NATIONAL ENERGY TECHNOLOGY LABORATORY

U.S. DEPARTMENT OF ENERGY

TECHNICAL REPORT ON NETL's NON-NEWTONIAN MULTIPHASE SLURRY WORKSHOP

A path forward to understanding non-Newtonian multiphase slurry flows

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August 19-20, 2013, Morgantown, WV

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ACRONYMS

BNI	Bechtel National, Inc.
BNFL	British Nuclear Fuels Limited
CFD	Computational Fluid Dynamics
DEM	Discrete Element Method
DNFSB	Defense Nuclear Facilities Safety Board
DOE	Department of Energy
E-E	Eulerian-Eulerian (two-fluid or multi-fluid)
E-L	Eulerian-Lagrangian (discrete element model)
EM	Office of Environmental Management
FSVT	Full-Scale Vessel Testing
HLW	High Level Waste
LANL	Los Alamos National Lab
LBM	Lattice Boltzmann Method
MPM	Material Point Method
MPPIC	Multiphase Particle In Cell
MRI	Magnetic Resonance Imaging
NETL	National Energy Technology Laboratory
NNMS	non-Newtonian Multiphase Slurries
ORP	Office of River Protection
ROM	Reduced Order Models
PIV	Particle Image Velocimetry
PJM	Pulse Jet Mixing
PNNL	Pacific Northwest National Laboratory
PR-DNS	Particle Resolved Direct Numerical Simulations
PSD	Particle Size Distribution
PSDD	Particle Size and Density Distribution
R&D	Research and Development
SEM	Scanning Electron Micrographs
SRNL	Savannah River National Laboratory
SNL	Sandia National Laboratories
TFM	Two-Fluid-Model
UQ	Uncertainty Quantification
V&V	Verification and Validation
WTP	Waste Treatment & Immobilization Plant

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DISCLAIMER

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EXECUTIVE SUMMARY

The Department of Energy's (DOE) National Energy Technology Laboratory (NETL) sponsored a workshop on non-Newtonian multiphase slurry at NETL's Morgantown campus August 19 and 20, 2013. The objective of this special two-day meeting of 20-30 invited experts from industry, National Labs and academia was to identify and address technical issues associated with handling non-Newtonian multiphase slurries across various facilities managed by DOE. Particular emphasis during this workshop was placed on applications managed by the Office of Environmental Management (EM). The workshop was preceded by two webinars wherein personnel from ORP and NETL provided background information on the Hanford WTP project and discussed the critical design challenges facing this project.

In non-Newtonian fluids, viscosity is not constant and exhibits a complex dependence on applied shear stress or deformation. Many applications under EM's tank farm mission involve non-Newtonian slurries that are multiphase in nature; tank farm storage and handling, slurry transport, and mixing all involve multiphase flow dynamics, which require an improved understanding of the mechanisms responsible for rheological changes in non-Newtonian multiphase slurries (NNMS). To discuss the issues in predicting the behavior of NNMS, the workshop focused on two topic areas: (1) State-of-the-art in non-Newtonian Multiphase Slurry Flow, and 2) Scaling up with Confidence and Ensuring Safe and Reliable Long-Term Operation. The participants were divided into three parallel break-out groups to discuss specific questions (Figure 1 and Figure 2) under each topic area and to identify the challenges and technical gaps, propose solution strategies, identify resources and references, and place priorities and timeframes to each topic question.

Detailed information on the 2013 Non-Newtonian Multiphase Flow Slurry Workshop and also the electronic version of this document can be found at https://mfix.netl.doe.gov/workshop/NNMSW-2013/.

Topic Area 1 Overview

Overall discussion of topic area questions tended to gravitate towards issues and challenges at DOE's Office of River Protection's (ORP) Waste Treatment & Immobilization Plant (WTP) Project. Using WTP as a case study to discuss topic area questions was appropriate because of the immediate need to address technical issues at WTP and the fact that nuclear waste at the Hanford site represents one of the most challenging conditions for any of the EM clean-up sites. Hanford nuclear waste management is complex in nature due to various separation practices conducted over a long time period with limited documentation on the makeup of

Topic Area 1: State-of-the-Art in NNMS Flows

a) What steps need to be taken to increase our understanding of Hanford non-Newtonian slurries?
b) What predictive theories are available for non-Newtonian multiphase flows?
c) What kind of sensors and measuring probes are needed or available?
d) Can we change the rheological behavior of non-Newtonian slurry?
e) Can Newtonian fluids be used to understand and bound non-Newtonian behavior?

Figure 1: Topic area 1 questions

the feed streams into tank farms along with lack of data to fully characterize the waste stored in the tank farms. As a result, one of the common themes throughout the workshop was how to account for this large source of uncertainty arising from limited amount of data on the actual waste characteristics, and how to design representative waste simulant with similar rheological properties. Discussions also centered on the various Pulse Jet Mixing (PJM) vessel designs being considered to mix the NNMS and the challenges these vessels pose in verifying their design; WTP plans to conduct full-scale vessel testing (FSVT) for design confirmation of the heavily loaded non-Newtonian PJM vessels. Experts debated the ability of the Hanford clean-up process both at the tank farms and within WTP to control the rheological behavior of the NNMS to meet all waste acceptance criteria, mixing and safety requirements. Industrial experts provided practical suggestions on the use of rheological modifiers and, overall, the participants concluded that modifiers should be considered both at the tank farms and within WTP only after conducting a comprehensive cost-benefit based engineering analysis that considers the downstream effects and the increase in the plant's lifespan due to possibly increased waste. Experts debated the use of predictive theories and the readiness level of various models for NNMS. In general they agreed that for many of the WTP PJM vessels, those considered single phase or lightly loaded Newtonian vessels, the readiness level of models is sufficient to warrant their use following appropriate verification and validation (V&V) and uncertainty quantification (UQ) procedures. Issues surrounding the use of sensors and the availability of these sensors were discussed and, in general, concerns were primarily about the ability to quantify the uncertainties in the measurements at full-scale. A strong consensus existed for the increased use of sensors during WTP black cell operation.

Topic Area 2 Overview

The use of dimensional analysis to support proper scaling studies was discussed and widely accepted by the participants as a tool to support the design of NNMS tanks and the selection of simulants. Concerns about scaling up were raised because of the unsteady nature of flow, which transitions from possibly stagnant regions to highly turbulent regions, and the complexity of the PJM vessel internals. The experts agreed on the need for experimental data to verify any non-dimensional analysis. Similar to the discussions in topic area 1, experts discussed the uncertainties in the characterization of the Hanford waste. However, more emphasis was placed (and discussed) on incorporating chemistry effects and understanding cohesion and agglomeration. There was strong

Topic Area 2: Scaling up with Confidence and Ensuring Safe and Reliable Long-Term Operation

a) ***What is the accepted practice in scaling (up or down) for non-Newtonian multiphase slurries?***

b) ***How can we simulate the Hanford nuclear waste and account for the uncertainties in an experimental test plan (PSDD and chemistry)?***

c) ***Is there a need to maintain a testing facility during plant operation to test for off-normal conditions or for troubleshooting?***

d) ***What kind of monitoring is needed at WTP and how will the data be used for control and troubleshooting during plant operation?***

e) ***What is the existing industrial experience that would provide input into black-cell long-term operations?***

Figure 2: Topic area 2 questions

agreement among the experts that a parallel testing facility should be maintained during the commissioning and operation of WTP. The experts expressed a strong desire to increase the level of monitoring over what is currently being planned in the black cells during WTP operation. Finally, experts discussed the leveraging of existing industrial experience. While the WTP operating conditions and requirements are relatively unique, there are examples of commercial vessels operating in various industries (especially mining and oil-sands) which (a) are of similar size (and larger), (b) contain complex non-Newtonian slurries with settling solids, and (c) utilize gas spargers and other solids suspension systems. Every effort should be made to use the insights gained from these existing systems related to design, operation and erosion. A "lessons learned" exercise would be useful to learn from industrial successes and failures in the long term operations of processes at scales similar to WTP.

A total of ten topic area questions were addressed during the first day of the workshop and results of the break-out groups were presented to all the participants for comments and questions during the second day of the workshop. NETL organizers compiled input from the workshop and circulated it to all the participants for review and comments before circulating a draft workshop report for final review and comments. This report is an assemblage of detailed input from the experts.

The intent of the workshop and this report was to bring together a multi-disciplinary team of experts from industry, national labs and universities such that their expertise and past experiences can be effectively exploited to provide insight into how to address technical issues surrounding NNMS, which can then be leveraged by EM to map out and define priorities of future R&D needs in the design of NNMS waste applications. The breadth of the topics discussed enabled the development of a holistic approach made-up of various design elements. The discussions during the breakout sessions identified the technical gaps for each of the design elements critical to the development of NNMS applications, and also proposed the future R&D needed to overcome the identified technical gaps. Owing to the complexity of NNMS flows and critical technical gaps in the current state-of-the-art requiring long-term and multi-disciplinary R&D efforts, although a roadmap is ideally needed for each of the design elements, such a road-mapping process was beyond the scope of this workshop given the wide breadth of the topic areas and limited time in discussing each area. This report provides a technical framework for designing NNMS applications and identifies the technical gaps and proposed solutions as perceived by the workshop attendees. It is anticipated that this report will be leveraged by EM to inform planning and map out future R&D needs and priorities in staging and handling NNMS wastes and the information in this report can be immediately used by ORP in addressing technical issues associated with WTP-PJM non-Newtonian vessels.

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1 KEY FINDINGS AND RECOMMENDATIONS

Input from the experts during the workshop was collected to define both a timeframe and a priority to activities to address each of the topic area questions. The following guidelines were used throughout this process:

Timeframe

In recommending future work leading to better understanding of NNMS flows, the experts also estimated the duration of the activity. Below are the definitions of the terms used in this document with respect to defining the duration of future R&D.

> ***Near-Term (<3)***: Activities that the experts estimated could be finished within two years.
>
> ***Mid-term (3-8)***: Activities that the experts estimated will require 3-8 years for completion.
>
> ***Long-Term (9+)***: Very long term R&D activities that the experts estimated will require over 9 years for completion.

Priority

The experts noted the urgency of any recommended R&D activity with respect to broader question of enhancing the understanding of NNMS flows (applicable to tank Farms, other EM cleanup sites, etc.). Hanford's WTP was the center of the discussion, and only a few of the topic area questions were targeted toward issues identified for FSVT and black cell operations. Therefore, in addition to the assigning priorities for the R&D activities for understanding NNMS flows, the experts also assigned priorities to filling critical gaps identified in discussion of Hanford WTP activities. The priorities were defined as:

> ***Low (L)***: R&D activities that have limited potential to increase our knowledge of NNMS flows. Within the scope of WTP, activities that addressed operation needs for WTP but have no bearing on the understanding of NNMS flow.
>
> ***Medium (M)***: R&D activities that are relevant to the understanding of NNMS flows but could be leveraged across tank farm mission (e.g., controlling rheology).
>
> ***High (H)***: R&D activities that, according to experts, will fill the most critical gaps in the understanding of NNMS flows. Also includes activities that could support near-term design confirmation activities for mixing vessels at Hanford's WTP (such as, optimizing design for heavily loaded Newtonian and non-Newtonian vessels, full-scale vessel testing).

1.1 Key Findings

The key findings during this two day workshop are summarized in Table 1 where timeframe, priority and justifications are placed next to each of the topic area questions discussed during the workshop. Many of the topic area questions in the tables below are assigned a high priority. This is a direct consequence of the type of topic area questions selected for discussion by the experts. Topic area questions were developed based on critical needs in understanding NNMS flows under EM's tank farm mission. In large part, these needs are directed towards the needs for WTP because of both the urgency in addressing technical issues at WTP, and the challenging conditions of the Hanford waste. The findings summarized in this report will not only allow EM to better plan and assess proposed methods for future nuclear waste clean-up efforts but the priorities listed can be immediately leveraged by ORP to support the design of Hanford WTP PJM vessels, help address technical issues at WTP from construction through commissioning, and plan for safe and reliable WTP operation.

