with a yield stress and a constant viscosity that governs the flow in regions where the yield stress is exceeded. The yield stress acts to keep particles in suspension. The yield stress will also be important for heel cleaning. Since the yield stress will depend on the particle concentration and other particle properties, it is possible that the yield stress of the heel will be larger than the yield stress of the well-mixed suspension.

SAVANNAH RIVER TECHNICAL REVIEW

The report from the Savannah River group addresses issues of non-Newtonian effects during normal operation. They identify four lines of inquiry that address questions regarding the normal operations of the vessels.

Lines of Inquiry

The discussion provided in the Savannah River technical review proceeds along four lines of inquiry (LOI). These are stated at the outset and restated in the conclusions.

LOI-1: Have appropriate waste characteristics and operating boundaries for these vessels been established?

This LOI leads to the conclusion that the operating range for yield stress of the slurry should be adjusted. The lower operational limit for the yield stress should be raised from1 Pa to 6 Pa and the upper limit of 30 Pa should be maintained. As is stated, the yield stress at the lower levels is difficult to measure, even in a laboratory setting. At

[1] *Independent Technical Review of the Assessment of Pulse-Jet Mixing Performance in Vessels Containing Non-Newtonian Sludges at the Waste Treatment and Immobilization Plant. Includes WTP Factual Accuracy / Comments not yet Resolved by IRT (SRNL-RP-2010-00898)* June 2010.

[2] Alexander, D.H., *Inadequate Mixing Design to Prevent Accumulation of Rapidly Settling Solids in HLW Concentration, Storage, and Blend Vessels -Issues and Improvements,* Chemical Processing Oversight Report, U.S. DOE, Office of River Protection, Richland WA.

these yield stresses, it would be difficult to differentiate between a shear thinning fluid with a small power law exponent and a material with a finite yield stress. Under normal processing conditions this is probably not important. A small particle settling during mixing experiences settling forces due to the net effects of gravity, buoyancy and viscous resistance, and hence low nominal shear rates that would give rise to high viscosities and inhibited settling. A similar conclusion would be reached for a material with a low yield stress.

The authors provide an analysis to determine the range of yield stresses that they suggest are adequate for operation. The key equation for ascertaining whether a particle would be suspended is Eq. 1 on Pg. 17. The original reference is not in an archival journal, but a few things are key. First, the denominator contains the difference between the density of the solid (particle), ρ_s, and the density of the "mixture", ρ_m. It is unclear as to what the latter is. If the term, "mixture" refers to the overall average density of slurry, this increases the density of the suspending medium by a factor of almost three from the density of the fluid. In fact, it is probably the case that the two densities represent bounding values for calculations depending upon the effective medium that particles experience, It is likely that the smallest particles "experience" a density difference ρ_s - ρ_f (ρ_f being the continuous phase fluid density) and the larger particles experience the difference $\rho_s - \rho_m$. This would imply that the larger particles have a smaller density difference driving their sedimentation than the smaller particles. This is likely to be an oversimplification as it is based on the picture of single particle hydrodynamics. The actual dynamics of sedimentation is much more complicated (see the main body of the CRESP Letter Report 7, foot notes 4 and 5).

The logic of having a higher yield stress to assist with maintaining particles in suspension is sound. The actual value of the yield stress that is specified should be considered more correlative than actually governing the physical processes. The measured values are obtained using traditional viscometers. The physical properties that are operative in a vessel may be different due to the disruption of the microstructure that is formed by the smaller particles. Still, it is reasonable to expect some correlation and the practice being employed is consistent with that in other industries.

The analysis appears to essentially establish the criterion for incipient motion and predicts that even at the lower yield stress, most particles in a suspension would not settle. An alternative view of the slurry properties is that it is a rapidly shear thinning material[3]. This duality is common and is not an issue here, but it is important to explicitly recognize this possibility as dynamic models of the slurry are considered for computational fluid dynamics studies. This possibility would likely be more clearly seen if Figure 3 were replotted on double logarithmic axes.