Table 1: Key Findings

Topic Area Question	Time-frame	Priority	Finding
What steps need to be taken to increase our understanding of Hanford non-Newtonian slurries?	>9	H	The experts recommended various elements for a holistic design approach needed to comprehensively understand and successfully design NNMS flow applications. The details are described later in this report (Section: 3)
What predictive theories are available for non-Newtonian multiphase flows?	3-9+	H	The experts identified the current predictive theories at reasonable maturity levels for single-phase and lightly loaded conditions that could be leveraged immediately. For the NNMS flows, the experts expressed a high priority for developing high fidelity predictive theories. The experts noted that such a model development exercise will be a medium to long term campaign, as it will begin with identifying critical gaps and will require a concurrent detailed experimental plan and dimensional analysis (from elements of holistic design) supported by a multi-institutional and multi-disciplinary team.
What kind of sensors and measuring probes are needed/available?	<3	H	Recognizing the potential of advanced instrumentation on data gathering for design confirmation or for monitoring of black cell vessels at WTP, the experts identified a high priority to review, select, and quantify accuracy of instrumentation for specific data needs. According to experts, within the scope of Hanford WTP, such an effort should be completed prior to FSVT.
Can we change the rheological behavior of a non-Newtonian slurry?	3-8	L-M	The experts agreed that there are several methods to modify rheology, but they all call for a detailed engineering analysis. The experts identified this as a low to medium priority task and pointed to data that already exists from past studies by National Labs. The effect of modifiers can be analyzed in a medium timeframe for use at Hanford WTP. Experts noted the effect on rheology due to attrition and physical degradation of particles that should also be considered in any attempt to modify rheology.
Can we use Newtonian fluids to understand and bound non-Newtonian behavior?	<3	L	The overwhelming majority of experts did not recommend this approach or listed several idealized conditions (not applicable to Hanford waste) where Newtonian fluids could bound non-Newtonian behavior. Therefore, the experts identified this as a low priority to understand NNMS flows or for use in design confirmation activities at Hanford WTP.
What is the accepted	<3	H	The scaling/dimensional analysis is the key to bridging

practice in scaling (up or down) for non-Newtonian multiphase slurries?			tests of different scales; hence, it is an important component for design verification with high priority. The experts estimated such an analysis could be completed in the near-term. Considering the time and cost of full-scale testing, it is strongly recommended by the experts that small and medium scale experimental tests should be conducted to support any dimensional analysis and incorporated into the test plan to fill gap and account for various uncertainties.
How can we simulate the Hanford nuclear waste and account for the uncertainties in an experimental test plan (PSDD and chemistry)?	<3	H	It is critical to develop appropriate simulants for all the experimental testing including FSVT. This is identified as high priority and the associated uncertainty could be partially addressed if enough data on waste qualification is made available through additional tank farm waste sampling. The experts also reconciled with the fact that due to the extreme difficulties in comprehensively sampling and analyzing nuclear waste, complete waste qualification might be not possible ever and recommended relying on a conservative design approach.
Is there a need to maintain a parallel testing facility during plant operation to test for off-normal conditions or for troubleshooting?	3-8	H	The experts strongly recommended and assigned high priority to maintaining a parallel testing facility during commissioning and plant operation for rapid response to off-normal events and troubleshooting. Since the testing facility will be affected by the final design, within the scope of WTP, it can be completed in the mid-term.
What kind of monitoring is needed at WTP and how will the data be used for control and troubleshooting during plant operation?	3-8	H	The experts emphasized the need for monitoring in the black cells during WTP operation to secure the ability to predict potential failures beforehand, and raise the level of safety. Within the Hanford WTP scope, considering the time frame for finalizing the design and high cost of any re-design, the experts identified this as high priority effort that can be completed in the near to mid-term timeframe.
What is the existing industrial experience that would provide input into black-cell long-term operations?	<3	M	Acknowledging the fact that there is not much previous experience in similar black-cell long-term operations, the experts agreed that leveraging industrial experience with (generic?) new process start-ups and applications might provide insight. This is classified as medium priority and will require a near-term timeframe for completion.

1.2 Key Recommendations

All of the recommendations discussed among the experts during the workshop are collected under the individual summary discussions for each topic area question in this section. Recommendations spanned tank farm issues, FSVT, WTP, and long-term black cell operations. The key recommendations taken from the workshop where a strong and general consensus was reached are listed in Figure 3 and discussed in the paragraphs below the figure.

Key Recommendations

1. ***Adopt a holistic approach for design of NNMS flow applications that includes dimensional analysis, experimental testing spanning scales, advanced instrumentation, and modeling.***
2. ***Incorporate uncertainties of nuclear waste characteristics into waste simulant development and vessel testing.***
3. ***Maintain a parallel testing facility during WTP commissioning and operation.***
4. ***Review, select, and quantify uncertainties of instrumentation prior to FSVT***
5. ***Increase the instrumentation in the black cells.***

Figure 3: Key Recommendations from the workshop

1. *Key Recommendation - Adopt a holistic approach for design of NNMS flow applications that includes dimensional analysis, experimental testing spanning scales, advanced instrumentation, and modeling*

Confirming design for a NNMS in a large scale PJM vessel with complex internals operating under a wide variety of flow regimes is obviously a difficult task, further complicated by the need to test with different waste simulants to account for large uncertainty in actual waste qualification. Under such difficult conditions, FSVT can only provide a limited amount of data because it is simply not feasible at full-scale to conduct a sufficient number of tests to adequately probe various flow conditions (both normal and off-normal) and physical characteristics (such as, waste rheology, PSD, etc.). This is true for all the WTP PJM vessels and is even more difficult for the non-Newtonian vessels. Such a difficult task requires leveraging all the available tools and information to maximize the ability to confirm design verification. In order to do this, the experts recommended a holistic approach for the successful design of NNMS applications, and the various elements of such an approach are shown by the schematic in Figure 4.

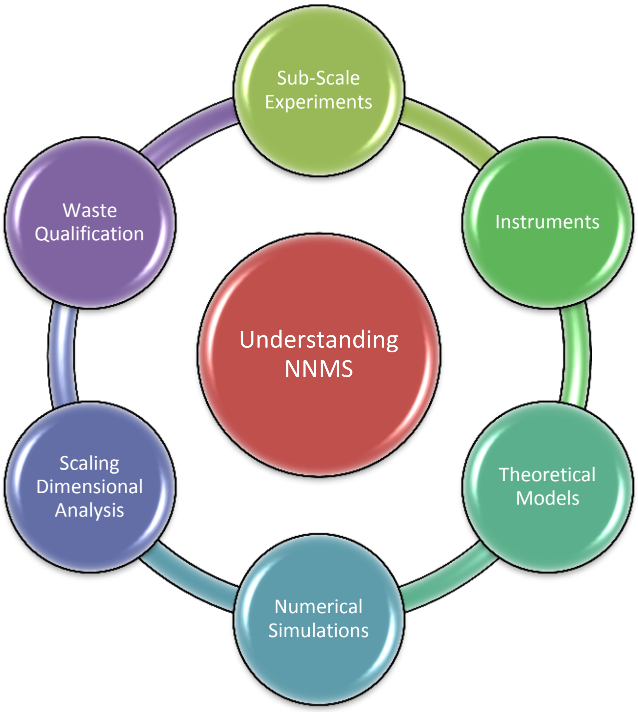

Figure 4 Schematic showing various elements required for understanding NNMS flows.

The elements shown by the schematic interact with each other, yielding a capability made up of empirical data, scaling laws, advanced instrumentation, and predictive numerical models. For example, the experts generally agreed that any FSVT campaign must be supported by dimensional analysis to guide sub-scale testing needed to verify the scaling relationships, probe uncertainties in the waste characteristics, and investigate off-normal events, all at a scale or scales that are not time and cost prohibitive. Furthermore, properly scaled vessels can reduce the scope of FSVT by filling critical data gaps, provide insight into the functional dependence of vessel mixing requirements, provide data to support design verification for untested vessels, and reduce the number of full-scale vessels required for testing.

Most of the experts agreed that physics-based modeling also has a significant role to play in any design effort because V&V'ed models enable predictions beyond experimentally tested parameter ranges. Development of V&V'ed models for NNMS flows is important not only during the design confirmation studies, but also during the operation and trouble-shooting of WTP processes, and could be leveraged by future EM or DOE projects. During the testing, validated models can be used to support scaling laws and probe PJM vessel responses to a wide variety of simulants and flow conditions (both normal and off-normal). These models can also support placement of instruments and help guide FSVT plans. It was generally agreed that the readiness levels for Newtonian single and multiphase models are very high and the experts strongly recommended their use, provided adequate validation and steps to quantify uncertainties in the model predictions are conducted. The experts also agreed that although many advances have been made in the model development for NNMS, the theory is still lacking key constitutive laws and the readiness level of these models is difficult to ascertain. It was recommended that the maturity of existing Newtonian models could be leveraged to accelerate development and deployment of NNMS computational tools. In addition a set of challenge problems could be used to assess the state-of-the-art in NNMS models, determine their readiness level andidentify gaps to direct future R&D efforts.

2. *Key Recommendation - Incorporate uncertainties of nuclear waste characteristics into waste simulant development and vessel testing*

The hazardous environments of nuclear waste and the resulting difficulty in waste handling pose severe challenges in waste sampling and analysis. As a result of limited sampling, the waste is generally poorly qualified. However, the target applications (such as WTP-PJM vessels) for waste handling are required to be design verified for possibilities of very different waste streams during pre-treatment and vitrification processes. Due to the prohibitive cost incurred in objective evaluation of waste uncertainty at full-scale, the experts recommended testing over a range of scales smaller than the actual vessels. According to experts, the appropriate sub-scales and simulant make up (e.g., PSDD) could be identified by scaling or dimensional analysis that identifies the most critical non-dimensional groups. Sub-scale tests are also ideally suited for parametric studies of variables affecting key waste properties, such as, density, and porosity, etc. Considering the time and cost of full-scale experimental testing, small- and medium-scale testing is recommended as the key approach to investigate the uncertainties due to wide PSDD, shape, and complex chemistry, and to evaluate design alternatives and modifications to address performance deficiencies. Acknowledging the limits to data collection in FSVT, a series of sub-scale tests to determine the operational effectiveness or failure points under the worst case scenarios is recommended while matching the most critical non-dimensional group as accurately as possible by tailoring the properties of the simulant to maximize similitude between the full scale process and the scale model. In addition to providing data points for determining functional dependence of mixing requirements, sub-scale testing over a wide range of simulants will also provide critical failure data points that will point to additional testing at full scale. According to experts, matured numerical models can also be used as a cost-effective tool in understanding the effect of different simulant make-ups on mixing or transport of waste streams. Additionally, modeling can also be used in conjunction with scaling analysis to identify critical non-dimensional groups for defining sub-scale testing.

Within the scope of Hanford WTP, the experts recommended more waste sampling and analysis in order to better qualify the key waste properties affecting design of transport and mixing vessels. According to experts, the current activity of transferring waste from single-shell tanks to double-shell tanks could be opportunistically leveraged for additional sampling and analysis provided representative samples can be extracted. Acknowledging the extreme difficulties in comprehensively sampling and analyzing nuclear waste, the experts agreed that a complete waste qualification might not be possible ever and recommended relying on a conservative design approach based on empirical evidence and engineering judgment.

3. Key Recommendation - Maintain a parallel testing facility during WTP commissioning and operation.

An overwhelming majority of the experts recommended maintaining a testing facility during the plant's life cycle, and dimensional analysis (identified as one of the key elements of design approach) could be used for identifying appropriate scale of the testing facility. Because of the large sources of physical uncertainties arising from waste properties and chemical processes, a parallel facility will provide a cost effective platform to test the effect of off-design specification waste on PJM vessel performance. Other off-normal conditions (such as failure of some PJM's, restart from power outage, etc.) that cannot all be currently anticipated could be studied in this facility in the event of a failure to determine mitigation and preventive maintenance strategies. Furthermore, such a facility can be used to develop and test new instrumentation, provide data for future advanced model development and V&V, and can provide a platform for collaborative research by attracting leading experts from various organizations to work jointly. The experts cited various industries that maintain a parallel testing facility through the commissioning stages and depend on these types of facilities to answer critical questions that arose post commissioning.

4. Key Recommendation - Review, select, and quantify uncertainty of instrumentation prior to FSVT

Experts agreed there are a variety of available sensors that could be used to collect data from FSVT for design verification. However, calibration of the measurements made by these sensors and the applicability of these sensors need comprehensive evaluation to quantify the uncertainties in these measurement devices and assess their readiness level for FSVT. It was recommended that sub-scale testing should play a primary role in this process to confirm the accuracy of these sensors and help to guide placement of these sensors at full-scale. Comparing measurements in sub-scale facilities mimicking critical aspects of the NNMS flows can help in validating the sensors by defining their operating range along with quantifying accuracy and sensitivity. In addition, these comparisons would help in better interpretation of the readings obtained from the sensors, thereby reducing the cost of FSVT. To confirm the mixing and safety requirements during FSVT, the available global measurement techniques should be utilized, complementing the sensors and probes, for a thorough validation of vessel performance.

5. Key Recommendation - Increase the instrumentation in the black cells

Lack of sufficient sensors and instrumentation in the black cells was identified as a critical gap in the current WTP plant design. Experts agreed that some appropriate instruments are available, and that these instruments could be used to increase the measurement capabilities in the black cells to provide important operational information such as the buildup of highly radioactive and/or fissile materials (as an early warning system), and these devices could also be used to monitor the pre and post radioactivity during batch operation of various PJM mixing vessels along with monitoring NNMS transport along pipelines.

The details of the key recommendations summarized above are provided along-with details of the break-out sessions in this report. The experts agreed that the scope of the key recommendations should be reconciled with the time and financial constraints of designing, constructing, and commissioning of complex WTP like applications. The experts agreed that it is not always tractable or even possible to perform detailed analysis because of the complex interacting mechanisms affecting operational performance and recommended relying on past experience and engineering judgment to develop a conservative design, having sufficient safety margin. As an example of balancing ideal world expectations with ground realities, the experts pointed out the need for a parallel test facility that could be used to trouble shoot during WTP operations. The parallel test facility will contain only the critical elements of WTP that are identified a-priori based on their significance to WTP operations, such as, for example, those that are susceptible to failure. Likewise, the experts agreed that although actual waste should be qualified as comprehensively as possible, the qualification could be limited because of technical challenges, such as, hazardous environment, large waste variability between tanks, wide variability in sampling techniques, and high cost of waste sampling and analysis. The experts concluded that the comprehensive waste qualification might not be possible at all and recommended a conservative design approach based on waste properties deemed most challenging to the storage, mixing, or transport of wastes.

WTP is the largest chemical separations facility of its kind for handling and treatment of nuclear waste and a facility of this scale has never before been constructed or operated. There are many open technical issues at WTP surrounding the performance of the PJM vessels for both Newtonian and non-Newtonian materials. Furthermore, based on the discussion at this workshop, there exist critical knowledge gaps in our current understanding of the rheological behavior of NNMS flows. The magnitude of the WTP project, the national importance of WTP, and the technical issues that must be overcome present a grand engineering challenge seldom encountered. Addressing these challenges can neither be done by a single organization nor by small teams working independently. A challenge such as WTP requires bringing together the "*best-of-the-best*" talent from multiple organizations (industry, academia, and national labs) and multiple disciplines collaboratively working on the challenges facing the WTP-PJM vessel performance since no single organization has the requisite experience and expertise to adequately address these problems alone. A workshop such as the present one provides a multi-disciplinary pool of talent which can be leveraged to address the key findings summarized herein.

"Alone we can do so little; together we can do so much." ***Helen Keller***

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2 INTRODUCTION

2.1 Overview

NETL organized a non-Newtonian multiphase slurry flow workshop that was hosted at its Morgantown campus from August 19-20, 2013. The objective of this two-day meeting was to solicit input from experts on how to address technical issues associated with the handling of non-Newtonian multiphase slurries across various applications managed by Department of Energy’s Office of Environmental Management (EM). These include the Tank Farm Project and Waste Treatment & Immobilization Plant (WTP) Project, which store, mobilize, and transport slurries at the Hanford Office of River Protection (ORP) in Richland, WA. The workshop was attended by 39 people, including 27 invited experts from universities, industry and national labs, researchers from NETL, and representatives from EM and the Defense Nuclear Facilities Safety Board (DNFSB). Two topic areas (State-of-the-art in non-Newtonian multiphase slurry flows, and scaling up with confidence and ensuring safe and reliable long-term operation) were selected for open discussion among the experts, leading to the development of this report. Key questions under these topic areas were selected for discussion by NETL in consultation with experts. Issues associated with these questions and steps to address the issues were documented along with the timeframe and priorities. That information has been captured into this report, which EM can use to help solve technical issues within the tank farm mission. In addition, ORP can immediately leverage the output from this workshop (for example, dimensional analysis, sub-scale testing, instrumentation, controlling rheology) to support their current full-scale vessel testing immediately and the future WTP operation when construction is completed.

2.2 Background

The WTP project at Hanford is being designed to treat fifty-six million gallons of radioactive waste contained in 177 underground storage tanks from plutonium production at Hanford from the 1940s to the 1980s. Separation and vitrification of the radioactive materials from the tanks offers the best solution for immobilizing the waste and preventing an environmental catastrophe caused by leakage from the storage tanks into the subsurface and eventually the Columbia River. The storage tanks contain a liquid supernate, salt cake, and sludge; is highly caustic (>10M Na); has moderate radioactivity (~176 million curies total); has textures similar to wet salt, salt lick, peanut butter, heavy sand, gravel; has properties that vary from tank to tank; and may produce hydrogen bubbles. Storage tanks sizes range from 55,000 to 1.2 million gallons.

The waste would be mobilized in the Tank Farms, and transported to the WTP as low-activity waste and high-level waste streams. At the WTP, the waste undergoes several unit operations, including caustic and oxidative leaching, ultrafiltration, and cesium ion exchange. The waste is intended to be ultimately vitrified and stored in stainless steel containers for disposal. The construction and commissioning of the WTP is expected to be finished in 2018, and the operation of the plant is expected to continue for decades. The plant contains 18 “black cells” where the equipment is designed to operate maintenance free without any moving mechanical parts and is not designed to be replaced.

Waste will be sampled in the staging tanks at Tank Farms prior to transfer to the WTP. The waste will be analyzed for physical and chemical properties of interest, such as slurry density, Na molarity, Pu concentration, etc. Uncertainty with the sample exists because of the staging tank mixing capability, limited sample collection points, and segregation of solids. The sample collection from the storage tanks is very expensive. Furthermore, much of this waste is going to stay stored in these tanks for decades before it is even treated at WTP. The slurries can have non-Newtonian characteristics; produce sludge piles with trapped hydrogen along with gels and foams. Highly accurate data generated under a sub-scale experimental program and models that could address some of these issues would be extremely valuable now and in the future.

The main need for data and modeling is in the area of mobilization, mixing, and transport of non-Newtonian slurries. The yield stresses of tank waste can vary by 2 orders of magnitude, and at this time there is no ability to assess the sources of this variability. On-line sampling methods do exist, however, dependence on the waste properties and vessel operations have resulted in open technical issues. The mixing performance by the PJM's in the non-Newtonian vessels is not fully understood. The effect of the periodic mixing by PJM's on solids mobilization, leaching, hydrogen gas release, and in-tank instruments needs to be studied. Data generated under prototypical conditions in sub-scale experiments combined with modeling will help provide confidence in WTP PJM vessel design and instrumentation prior to full-scale testing efforts, as well as, provide confidence in the ability of the non-Newtonian PJM vessels to address such critical safety issues as particle accumulation that may cause unsafe levels of hydrogen or criticality. There is also potential attrition or particle to particle degradation due to continuous mixing and pumping. This may reflect in an increase of fines and higher viscosity, change to yield stress.

2.3 Topic Areas

The workshop brought together a group of experts with expertise in modeling and experimentation in diverse fields that are relevant to NNMS flows. During the first day the workshop was kicked off with three short presentations focused on engineering [1], experiments [2] and modeling [3] relevant to NNMS flows. After the presentations, the participants were split into three groups that independently discussed the two workshop topics. The discussions resulted in identification of technical gaps in our current knowledge for which solutions in the form of future R&D efforts were proposed by the experts. These technical gaps and the subsequently proposed solutions are captured in this technical report. The two main topics of discussion are as follows:

Topic 1: State-of-the-art in non-Newtonian Multiphase Slurry Flows:

The groups sought to ascertain the current state of the art in the understanding of NNMS flows. The discussion focused on identifying current state-of-the-art in experimentation and instrumentation techniques for the mixing and transport of NNMS with the aim of leveraging from what is already known in other similar fields, such as waste treatment facilities, liquid-solids fluidization, slurry reactors in chemical processing, ore separation in mining, pulp and paper process modeling, etc. Identified subtopics are as follows:

a) What steps need to be taken to increase our understanding of NNMS?
b) What predictive theories are available for NNMS flows?
c) What kind of sensors and measuring probes are needed or available?
d) Can we change the rheological behavior of non-Newtonian slurries?
e) Can we use Newtonian fluids to understand and bound non-Newtonian behavior?

Topic 2: Scaling up and long term operations

The groups tried to define the lab and bench scale tests needed to better understand the rheology, transport and mixing of NNMS, and address issues associated with the scaling up of these tests to real world applications (e.g., WTP pulse jet mixing vessels). The group addressed how the data and models obtained from testing and the data collected during the long-term operation can be combined to ensure safe and reliable long-term operation of black cells. Subtopics are as follows:

a) What is the accepted practice in scaling for NNMS?
b) How can we simulate the Hanford nuclear waste and account for that uncertainty in an experimental test plan (PSDD and chemistry)?
c) Is there a need to maintain a testing facility during plant operation to test for off-normal conditions or for troubleshooting?
d) What kind of monitoring is needed at WTP and how will the data be used for control and troubleshooting during plant operation?
e) What are the existing industrial experiences useful for black-cell operations?

During the second day results from the individual break-out sessions were presented and discussed among all the participants in a large group. Primary topics were further discussed and resources were identified. The consolidated comments from the two breakout sessions and the large group session are presented below.

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3 TECHNICAL DISCUSSION

3.1 Topic 1a: What steps need to be taken to increase our understanding of NNMS?

3.1.1 Background

The waste at the Hanford site and at other nuclear waste sites is a highly complex mixture of heavy metals, radioactive materials, and very toxic and corrosive chemicals. The hazardous environment poses severe impediments to comprehensive qualification of the waste. For the WTP under construction at Hanford site, the rheology of the waste undergoes several changes due to combination of chemical processes and desired plant design. The design of several vessels (such as, Ultra-filtration, HLW lag storage vessels) calls for concentrating the waste stream. The increased loading of fines in the concentrated waste transforms the rheology of the waste to non-Newtonian. In addition to the rheology transformation by fines, the handling of waste is further complicated due to the wide particle size and density distribution (PSDD) of the waste particles. As shown in Figure 5, the large and/or dense particles do not remain suspended in the slurry and, if not agitated periodically, separate out forming sludge banks at the bottom of the vessel. To emphasize the presence of separating particles or PSDD in the non-Newtonian slurries at Hanford and other DOE-EM sites, they are referred to as non-Newtonian multiphase slurries (NNMS).

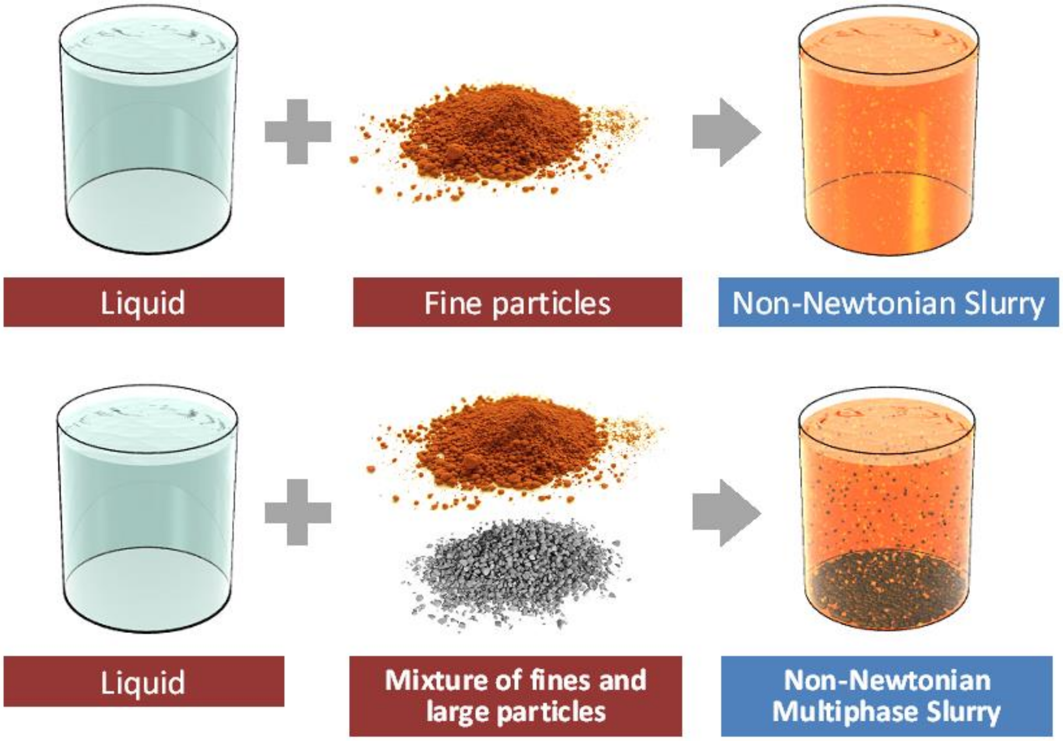


Figure 5: Schematic showing difference between non-Newtonian and non-Newtonian multiphase slurries

The design of mixing vessels fed by NNMS is a challenging prospect due to the complex hydrodynamics of such flows further compounded by radioactive chemistry. The current design at WTP is based on PJM mixing vessels wherein the bottom scourging and re-suspension of particles is achieved by impinging jets on the vessel bottom. Upon impinging the vessel bottom, the jets travel out as radial wall jets which produce shear stress and turbulence responsible for entraining the settled solids. The interaction of radial wall jets from different PJMs forms stagnation regions and an upward flow (upwash) that is responsible for re-suspending the settled solids. Based on the several testing campaigns for NNMS fed PJM vessels, the power produced by PJMs was found to be insufficient to ensure the well suspended state of the waste in the entire mixing vessel, which was addressed by the introduction of air spargers in the middle region of the NNMS PJM vessels. The mixing vessels have to be designed to satisfy several mixing requirements derived from a combination of safety concerns and process designs. Confirming the design of PJM vessels at WTP that satisfies all the mixing requirements has proven to be an onerous task, and especially severe for heavily loaded Newtonian and NNMS fed mixing vessels.