The findings and recommendations of the Savannah River IRT team with respect to LOI-1 are mostly consistent with findings and recommendations made by CRESP in its previous Letter Reports to DOE.

[3] H. A. Barnes and K. Walters, The Yield Stress Myth, *Rheologica Acta* 24: 323-326 (1985).

LOI-2: Are the proposed process controls reasonable and likely to achieve their objectives?

The reviewers consider the control strategies to be viable and very similar to those used at Savannah River which has been operating for almost 15 years. There is no mention of sampling or closing mass balances, to the extent possible. Furthermore, operations at Savannah River do not use pulse jet mixing.

LOI-3: Are the analyses of mixing sound, methods appropriately substantiated, and the conclusions valid?

The Savannah River review team could not find or follow the logic used in determining that vessels are "confirmation ready". The authors argue that, "sufficient data exists to derive an appropriate model" and that these data for three different scales be reanalyzed. Buried into the data interpretation is a geometric issue. "The review team is concerned that all tests were not conducted under exact geometric similarity and similarity to the plant [WTP] vessel configuration. These issue(s) as well as new findings could result in additional testing needed to resolve these geometric scaling issues. " These views are entirely consistent with findings and recommendations made by CRESP in this report and in previous letter reports to DOE.

The issue of cavern formation[4] is coupled with the overall issue of scale–up. The Savannah River review team is concerned that caverns will be formed especially for the low yield stress slurries. They were particularly troubled by the correlation that was developed. They recommend a new analysis of the data, possibly by a third party, which includes sensitivity and uncertainty analyses. The CRESP team members concur with this concern and recommendation.

LOI-4: Are the heel management features to be incorporated into the design as additional design features appropriate?

The actual settling process is considered by the Savannah River ITR Team. The authors conclude that the volume fraction is a better measure of concentration than weight percent. This view is supported by the CRESP team. Volume fraction is typically used in the analysis of concentration effects in suspensions. The authors specifically note that the effect of particle shape on settling has been neglected. This comes back to the issue of the yield stress being capable of maintaining a 291 µm Pu particle in suspension. The authors note that apparently PNNL believes that there is settling in slurries with yield stresses, but, the ITR team was not provided with information that would allow them to reach this conclusion.

[4] "Cavern formation" refers to a region of flow surrounded by a region where there is stagnation.

Finally, the authors withhold their judgment on the efficacy of the proposed strategy for heel cleanout. They cite the unavailability of a critical, recent report[5]. The CRESP team members concur with this conclusion.

ALEXANDER REVIEW

A more comprehensive review of non-Newtonian systems that discusses dynamic (settling) effects is given by Alexander[2]. This paper summarizes the concerns that the CRESP team has expressed for many years – selection of representative simulants is a challenge, particle size and density distributions play a significant role, rheology is important but not definitively understood, effectiveness of hydrogen clearing is dependent on understanding of the rheology and confidence in the scale-up basis for the vessels, and the depth of the heel is important. This paper provides an excellent summary of these issues but it would require much more extensive review by the CRESP team to independently ensure that all of the existing data and studies support all of the conclusions that are drawn. The major conclusions are grouped in terms of three Findings.

***Finding 1: Non-Prototypic Simulant:* The typical particle size of the clay simulant is submicron to several microns with a crystal density of ~ 2.4 gm/cc. The new information indicates these vessels will contain particles ranging from sub-micron to over 700 microns with crystal densities up to 11gm/cc and will behave as Newtonian slurries. Accordingly, new evaluations, possible testing, and probable design changes will be required to ensure these vessels can perform the required functions.**

Alexander argues that as a result of leaching the size distribution will change and that there will be a higher fraction of large particles, especially particles over 100 µm (up to 700 µm) with densities up to 11 g/cm^3. Alexander also claims that the density of the feed will be higher than previously considered. This shift results from the dissolution of the aluminate phases (e.g. gibbsite and boehmite). The correlation cited by Alexander to characterize the incipient pick up of settled particles is said to show that the most significant parameter is the density of the particle. Given these issues, the author clearly states that simulants composed of clay and glass beads cannot be considered to be a bounding simulant for either HLP-22 or HLP 27A/B (see page 7). Also, there is a need for additional testing to ensure bottom clearing.