Under this topic, the experts discussed ways to enhance our understanding of NNMS that can be used in the design of devices for their storage, transport, and mixing. The experts discussed the critical technical issues currently plaguing the WTP project to develop an appreciation for the complexity of the problem in a real world application. Although the discussion centered on WTP, the issues identified in this report and the recommended possible steps are general enough to increase our understanding of NNMS and the knowledge gathered can be leveraged in any application handling NNMS.

3.1.2 Challenges and Technical Gaps

- **Lack of Waste Qualification:** Lack of confidence in the current available data for actual Hanford waste was identified as a major data gap. The waste exhibits a very wide particle size distribution (shown in Figure 6) with particle size ranging from submicron particles to 1 mm sized particles along with a whole gamut of particle shapes. The availability of limited data on actual waste makes it very difficult to engineer representative waste simulants. Several concerns were noted by experts with regard to waste simulant. For example, there was concern if the cohesive nature of the sedimentation layer formed by actual waste is captured by the waste simulant. The cohesive nature of waste further complicates the design of WTP vessels due to the agglomeration and breakup effects. The agglomeration of waste particles due to cohesive or other forces was identified as a concern that might not be accurately mimicked in the waste simulant due to the lack of information on the exact nature of driving mechanisms behind inter particle interactions leading to non-Newtonian rheology.

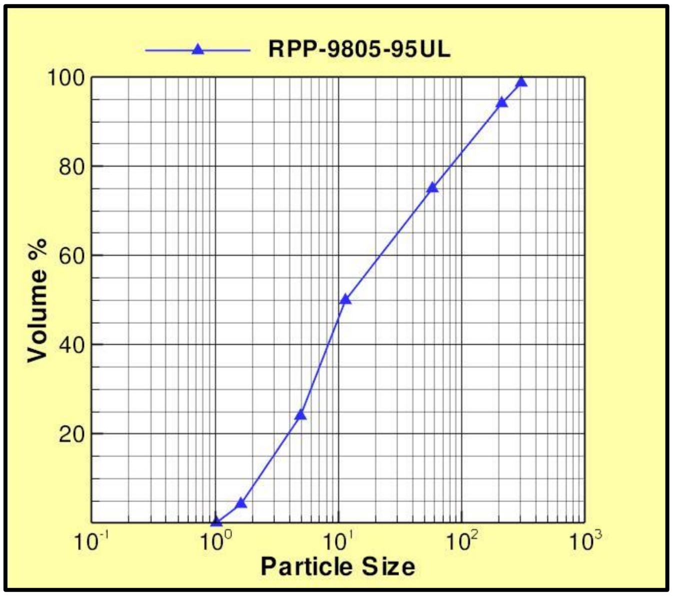


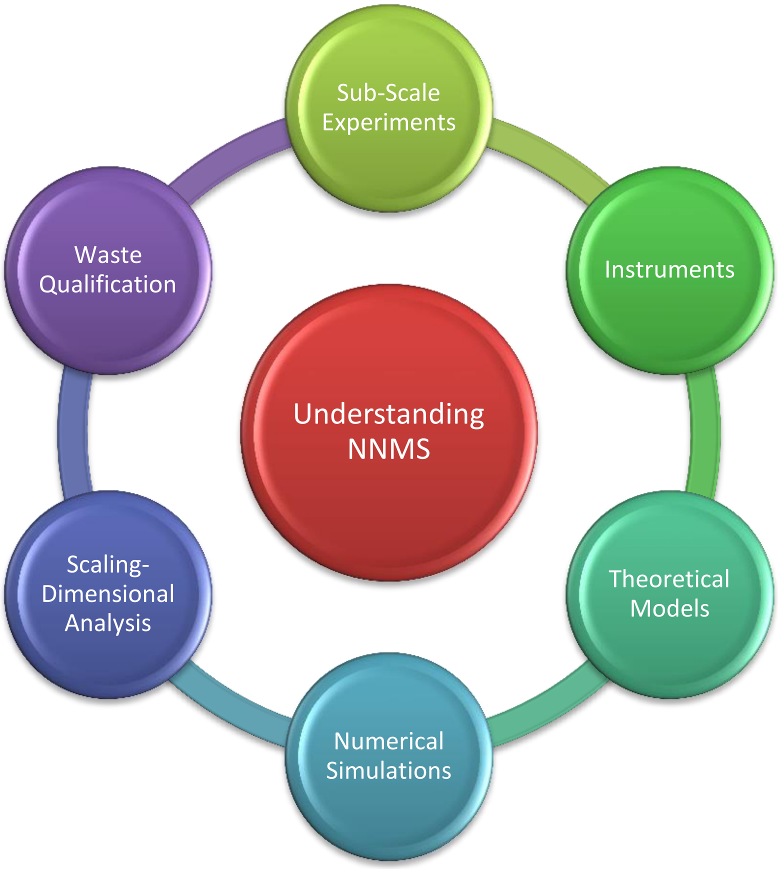
Figure 6: The cumulative distribution function of the particle size (microns) in Hanford waste. Nearly 50% of waste has particles under 11 micron and 75% of waste has particles under 60 micron.

Attrition of larger particles (typically>65 microns) can be a factor producing more fines over time and higher viscosity and yield stress. Since the yield stress is time dependent due to various chemical reactions occurring during WTP processes, lack of incorporation of time-varying rheology in waste simulant was identified as a concern. Due to the non-radioactive nature of the waste simulant, several of the key safety issues (such as, hydrogen gas release rate, criticality) cannot be addressed using the waste simulant. Experts questioned the reliability or extensiveness of past testing that led to the conclusion that waste particles remain suspended at 6-30 Pa yield stress conditions. This conclusion has a major influence on the interpretation of mixing in a NNMS vessel and experts emphasized the need to review the data to verify this conclusion. Experts also expressed concerns over how well this assumption holds when off-normal events are taken into account.

- **Lack of Understanding of Off-Normal Conditions:** The experts were also concerned about the off-normal conditions (such as, power outage) and noted that their effects on PJM performance should be understood as best as possible given the black-cell operating nature of WTP plant. PJM failure also created concerns during discussions on the impact such an event has on settling rates and the ability for particles in a NNMS under 6-30 Pa yield stress conditions to remain suspended. There was also concern about the magnitude and rate of development of yield strength in the non-agitated settled slurry and the ability of PJMs to re-suspend high yield strength materials. The level of instrumentation of black-cells was also identified as a concern which is discussed in more detail under Topic 1c: *What kind of sensors and measuring probes are needed or available*? In addition to the issues identified above, the experts were concerned with the effect of non-Newtonian slurries on erosion and corrosion, hydrolysis, foaming, and interfacial phenomena.
- **Lack of Advanced Theories for non-Newtonian Multiphase Slurries:** The experts discussed the theoretical perspective of the problem as well. The experts agreed that the current theory is not able to accurately model the non-Newtonian multiphase slurries. For example, the current models cannot handle the transition of suspended solids from liquid-like behavior to solid-like behavior, and identified a critical need to develop stress models spanning sludge, cake, and suspended solids. Furthermore, there is no general model that allows transition from turbulent flow near PJM nozzles to Stokes flow far from the PJMs. There was a concern with the application of theoretical models to large-scale real vessels that is further discussed in Topic 1b: *What predictive theories are available for non-Newtonian multiphase flows?*

3.1.3 Proposed Solutions

Given the general nature of this topic, the discussion was on a very high level and identified major elements that require development in order to better understand and successfully design NNMS flow applications. These elements are shown by the schematic in Figure 4 and shown again here. Several of the elements identified in the schematic are discussed in detail under their own dedicated topic and are briefly summarized below:



- **Waste Qualification:** According to experts, one of the first steps in any such exercise should be comprehensive qualification of actual waste's properties, such as, waste rheology, waste PSDD, waste chemical make-up, etc. A reliable waste qualification will provide increased knowledge needed to develop waste simulants for testing purposes that bounds the actual waste in terms of critical parameters, such as, settling rates, yield stress, cohesive properties, etc. This was identified to be a high priority task. In addition, clearer definition of waste will lead to more fruitful collaboration with industry for new equipment development. During the discussions emphasis was placed on the need to leverage current waste transfer efforts from single to double wall storage tanks. Experts felt that these efforts should be done in conjunction with sampling and analysis to significantly reduce the uncertainty in qualifying the waste characteristics.
- **Detailed Experimental Plan:** One theme concurrent to all breakout sessions was the need for a detailed experimental effort leveraging the state-of-the-art in instrumentation technology (both non-intrusive and in-situ) that can be exploited to quantify and characterize the flow and compositional fields as thoroughly as possible. Any experimental effort should span scales ranging from bench-scale to full-scale and include testing under normal and off-normal conditions. The flow field should be comprehensively characterized under a variety of operation conditions and include uncertainties in particle properties arising from wide PSDD and, if possible, from radioactive chemistry as well. Since such an exercise is intractable at full scale, testing in sub-scale vessel geometries that are geometrically similar to full-scale vessel, and which use simulants and operating conditions selected on the basis of dimensional analysis to

achieve optimum similitude with the full-scale vessel operating with real materials, was recommended. The experts agreed that dimensional analysis is needed to develop an appropriate set of non-dimensional groups that characterize the problem, combined with an appropriate analysis and sub-scale testing to identify leading order parameters of the target application. The leading order parameters will guide the design of the sub-scale experiments including the selection of the simulant properties, flow rates, time scales, etc. to ensure maximum similitude with the actual process at full scale. This was also identified to be a high priority task with the understanding that an experimental campaign of this nature would be continued over the long term. The detailed experimental plan will increase the knowledge required for successful design of applications handling non-Newtonian multiphase slurries in addition to providing data points that can be exploited for scale-up, aid in safety, process control, and inform model development driven experiments.

- **Advanced Instrumentation:** The experts recommended a step-by-step procedure beginning from identification of data needs to appropriate review, selection, and accuracy quantification of instrumentation. Advanced instrumentation, such as, acoustics, ultrasound, MRI, PIV, etc., were mentioned as possible techniques for complete characterization of the flow field. Under the scenario of inadequate instrumentation for critical data needs (such as solids build-up), the experts recommended development of new instrumentation techniques by testing them out in well controlled sub-scale experiments.
- **Model-Development Driven Experiments:** Since the current theory is found to be lacking and as a result modeling limitations exist in the ability to predict NNMS flow behavior, the experts recommended a model-development driven experimental plan to fill critical gaps and advance current theories. According to experts, sub-scale experiments are well suited to understand the time varying waste rheology due to chemical processes. Among other phenomena of interest, the time varying rheology testing could be used to test the effect of cohesive particles and agglomeration in the design of mixing vessels. The experts concurred that the extensive data obtained from such comprehensive experiments should be used to develop theoretical models for suspension, sludge formation, and liquid-solid transition of waste particles. Any such model-development driven experimental campaign of carefully designed experiments should ideally span scales, incorporate waste uncertainty, capture time dependent rheology, and leverage on state-of-the-art in measuring techniques.

Additional Reading

1. *MCE, PNNL, Monarch Machine (tank farm support, Energy Solutions), Coanda, CalTech rheological measurements,*
2. *Society of Rheology Meeting in October to assess expertise, University of Delaware, P&G*
3. *Limited capability and availability to analyze hot sample (2-3 locations available).*
4. *WTP-RPT-095, Rheological and Physical Properties of AZ-101 LAW Pretreated Waste and Melter Feed*
5. *WTP-RPT-043, Filtration, Washing, and Caustic Leaching of Hanford Tank AZ-101 Sludge*
6. *RPP-6548, Test Report, 241-AZ-101 Mixer Pump Test*
7. *BNFL-RPT-038, Characterization, Washing, Leaching, and Filtration of AZ-102 Sludge*
8. *WTP-RPT-004, Rheological Studies on Pretreated Feed and Melter Feed from C-104 and AZ-102*
9. *BNFL-RPT-030, Characterization, Washing, Leaching, and Filtration of C-104 Sludge*
10. *BNFL-RPT-021, C-104 High-Level Waste Solids: Washing/Leaching and Solubility Versus Temperature Studies*
11. *WHC-SD-WM-ER-588. Tank 241-C-106 Sluicing Evaluation*

12. *BNFL-RPT-017, C-106 High-Level Waste Solids: Washing/Leaching and Solubility Versus Temperature Studies*
13. *WSRC-TR-2003-00240, Filtration of a Hanford AY-102/C-106 Sample*
14. *PNNL-11381, Washing and Caustic Leaching of Hanford Tank C-106 Sludge*
15. *WTP-RPT-167, Characterization and Leach Testing for PUREX Cladding Waste Sludge (Group 3) and REDOX Cladding Waste Sludge (Group 4) Actual Waste Sample Composites*
16. *WTP-RPT-169. Characterization, Leach Testing, and Filtration Testing for Tributyl Phosphate (TBP, Group 7) Actual Waste Sample Composites*
17. *WTP-RPT-170, Characterization, Leaching, and Filtration Testing of Ferrocyanide Tank Sludge (Group 8) Actual Waste Composite*
18. *WTP-RPT-166, Characterization, Leaching, and Filtration Testing for Bismuth Phosphate Sludge (Group 1) and Bismuth Phosphate Saltcake (group 2) Actual Waste Sample Composites*
19. *WSRC-TR-2004-00394, Hanford HLW AY102/C106 Pretreated Sludge Physical and Chemical Properties Prior to Melter Feed Processing*
20. *BNFL-RPT-002, Ultrafiltration and Characterization of AW-101 Supernatant and Entrained Solids*
21. *Correspondence 9101055, Results of the Analysis of the Large Chuck of Material and the Measurement of the Miller Number for DST 101-AZ Core #3 Waste*

3.2 Topic 1b: What predictive theories are available for NNMS flows?

3.2.1 Background

Overview of Multiphase Flow Theory and Modeling

The computational fluid dynamics (CFD) of Newtonian multiphase flows is a matured science with availability of several different theoretical models and numerical simulation tools [4,5]. The CFD models of multiphase flows involving dispersed solids in liquids or gases fall into two broad categories. As shown by the schematic in Figure 7, in the first category, continuum representation is used for both the carrier phase liquid and the disperse phase solid particles. In the second category, while the carrier phase liquid is still treated as continuum, the dispersed phase particles are represented as discrete entities whose trajectories are followed in a Lagrangian frame of reference. The first category is generally referred to as Two-fluid or Multi-Fluid or Eulerian-Eulerian model in the literature. Likewise, the second category is referred to as, continuum-discrete, Eulerian-Lagrangian, etc. In this report Eulerian-Eulerian (E-L) and Eulerian-Lagrangian (E-L) will be the preferred terminology.

Figure 7 lists several different simulation techniques under each category. Although grouped under broader categories of E-E and E-L, these simulation techniques under each category differ quite significantly with each technique having its own advantages and limitations relative to other techniques based on requirements on computational resources and range of applicability. For example, the Two-Fluid-Model (TFM) [4,6,7] under the E-E category is based on solving average Navier-Stokes like equations for each phase augmented by inter-phase interaction terms. Under the same E-E category, Quadrature based methods [8-10] and the Lattice Boltzmann Method (LBM) [11-13] do not solve Navier-Stokes equations. While the LBM solves for the evolution of the single-particle distribution equation referred to as the Boltzmann equation (that reduces to Navier-Stokes equation under the continuum hypothesis), the Quadrature based methods solve for the moments of the single-particle distribution equation [14].

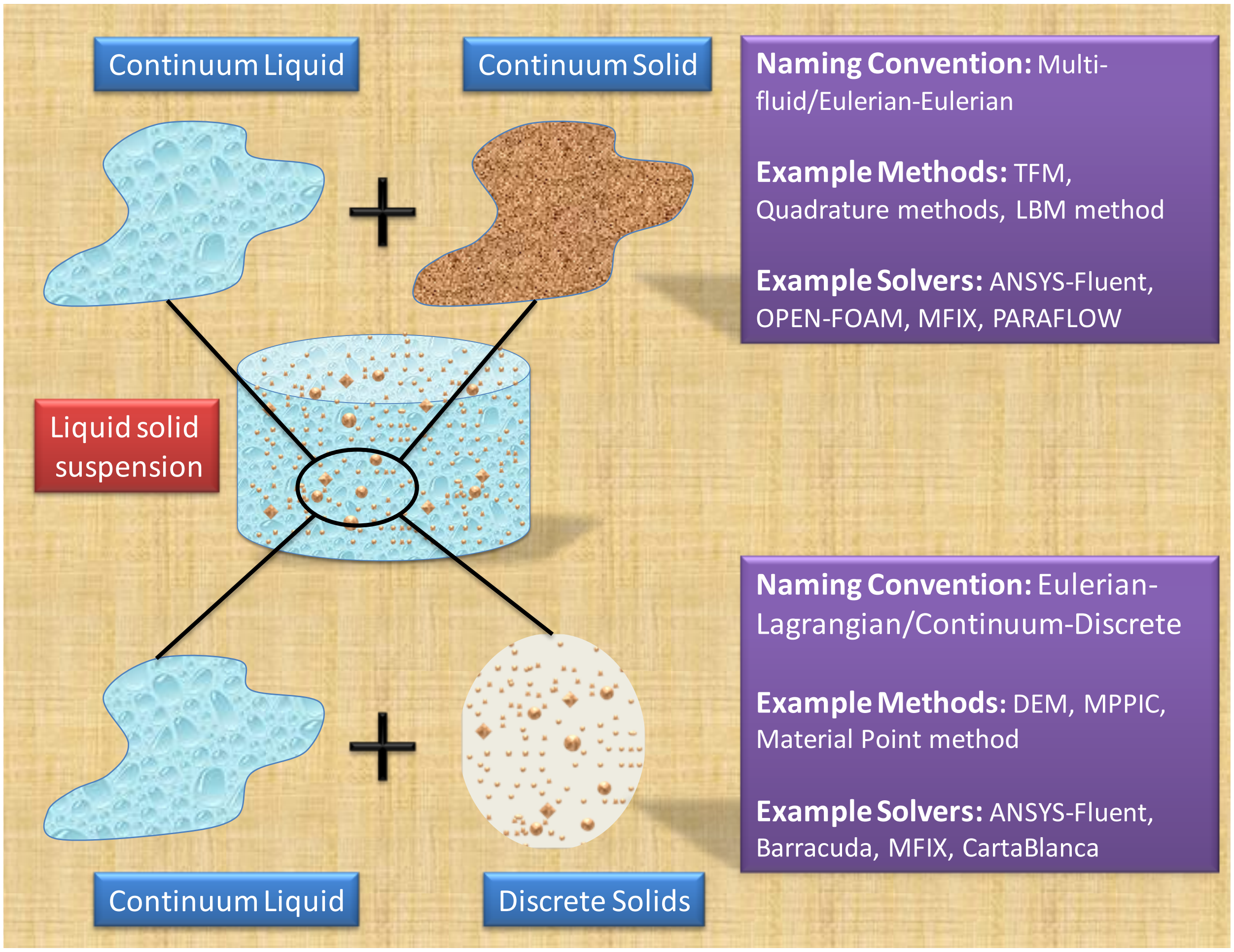


Figure 7: The different treatment for solids phase in current multiphase flow models

For the various methods listed under the E-L [6,15] category, the differences between methods lie in the level of details of the solid-phase and the subsequent modeling requirements. The DEM model represents the solid phase by spherical particles with the number of particles determined by the solids loading and resolves every particle-particle collision using hard-sphere (dilute regimes) and soft-sphere (dense regimes) algorithms. Other inter-particle interactions (such as, cohesive forces, electrostatic forces, etc.) can be naturally incorporated as well. In the MPPIC [16] and Material Point Method (MPM) methodology [17,18], parcels or notional particles are used to statistically describe the solid-phase, wherein each parcel represents more than one real particle. Although the statistical representation of solid phase by parcels representing more than one particle reduces the computational cost of MPPIC or MPM methodologies, it has the drawback that particle-particle interactions cannot be easily incorporated and need to be modeled. Additionally, MPM's framework is not well suited to add a background fluid unlike other Lagrangian tracking methods, such as DEM and MPPIC.

Each of the modeling technique has its own advantage and limitations and a detailed discussion is beyond the scope of this report and the readers are referred to several references listed at the end of this report. The choice of a particular technique is based on the target application and in many cases multiple techniques could be applied to the same application. Below the E-E and E-L categories are briefly compared.

Comparison of E-E and E-L

- E-E methods are amenable to scaling up on parallel computers because very efficient domain decomposition strategies exist for its underlying Eulerian grid. E-L methods are relatively more challenging to scale up on parallel computers because of the use of discrete entities.
- The DEM methodology under E-L, albeit the most expensive of the techniques mentioned, is an excellent tool to develop and test closure models for interaction terms needed in other methodologies. DEM can predict the behavior of a powder (spherical or not) over a wide range of flow conditions. The DEM approach, when carefully V&V'ed for a particular application, is a source of very detailed data not readily obtainable from experiments due to which DEM is often used as a numerical experiment to develop or validate rheological models for the continuum approach. Therefore, DEM methodology is a valuable tool in any toolkit for multiphase flow CFD simulations.
- Eulerian methods suffer from diffusion of sharp interfaces while Lagrangian methods are meshless and, therefore, diffusion free.
- All the E-L methods (DEM included) suffer from statistical noise arising from the use of a finite number of particles/parcels to estimate field variables, which could affect the stability of these methods. Therefore, any use of E-L method should be preceded by careful V&V process and uncertainty quantification.
- Unlike DEM, all types of particle-particle interactions cannot be directly incorporated into E-E models, and need to be modeled.

Overview of non-Newtonian Multiphase Flow Theory and Modeling

Although the Newtonian fluid model has been widely accepted as a standard in modeling fluid behavior for wide range of applications and has reached a respectable level of maturity, many real multiphase flow applications are far from being classified as Newtonian, and as a result, pose modelling challenges and defy predictability. Even simple non-Newtonian-fluid experiments cannot be explained (even qualitatively) by Newtonian fluid models [19]. There has been an increasing recognition that most materials encountered in wide range of practical and industrial interests do not confirm to the simple Newtonian fluid behavior, and are collectively referred to as non-Newtonian fluids.

The liquid slurry encountered in WTP waste tanks could be non-Newtonian. The non-Newtonian nature of the liquid-phase arises from the presence of "fines" or colloidal particles in the liquid phase. These small particles follow the motion of the fluid and will not settle even when the fluid is quiescent for long periods of time (in the event of a power failure, for example). Before going further into the discussion of predictive theories for non-Newtonian fluids, a quick overview of various classifications of non-Newtonian fluids is provided below.

The non-Newtonian rheology is generally classified under three categories based on the behavior of the shear stresses. The first category is time independent for which the shear stress is dependent only on the shear rate or vice-versa. Such fluids are also referred to as generalized non-Newtonian fluids. Under the second category of time-dependent, the shear stress and the shear rate is a function of the duration of shearing, kinematic history, etc. Under the third category of visco-elastic fluids, the materials exhibit the dual characteristics of both an elastic solid and a viscous fluid.

The first category of time-independent behavior can be further classified as shear-thinning or pseudoplastics, viscoplastics, and shear thickening or dilatant fluids (cf. left panel in Figure 8). For the shear-thinning or pseudoplastics, the apparent viscosity (defined as the ratio of shear stress and shear rate) decreases with increasing shear rate, while the inverse relationship holds for shear-thickening or dilatants fluids. Viscoplastic fluids are characterized by the presence of a yield stress that delineates between the solid-like and fluid-like behavior of the material. Once the yield stress is overcome, the flow curve (stress vs. strain relationship) may be linear or non-linear. Viscoplastic fluids displaying a linear stress vs. strain relationship are generally referred to as Bingham plastic fluids [20] that are characterized by a constant value of plastic viscosity.

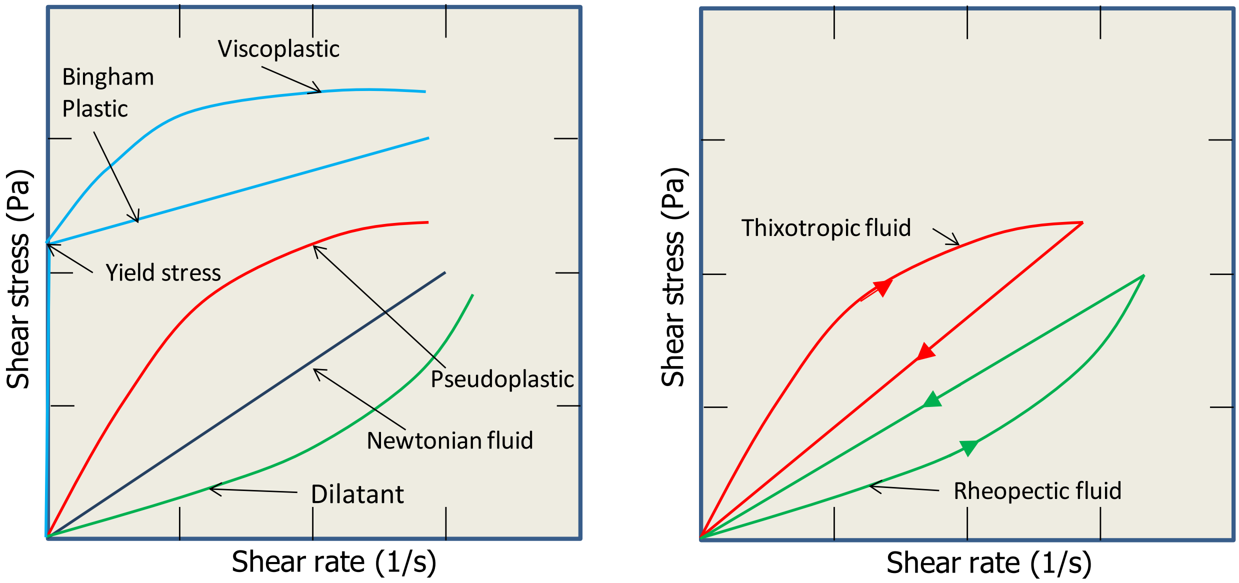


Figure 8: Comparison of qualitative rheograms for different types of non-Newtonian fluids under the broader categories of time-independent (left) and time-dependent (right) rheologies.