***Finding 2: Non-Prototypic Conditions:* Regardless of whether the received slurry is Newtonian or non-Newtonian, shear thinning will result in Newtonian conditions in the five Non-Newtonian vessels. Shear thinned slurries will allow rapid settling of the large caustic leached size fractions. These vessels have not been tested under rapidly settling Newtonian Conditions.**

---

[5] J. Olson and K. Jenkins, “Pretreatment Vessel Heel Dilution/Cleanout Feasibility Study,” 24590- WTP-RPT-PET-10-13, Rev. A, June 3, 2010.

Finding 2 is not entirely correct. While it is true that large scale stresses will be sufficient to overcome yield stress resulting in turbulent Newtonian like flow behavior on the macro scale, the stress experienced on smaller scales may not be sufficient to overcome the yield stress. That is, large rapidly settling solids may experience an additional resistance or surface drag due to the presence of small particles in their boundary layer, which create an effective medium with a yield stress. The dominant forces acting on these particles may not be due to the turbulent flow at larger scales but, rather the resistance to yield stress on the particle scale that must be overcome in order to settle. Consistent with these arguments, the SNRL ITR report (see above) recommends that non-Newtonian conditions be maintained in the vessels under consideration to insure that the additional microscale resistance to settling due to yield stress be maintained. These points of view appear to be in conflict with those of Alexander. In particular, the implicit assumption in the Alexander report that non-Newtonian materials would be the most difficult to keep mixed is not clearly substantiated.

Despite the arguments made above, the vessels under consideration may behave on a large scale in a more Newtonian like fashion than previously considered. At the very least, shearing of the suspension will result in shear thinning of the slurry which will have an apparent viscosity along the direction of flow that approaches that of the suspending fluid. The disruption of the microstructure that leads to Newtonian behavior does not depend on particle concentration alone and is affected by other particle properties including cohesive characteristics. Given the widening use of these vessels for a variety of systems, it is not surprising that the choice of clay as a bounding stimulant may have been too optimistic.

<u>Finding 3: Design Requires Improvement:</u> The design configuration of the pulse jets in the five Non-Newtonian vessels will not clear the bottom of the more challenging concentrated wash leached solids under Newtonian conditions.

In Section 4.0 the author argues that HLP 27 A/B and HLP 28, as currently designed, will accumulate solids. This is solely based on consideration of the PJM drive cycle. There is no consideration of the PJM suction cycle. Furthermore, it was not clear based on previous communications and documentation, that the outer PJMs employed angled rather than downwardly directed nozzles. This Finding needs to be better documented.

Summary

The path forward is discussed by Alexander in Section 6. While the arguments for this path may not be entirely rigorous and some details may not be optimally described, there is sufficient evidence to recommend that further testing at full scale or near full-scale is required to demonstrate the adequacy of mixing with redefined and thoroughly justified prototypical stimulants and operating conditions. The use of CFD is recommended to aid in experimental design. The use of CFD is covered in Appendix E.

The two studies described in this Appendix provide a sound set of analyses of the major issues facing DOE in the tanks containing non-Newtonian slurries. Some of the items are clear. More comprehensive analysis of existing data is needed to understand the scaling[1]. Alexander believes that testing at additional scales is indicated at this point whereas the SRNL ITR team provides a strong hint that this may be the case but does not make a commitment at this time. There is clearly a need to understand more about the effects of particle settling. We address this in our remarks on criticality. Here, since the particles induce structure and alter the rheological properties, there is a need to pay closer attention to the effects of particle distributions, concentration and the effect of flow. There is concern that the simulants that have been used will not provide an accurate picture of the dynamics of the WTP. The one area where there appears to be some difference of opinion between Alexander and the SRNL ITR team is with respect to the desirability of operating under non-Newtonian conditions. Here, the CRESP team believes that full scale or near full scale testing can resolve this issue.