Similar to the distinction made on the basis of stress-strain relationship for time-independent non-Newtonian fluids, further classification is adopted for time-dependent non-Newtonian fluids. They are classified as thixotropic and rheopectic fluids (cf. right panel in Figure 8). Thixotropic fluids (examples, some clays, drilling muds in geotechnical applications) are similar to shear-thinning fluids under the time-independent category, only that here the apparent viscosity decreases with time when sheared at a constant shear rate. If the shear rate is steadily increased at a constant rate from zero to maximum value, and then decreased at the same rate to zero again, it results in the hysteresis loop as shown by the qualitative rheograms in Figure 8. Rheopectic fluids, on the other hand, exhibit an inverse relationship (i.e., the apparent viscosity increases with time when sheared at a constant shear rate) and are much less common.

It should be noted that although the above classifications help to classify different non-Newtonian fluids, a same fluid might not be constrained to a specific behavior and exhibit stress-strain relationships characteristic to other types of non-Newtonian fluids. Thixotropic fluids sometimes display a purely viscous behavior, while simple yield-stress fluids have been shown to have elastic properties in both the fluid-like and solid-like regimes. Testing at Hanford showed that the slurry had a yield stress and was shear-thinning once flow began. The fines exhibit colloidal behavior, which can range from Newtonian at low volume fraction of fines to thixotropic, and more complex at volume fractions nearing maximum packing [21]. For example, at 50% volume fraction, colloids exhibit yielding behavior at low shear rates, shear-thinning at moderate shear rates, and shear-thickening at higher shear rates [21].

Such wide behavior of a material can be modeled through a Generalized Newtonian rheology model based on constitutive equations that is capable of capturing yield stress, thixotropy, and shear-thinning [43,44] and even particle resuspension [45] without resorting to an additional stress tensor [46]. In the generalized Newtonian rheological model, the stress is still related to the shear rate in a linear fashion, but here the viscosity is no longer constant. A generalized Newtonian rheological model is most desirable to describe the macroscopic rheology of the Hanford slurries but can be completely described only upon comprehensive testing of the actual waste that can be used to obtain model parameters. Therefore, the experts recommended starting with simplified rheological models (such as Bingham plastic fluid model for viscoplastic fluid and Herschel–Bulkley model for shear-thinning viscoplastic fluids) and gradually increasing the level of physics modeled by the macroscopic rheological model.

The non-Newtonian behavior of the non-Newtonian slurries at Hanford is due to the presence of fine particles in the waste fluid. In addition to the fines causing non-Newtonian rheologies, as shown by the schematic in Figure 5, the waste at Hanford becomes rheologically even more complex due to the presence of fast settling particles, the presence of which have motivated the term "non-Newtonian multiphase slurries (NNMS)" in this report. According to experts, an ideal NNMS model for PJM applications will involve tracking of supernate along with separate tracking of the particles based on the PSDD from waste qualification data. The binning or discretization of waste particle size distribution can be modeled after the waste simulant design efforts at Hanford WTP. In such a model tracking all phases, advanced solids stress models will be required such that their interaction with carrier liquid yields the non-Newtonian behavior characteristic to Hanford NNMS. Some of the requirements of solid-stress model will be to accurately predict fluid-like, transitional flow (re-suspension and settling), and solid-like behaviors of waste particles as they get lifted off the vessel bottom during PJM drive phase to their settling to form sludge banks during PJM suction phase. The experts agreed that the current state-of-the-art does not allow one to readily assemble such a model due to the lack of advanced theories, constitutive relations, and numerical tools. The experts agreed that relatively less work has been done in the area of NNMS, unlike Newtonian flows.

Although the experts assigned high priority to R&D efforts aimed at developing an ideal NNMS flow model, recognizing the lack of the current state-of-the-art, the experts also suggested several alternative models to simulate NNMS flows with varying levels of underlying assumptions that should be pursued in conjunction with the above R&D efforts. Of the many ideas that were discussed at the workshop, one idea that found traction with many experts was to consider the supernate liquid and suspended fines as a homogeneous mixture that could be modeled as a single-phase non-Newtonian fluid assuming its rheological behavior is known or can be measured. Due to the intrinsic ability of non-Newtonian Hanford slurries to hold up suspended particles, the experts argued that the assumption of homogeneous mixing is not far from reality, and in addition, such a treatment could benefit from the vast literature on experiments and numerical modeling of mixing of non-Newtonian slurries often encountered in many chemical, biochemical, and mining applications.

A generalized Newtonian rheological model based on constitutive equations is needed to model complex dependence of Hanford slurries on shear stress. A constitutive equation based macroscopic rheological model is ideally suited to be implemented into CFD models unlike other models requiring changes to the stress tensor. The development of such a generalized model will require rheological analysis of existing data on testing of Hanford slurries in order to obtain model parameters. While such model is under development, the experts recommended viscoplastic fluids (shear-thinning fluids with yield stress, such as the Herschel-Bulkley fluid model) to be a good starting point to model Hanford slurries. The larger sized particles making up the solid waste will be tracked as separate phases and add to the list of challenges in modeling NNMS flows. To overcome the numerical instabilities caused by the Herschel-Bulkley model due to very high viscosity (approaching infinity) at small shear rates, the upper end of the viscosity is constrained to a user-specified high value. Research of single phase viscoplastic fluids [22-25] has been actively pursued due to their wide usage in many industrial and biological applications and processes. This wide body of past work on viscoplastic fluids has been comprehensively reviewed in a recent review article by Balmforth, Frigaard, Ovarlez [26]. The authors have identified the current state-of-the-art in modeling, experiments, and theoretical analysis of viscoplastic fluids and concluded with their prescription for future R&D efforts deemed necessary for increasing our understanding of these flows. Taking a step further, the technical gaps identified during the workshop in the current state-of-the-art for modeling of NNMS flows are discussed in the next section.

3.2.2 Challenges and Technical Gaps

The complexity of the physics and the wide range of scales within WTP make it difficult to predict the behavior of NNMS flows. The flow behavior ranges from possible stagnant regions, to slow-moving laminar zones, to high-speed turbulent jets. A theoretical description that spans this range of behavior does not currently exist and will need to be developed. These models need to be transient and predict small and long-term behavior in large geometric scales. The developed models must go through a rigorous validation process in order to ensure that the predictions obtained over a wide range of time- and length-scales are accurate. Some of the most significant challenges and critical gaps are discussed below in detail:

- **Multiphase Turbulent Flows:** Single-phase turbulence in Newtonian flows has received a lot of attention and mature theoretical and numerical tools exist to model and simulate such flows [27,28] for a wide array of applications. The turbulent multiphase flows, complicated by the presence of hard-to-quantify interactions between phases, are also a widely pursued research subject [29-31]. Due to the stochastic nature of turbulence in multiphase flows emanating from both the carrier-phase turbulence and from the interaction of dispersed phase particles with the carrier phase (also sometimes referred to as pseudo-turbulence) [32-35], the problem of turbulent multiphase flow is far more complex than its single-phase counterpart. Quantification of pseudo-turbulence (carrier phase velocity fluctuations due to dispersed phase) has been mostly limited to sub-Kolmogorov [31,36-38] scales and only recent studies have extended such analysis to large particles [32,35] using Particle-Resolved Direct Numerical Simulations (PR-DNS)

  Traditionally, carrier-phase velocity fluctuations were neglected in CFD simulations of multiphase flows until their importance was made evident by carefully conducted experiments and the observation of considerable uncertainty in the predictive capabilities of multiphase CFD simulations. This led to the development of one-equation model [34], followed by two-equation model [33], and then followed by more sophisticated *k*-*ε* model [39,40]. It should be noted that these models are basically extended versions of single-phase *k*-*ε* models modified to be used in gas-solids flows, and by design, are limited to very dilute regimes only. Recent numerical studies using PR-DNS have attempted to quantify carrier-phase Reynolds stress for higher solids loadings as well [41,42]. A matured turbulence model incorporating both carrier phase turbulence and pseudo-turbulence (due to dispersed phase) still remains elusive, even for multiphase flows with a Newtonian carrier fluid.

For the non-Newtonian fluids, a quick literature search brings up hundreds of studies on turbulent channel flows devoted to the study of Toms effect [43], which is the observation of large reduction in frictional drag in pipes and channels upon the addition of minute amounts of a polymer to the flow. In such dilute polymer flows, shear-thinning behavior is unimportant and visco-elastic effects are dominant. However, for a wide range of important materials (including non-Newtonian slurries at Hanford), the non-Newtonian rheology is primarily due to the presence of shear-thinning and yield stress. Therefore, it is not relevant to discuss all the modeling and experimental studies of turbulent non-Newtonian flows in the context of Toms effect as the visco-elastic effects are not expected to be dominant in NNMS flows at Hanford. There have been a few published CFD investigations of the turbulent flow of power-law and viscoplastic fluids [44,45] that clearly show very different turbulence behavior due to the complex rheologies of non-Newtonian fluids. From the spectral element based DNS simulations of power-law and viscoplastic fluids, Rudman et al. [45] compared results for a power-law fluid to those of a yield stress (Herschel–Bulkley) fluid at the same generalized Reynolds number and found that the yield stress significantly dampens turbulence intensities in the core of the flow in turbulent channel flows.

In terms of NNMS flows at Hanford, the experts concluded that relatively very little work has been done or underway to develop turbulence models. It is widely accepted that yield stresses retard the transition to turbulence until Reynolds stresses are able to yield the fluid [46], and interesting coherent structures have been observed in turbulent viscoplastic shear flows [47,48]. The problem of developing turbulence models becomes even more challenging due to various subtypes in non-Newtonian fluids that oftentimes warrant an independent analysis. Since the flows in PJM vessels are very turbulent by design, lack of reliable turbulence models for NNMS flows was identified as a major technical gap.

- **Lack of Constitutive Models:** The experts cited various examples where the constitutive models required for CFD simulations are either not available or are deficient for non-Newtonian flows. One major area of concern for the experts is related to models for inter-phase momentum exchange term, generally referred to as drag force term in the literature. Past CFD simulations of Newtonian multiphase flows [6,49] have been found to be very sensitive to the choice of the drag correlation. Likewise, the choice of drag correlations will affect the predictive capability of multiphase non-Newtonian flow models.

  Drag force model development for non-Newtonian flows has been addressed in many studies over the last few decades, albeit not on the same scale as Newtonian drag model. A review book by Chhabra [50] provides an excellent summary of research activities in the last few decades that were aimed at developing a drag force model for non-Newtonian fluids. For time independent fluids without yield stress (i.e., pseudoplastic and dilatant fluids in Figure 8, collectively referred to as power-law fluids), most of the reliable data is either in the creeping flow regime or flow past a single sphere or cylinders in cross-flow. A single correlation proposed by [51] reconciles most of the literature data on spherical and non-spherical particles falling in Newtonian and power-law fluids for Reynolds numbers up to 200, and it should be noted that since the non-Newtonian effects manifest much more in the low Reynolds number region, it has been hypothesized that one can use the standard Newtonian drag curve for Reynolds numbers in the range of 1 to 1000 with an accuracy of ±30%, and it is noted that the maximum errors of even 100% are possible [50] due to this simplification.

For the viscoplastic fluid models, the majority of studies center on steady creeping flow past a sphere. One unique characteristic of viscoplastic fluids is the co-existence of yielded and unyielded regions due to the presence of yield stress. Lack of a priori information on the structure of yielded and unyielded regions does not allow for a straightforward theoretical analysis of the flow, even in the creeping flow regime. Quantitative flow visualizations were obtained through optical techniques [52,53] that were used as a basis to later verify theoretical [54] and numerical models [55,56]. A drag force correlation [57] expressed as a function of Bingham number and Reynolds number provides a fair to moderate correspondence between experiments and various models for the creeping flow regime as long as the yield stress is evaluated consistently. Although a large body of experimental data for flow conditions beyond the creeping flow regime have been correlated [50], none of these correlations have so far proved to be satisfactory and very few numerical studies have attempted to fill the void.

It should be noted that all the above efforts have been limited to flow past a single sphere. CFD simulations of PJM applications must, however, consider the flow of large number of particles and would require drag correlations similar to those developed based on flow in porous media or in packed beds [58,59] for Newtonian fluids. Recently, numerical techniques based on particle resolved DNS have been successfully developed and validated to simulate flows in porous media, and hence develop advanced drag correlations for poly-disperse systems [13,60-62] under Newtonian conditions. There is a wealth of information on the non-Newtonian fluid flow in porous media (see Table 7.5 in Chhabra's book [50]). However, visco-plastic fluids have received scant attention in such studies. In summary, reliable drag correlations for viscoplastic flows are limited to creeping flow past a single sphere. This was identified as a major technical gap by the experts.

In addition to the lack of constitutive models for drag force, the experts also pointed to the lack of robust solid-stress models that can seamlessly switch between the fluid-like and solid-like behaviors of the waste particles. In the non-Newtonian multiphase slurry flows, the solids settle down to form sludge banks with a yield stress. The formation of sludge banks leads to additional complication within the scope of Eulerian-Eulerian methodology as it requires tracking of miscible interface between fluid-like and sludge-like behavior of solids. That is, liquid and particles from within the sludge phase can pass into the suspension phase during pulsing. For this reason, the experts pointed to a need to develop a model for the sludge phase for which the particle volume fraction is a state variable that evolves with the flow, and in so doing permits fluid flow in and out of the sludge phase too.

- **Lack of Experimental Data:** Need for accurate experimental data cannot be over-emphasized, and a fine example can be found in Atapattu, Chhabra, Uhlherr [52] for creeping flow in viscoplastic fluids. Until their careful experiments, there existed much confusion amid numerous theories [63] and models of varying shapes and complexity for predicting the shape of yielded and unyielded regions in viscoplastic fluids. The quantification of flow fields in viscoplastic fluids in their study paved the way for validating the prediction of yielded and unyielded regions by various existing and subsequently postulated theories and models, eventually resulting in the development of a reliable drag correlation model for creeping flow past a single sphere in viscoplastic fluids [57]. The experts agreed that there is a general lack of good quality data for multiphase flows and even more so for NNMS flows. The opaque nature of flow due to the presence of fines in NNMS flows precludes the use of many advanced instrumentation techniques (such as, particle image velocimetry or PIV) that have been developed and exploited over the last few decades to understand basic flow mechanisms in single-phase and very lightly loaded flows.

  To overcome the instrumentation limitations posed by opaque nature of the slurries, the majority of the non-Newtonian experiments has been performed in microgel suspensions or concentrated emulsions. Colloidal glasses and foams are other materials used to represent viscoplastic fluids but they are not discussed here. Carbopol and CarboxyMethyl Cellulose (CMC) are examples of microgels that are polymeric gels designed to match the rheograms of the target application. Microgel materials exhibit normal stress (and hence elasticity) due to which they are not strictly viscoplastic fluids. Concentrated emulsions [64] are mixtures of two immiscible fluids where one liquid is present as droplets that are dispersed into the continuous phase of the other liquid. Concentrated emulsions can be made transparent [64,65] by matching the optical index of the continuous and dispersed phases and exhibit less elasticity. Therefore, they have been used widely in experiments of viscoplastic fluids. One of the difficulties in experimentation is designing suitable fluids that have well defined and adjustable rheological properties. For example, increasing the polymer concentration changes the shear-thinning index, consistency and yield stress simultaneously, therefore, developing fluids with independently adjustable properties is a challenge. Since NNMS flows are characterized by the presence of large particles in viscoplastic fluids, the instrumentation challenges become even more severe and will potentially require the development of new synthetic transparent fluids to represent NNMS or development of advanced instrumentation techniques.

  Noting that the development of predictive theories and numerical models cannot be done in the absence of high quality validation data obtained from careful experiments ideally spanning several length scales, the experts recommended detailed experiments that are developed based on the identification of key physical mechanisms to complement the development of advanced theories and models.
- **Lack of an Accepted Methodology for Modeling of NNMS flows:** CFD of multiphase flows has seen overwhelming transformation as a result of increased computing power and development of advanced theories and models. As a result, there is a plethora of predictive theories and numerical tools available in the literature for Newtonian multiphase flows and single-phase slurry flows but there are no accepted theories, methodologies or numerical tools for modeling of NNMS flows. This has led to a lack of clear understanding within the research community on the

accepted methodology to begin to approach development of high-fidelity CFD models for NNMS flows.

- **Lack of a Verification and Validation (V&V) Standard: Unlike** the ASME V&V 20 standard [66] for single phase, there is a lack of standard for verifying and validating multiphase CFD codes, a shortcoming compounded even further by multitude of modeling choices for multiphase flows differing significantly due to very different representations for dispersed solid phase (ranging from continuum to Lagrangian). Unlike for gas-solids flows wherein a series of challenge problems have been used to assess the validity of different models [67,68], such an exercise has not been conducted for non-Newtonian fluid flows. Notwithstanding a general lack of V&V standard for multiphase flows, the experts cited various successes at V&V'ing complex numerical models. For example, experts from Sandia National Laboratories (SNL) mentioned their success in V&V'ing numerical models used to analyze weapons performance in normal and abnormal environments, nuclear energy accident scenarios, and other high consequence applications. According to SNL researchers, V&V'ing complex solvers requires meticulous book keeping, and the need for modelers and experimentalists to work together. Despite the few examples of successful V&V'ing of complex solvers, the experts cited a general lack of standard and unavailability of high quality experimental data as primary impediments in the way of V&V'ing Newtonian and non-Newtonian multiphase CFD models.

3.2.3 Proposed Solutions

It was generally agreed that some predictive theories already exist in the commercial off-the-shelf and open-source computer codes, but they require further development and more rigorous verification & validation (V&V) in order to make them reliable for non-Newtonian design applications. The theoretical development of non-Newtonian multiphase flow models must proceed in parallel to detailed experimentation. Sub-scale experiments can be highly instrumented and will produce high quality data and are, therefore, indispensable for developing rheological models and for conducting validation and uncertainty quantification.

The experts agreed that development of an ideal model for the NNMS with the earlier discussed attributes may require a long term R&D effort. Therefore, the experts recommended a dual strategy of adapting the available tools concurrently with the development of advanced theoretical and numerical models. Specifically, lumping the fines and supernate together to be tracked as a non-Newtonian fluid (viscoplastic fluid, to be particular) as opposed to tracking supernate and fines as separate carrier and dispersed phases in the ideal NNMS model was recommended as a simplified model that could be used as a starting point to model the conditions encountered in homogenized non-Newtonian slurries in PJM vessels. There will be limitations of this simplified model; for example, it will not be valid to study startup of PJM from off-normal conditions (such as power outage), and this model will not be applicable to study precipitation of fines upon the addition of reagents. Limitations notwithstanding, this model will be able to predict other hydrodynamics of interest that are pertinent to understanding mixing and performance of WTP-PJM vessels. For both the ideal NNMS model and the simplified one, the development is complicated and challenged by common issues: presence of fast settling particles and turbulent operating conditions, to name a few. The development of predictive models or theories will require many steps, some of which are outline below:

- **Identification of Critical Gaps:** As discussed earlier, the availability of numerous theories and numerical models that are not comprehensively V&V'ed for target flow regimes have made it difficult to ascertain the current state-of-the-art in NNMS modeling. Any effort to develop predictive theories for NNMS must be preceded by an exploratory study to identify the deficiencies in existing models and to add data points in identification of future R&D needs.
- **Development of Turbulence Models:** The turbulence modeling of multiphase flows in general is a challenging prospect due to the presence and complex interaction of both the carrier phase turbulence and pseudo-turbulence arising from particle-particle and particle-fluid interactions. Turbulence modeling of multiphase flows has made dramatic progress [31] in the last decade owing to the advent of powerful computer hardware and efficient numerical methods. However, our understanding of key mechanisms responsible for turbulence attenuation, production, and cascading over scales in multiphase flows over a range of physical conditions is still lacking. PR-DNS of gas-solid suspensions resolving the flow around particles up to the smallest scales [32,41,61,69] presents itself as an excellent tool to study in-depth the above mechanisms and develop models that can be inputted into CFD simulations of PJM like applications. It should be noted that any activity relying on detailed numerical experiments (even PR-DNS) should be accompanied by detailed experiments for validation purposes.
- **Development of Non-Newtonian Drag Models:** Since the drag force term has been found to have the leading order effect on the predictive capabilities of CFD simulations, and noting the lack of reliable drag models for non-Newtonian fluids (and especially viscoplastic fluids, see the discussion under technical gaps), the experts identified the development of non-Newtonian drag model as a very high priority and on top of the list of "to do" for developing predictive theories and models for NNMS flows.

  Our understanding of viscoplastic fluids gained tremendously from the accurate experiments [52] of creeping flow past singe spheres. Several advanced theories and models were developed and validated based on this experimental data on viscoplastic flow past a single sphere which provided details on the yielded and unyielded regions due to presence of yield stress. Citing this example, the experts recommended a first-principles approach beginning from developing in-depth understanding of non-Newtonian flows in single particle systems. Reconciling the fact that the real applications are far from idealizations of single particle systems and are rather made up of swarms of clusters of particles, the experts reiterated the need to start any analysis from single particle systems as they provide useful insights into physical mechanisms uncontaminated by other complex interactions and also serve as a launching pad for analysis of more realistic applications.

  The powerful computer hardware of today allows one to perform detailed numerical simulations of flows past assembly of dispersed phase entities of varying shapes. The model development in Newtonian multiphase flows has gained tremendously from such an approach where particle resolved DNS [13,35,62,70] of gas-solids suspensions have been performed to extend the existing drag correlations to higher range of operating conditions and also to more demanding conditions of systems with particle size distribution [60,61] that are often times more difficult to measure even experimentally. A similar effort is recommended by experts for the non-Newtonian fluids as well. As is the case with any model development exercise based on modeling itself, the validation of the underlying numerical model should precede the model development efforts.

- **Development of Solid-Stress Models:** One of the conditions that occur during waste handling and treatment is the settling of large particles into sludge piles, which is observed even for viscoplastic fluids. This can occur in slurry transfer lines as well as in the mixing tanks. This can occur during normal operating conditions as well as during emergency conditions such as power interruptions. The interaction of radial wall jets from different Hanford WTP PJMs causes the formation of stagnation regions and an upward flow (upwash) is necessary for re-suspending the settled solids. Re-suspending sludge piles could pose a challenge. To accurately model the formation and break-up of sludge piles, it is necessary to include in any modeling framework a robust solid-stress model that can seamlessly switch between fluid-like and solid-like behavior of the large particles. The experts noted lack of such advanced model for solid-stresses in existing CFD models and assigned high priority to their development.
- **Model-Development Driven Experiments:** The above points on development of turbulence and drag force models have already explained the importance of this point. Since the scope of experiments for non-Newtonian fluids (or for that matter, any complex fluids) is unwieldy, it is not possible to test everything experimentally, and therefore, the experiments should be identified based on the model development needs. The scope of experiments will vary from validating the microscopic interactions required in development of drag correlation to validating macroscopic phenomena required in establishing the validity and quantifying the accuracy of CFD simulations.
- **Verification and Validation and Uncertainty Quantification of Models:** The experts agreed that V&V of numerical models is critical to the success of numerical modeling. V&V of CFD codes is a painstaking process and requires deep interaction between modelers and experimentalists. According to experts, a detailed V&V plan will allow quantifying the effect of assumptions made in the numerical models and establish their accuracy in addition to quantifying the uncertainty. These models must be verified against well-planned and well-equipped experiments that span several geometric scales in order to increase our confidence in the predictive nature of these models.
- **Development of V&V Standard:** Since there is a lack of a standard or protocol on V&V of multiphase CFD codes, the experts were unanimous on the urgency of developing a V&V standard for multiphase CFD codes that will benefit the entire research community at large. SNL has a long standing expertise in V&V [71,72] that can potentially be extended to develop V&V procedures for CFD of multiphase flows. This formalism consists of detailed steps, which could readily be applied to CFD. The first step in the validation process is development of a Phenomena Identification and Ranking Table (PIRT). This identifies all physics relevant to the application and quantifies how accurately the physics can be described with existing models. A simplified example is discussed below [73], although most PIRTs include much more detail. Once the PIRT is developed, an iterative technique is used to compare submodels to validation data in order to gain confidence in the approach. If there is poor agreement between model and experiment, the model is refined, usually by adding more complete physics. An example of such a tiered approach for multiphase flow of particle filled polymers is shown below:
    - Tier 1 ”Separable Effects” Examples:
        - Effect of particle concentration on viscosity
        - Migration of neutrally buoyant particles in simple fluids
        - Sedimentation of particles in simple fluids
    - Tier 2 “Coupled Effects” Examples:

        - Coupled particle buoyancy and migration
        - Temperature and viscosity of curing epoxy
        - Mold filling (Newtonian liquid displacing air)
    - Tier 3 "Many Coupled Effects" Examples:
        - Particle buoyancy and migration in epoxy during oven cure
        - Isothermal mold filling of particle-filled epoxy
    - Tier 4 "Full Scale Test of Real System"
        - Measure final particle state in actual manufactured part

  All four tiers of the validation process were completed and an example of this validation process can be found in a recent publication by Mondy et al. [74].
- **Use ofChallenge Problems:** The experts recommended a challenge problem concept wherein the modelers are invited to participate in simulating an application. The operating conditions and geometric details are made available to the modelers, and the data is made available only at the end of a specified time. The challenge problem will provide researchers an objective test to verify the accuracy of models and will also provide useful information on the current state-of-the-art and development needs to the community at large. To encourage broad participation, the experts recommended that some limited funding be provided to competing researchers.
- **Multi-Scale Modeling Paradigm:** The model development in Newtonian multiphase flows has gained tremendously from multi-scale modeling wherein the information flows through hierarchical models differing in levels of resolved flow details, and thus, accuracy. Several such examples have already been discussed in this report. Performing accurate but very expensive first-principles based PR-DNS simulations of idealized systems and using the drag model derived from the PR-DNS simulations in the CFD simulations of real applications is a fine example of multi-scale modeling. Likewise for the turbulence models.

  In the hierarchy of multi-scale modeling paradigm, at the top is Direct Numerical Simulations (DNS) of idealized systems (PR-DNS is a special case of DNS for disperse phase systems), where every continuum length and time scale is resolved. The PR-DNS of Newtonian multiphase systems [13,61,62,69] has led to major new insights into flows with a large number of suspended solid particles, drops and bubbles. Similarly verified and validated DEM simulations have been leveraged to develop and validate advanced particle-stress models for continuum simulations. The experts pointed to the lack of such hierarchical models in non-Newtonian flows and agreed that even a modest effort could lead to significant gains in our understanding of these flows. The experts noted the fundamental nature of such R&D activities but they also agreed that in the long run such studies are very likely to make major impact on modeling.

The development of accurate predictive theories for NNMS flows has significant benefits spanning different industries and engineering applications as well as naturally occurring processes. The inclusion of these theories in numerical codes will help guide the design and scale-up of processes as well as provide insight into troubleshooting mixing issues that can occur during the lifetime of a process. Reliable theories coupled with accurate numerical methods can provide a powerful tool to understand the scientific and engineering aspects of a process and even provide the operator information that cannot be easily determined experimentally. The high fidelity numerical models can be leveraged in future by DOE-EM in many ways and provides a cost-effective investigative tool. It can be used in performing design confirmation studies, perform exploratory studies to optimize vessel geometry/design, perform very detailed parametric studies not possible from experiments alone, or perform studies to identify critical regions for sensor placement. Many other similar possibilities exist for analyzing systems at costs that are negligible compared to actual experiments. For the cross-cutting benefits of predictive theories and models to EM and beyond, the development and application of advanced predictive theories and models for multiphase non-Newtonian theories was assigned a high priority that should be conducted alongside the other elements of the holistic design effort identified in Figure 4.

In addition to CFD modeling, the experts also pointed to non-CFD models that could potentially be applied to NNMS flows after careful review. For example, the flow of coarse particles in a non-Newtonian mixture was discussed by Darby [75] and Abulnaga [76] based on the work of Molerus [77]. Some experience and models are therefore available for NNMS in pipes, but research has been limited. Specialists for large slurry flows in mineral processing plants, mud drilling are focusing more and more on the concept of two layers and three layers models where the coarsest particles tend to move at the bottom layers at their own velocity, often encountering Coulomb friction forces that the suspended fines would not face. One approach to circumvent the difficulties of NNMS is to define a parameter of stratification, and to treat the various layers as entities with interface friction between them. In this regard, experts indicated that there are yearly conferences organized by mining industry (SME Society of Mining, Metallurgy and Exploration (www.smenet.org), Canadian Institute for Mining, Metallurgy and Petroleum (www.cim.org), PASTE (http://paste2014.com) for thickened tailings and Paste tailings. Proceedings from both conferences should be reviewed in the area of application modeling.

3.3 Topic 1c: What kind of sensors and measuring probes are needed/available?

3.3.1 Background Information

The opaque nature of NNMS flows has resulted in limited success of optics based measurement techniques that has proved to be successful in single phase flows. For example optics based techniques like laser Doppler velocimetry and particle image velocimetry are well established for measuring single phase fluid velocities for a wide range of flow conditions [78]. The measurement of fluid and particle velocities in NNMS, on the other hand, is an active area of research with different experimental techniques under development depending on the nature of the flow [79]. This has resulted in the development/adaptation of a wide variety of sensors for the purpose of measuring flow and particle concentration in NNMS. There are many experimental techniques for non-Newtonian multiphase slurry flows, but with uncertain accuracy.

The wide range of the measurement techniques that are currently being utilized to study various aspects of NNMS include non-intrusive techniques [79,80] like capacitance, electrical, ultrasound and X-ray based tomography. Also, tracer based techniques, which are essentially non-intrusive in nature, like radioactive particle tracking, particle image velocimetry, particle tracking velocimetry, laser Doppler velocimetry and positron emission particle tracking are primarily used to obtain velocity data in NNMS. Due to the inability of the non-intrusive techniques to measure accurately in all regions of the flow for a complicated applications like mixing of NNMS, intrusive techniques like piezo-pressure probes [81], optical velocity probes [82] and conductivity probes are also utilized to span the parameters space of measured data.

The main benefit of identifying and evaluating sensors is to improve engineering of a non-Newtonian multiphase flow process and control. Further it might increase the efficiency of the process thereby reducing the associated costs. As a bonus these experimental data can also be used to verify and validate the models that mimic these processes. A V&V'ed model can produce significant cost savings over the long term operation of the process.

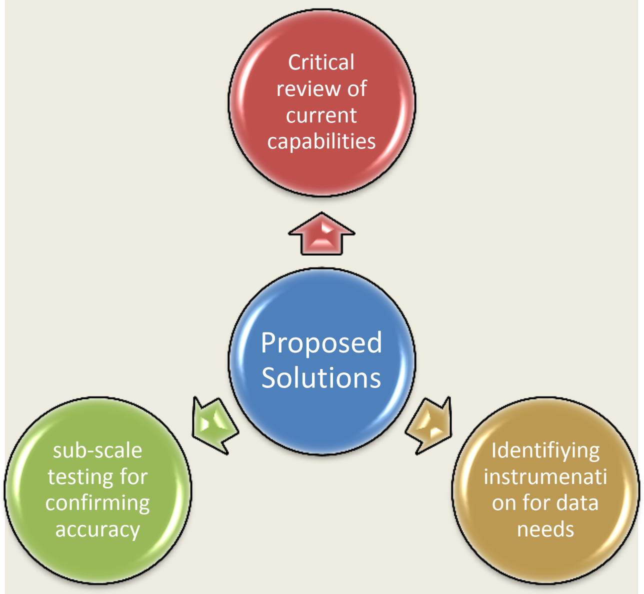
3.3.2 Challenges and Technical Gaps

- **Identifying Right Instrumentation for the Job:** The main concern of the group of experts is the identification of the right instrumentation for the data needs coupled with validation of these instrumentations for NNMS. This is due to the availability of many sensors but a lack of general applicability. Although a number of sensors/probes and other measurement techniques were suggested, there was a near unanimous view that significant short and long-term development were needed before these could be considered as ready for performing critical measurements required at Hanford WPT facilities.
- **Data Needs for Understanding NNMS Flows:** The issues regarding availability of instrumentation were broken down into specific measurement needs and capability. For example, sensors suited for full scale or sub-scale testing might not be applicable for long term monitoring and this has to be accounted for into any decision making. A variety of data needs was identified for experiments aimed at understanding NNMS flows, including: (i) accurately measuring rheology and composition of the NNMS and PSDD of particles and its properties; (ii) measuring heterogeneity in the flow caused by solids accumulation; (iii) measuring the fluid and solids velocity and the stress near the walls; (iv) measurement of pressure at different elevations and locations; (v) level measurements of NNMS with the ability to mitigate measurement port plugging; (v) measurement of erosion and corrosion, and (vi) extrapolation of the local measurements made towards global process control and extracting sufficiently accurate local information from global measurements.
- **Data Needs for Hanford WTP:** The main concern for the current WTP project is that there is a lack of thorough experimental validation along every step of the design process, including the design of simulants to mimic the actual slurry in FSVT, and appropriately adjusted simulants for sub-scale modeling to achieve the best possible similitude relative to the full scale process. Further, specific to the Hanford project, there were some serious concerns about the monitoring of the PJM operations. A meticulous analysis of the instrumentation to be utilized for PJM control, including liquid-level monitoring, has been deemed necessary especially for smooth and successful long-term operation. The lack of current efforts to properly understand the sparger effects and in-line rheology tracking were other causes of concern. However, the critical concern was regarding the lack of instrumentation in black cells, required for risk mitigation and operational assurances. The development of new sensors or improving the existing ones for monitoring the black cells was regarded as the most important long-term concern.

3.3.3 Proposed Solutions

- **Critical Review of Instruments Currently Used for NNMS:** The first step towards the selection of sensors for measurements in flows of NNMS should begin with a critical review of all of the existing technology including their scope, limitations, and accuracy. Although there was a general consensus that a variety of sensors and measurement techniques are available, there was no agreement on the specific sensors or measurement techniques that could be used in full-scale testing or the black cells in WTP.

- **Identification of Instruments for Specific Data Needs:** In addition to the widely used measurement techniques as stated at the start of this section, specific instruments were identified for addressing some of the issues raised in the meeting, these include: (i) pressure profile sensors in non-Newtonian facilities to measure static pressure at various heights; (ii) surface pressure detectors that could characterize the stagnation regions in the bottom of the tanks; (iii) corrosion and erosion monitors for sensitive regions; (iv) radiation gauges for monitoring radioactivity of waste; (v) mass spectrometer for the characterization of the waste; (vi) Gamma-ray spectrometers for detecting various species and to monitor the zone of influence or solids mobilization in PJM vessels; (vii) measuring particle concentration by observing x-ray attenuation; (viii) analyzing the nature of the flow by observing the sonograms and, (ix) measuring slurry flow rate using Magnetic flow meter.



- **Sensor Calibration and Sub-Scale Testing for Confirming Accuracy:** Appropriate facilities and/or devices should be identified and employed to adequately calibrate each type of sensor, and to determine the accuracy and sensitivity of each device. Furthermore, selected sensors (with their measurement ranges appropriately adjusted) should also be tested in the sub scale experiments to evaluate their efficacy with regard to characterizing the parameter of interest. A systematic evaluation of sensors, either already available or new designs, by making and comparing measurements in sub-scale facilities mimicking critical aspects of the NNMS flows can help in validating the usefulness of the sensors with respect to the process. Furthermore, with regards to WTP, testing the sensors in the sub-scale models might also facilitate identifying critical regions that need to be monitored in the full scale process.

Even though measurements of solid and fluid phase in non-Newtonian multiphase flow is a challenging proposition, the overarching message of the experts was that there is a variety of available sensors that could be used to satisfy the majority of data requirements. However, calibration of the sensors and the applicability of the sensors over a wide range of applications that fall under EM's purview need a comprehensive evaluation.

Additional Reading

1. *FSVT (Savannah River/PNNL) Instrumentation team report.*
2. *PNNL document; Tank Farms mixing report (RPP-RPT-53931).*
3. *PNNL Tank Farms certification loop testing report (PNNL-19441, PNNL-22029, and RPP-RPT-53930).*
4. *M3 phase 1, AZ101 mixer pump test (RPP-6548 Rev. 1).*

3.4 Topic 1d: Can we change rheological behavior of non-Newtonian slurry?

3.4.1 Background

The 56 million gallons of nuclear waste are stored in 177 underground tanks. Each tank contains a mixture of sludge, saltcake and supernatant liquids. It has been shown that the property of the waste varies from tank to tank. The rheological property of the waste is one key parameter for the design and operation of the waste processing facilities, which affects the success of safe storage, retrieval, transport, and processing operation for both the tank farms and the WTP. On one hand, it is critical to gain the best knowledge of the physical and rheological properties to be considered during the design. On the other hand, it is important to have an appropriate strategy to control the rheological behavior of each feed stream so that they meet the design requirement of each process during the operation.

This topic seeks possible approaches to alter the rheological behavior of the problematic non-Newtonian slurry so that it can be safely handled by the current design of mixing vessels, which handle Newtonian slurries well. Overall, the ultimate goal is to maintain the rheological behavior of the slurry within the scope of design to meet all mixing and safety requirements. In addition, an effective way to change the rheological behavior of the non-Newtonian slurry might become critical when an off-normal event takes place, for example, electrical power failure. At the same time, it is also of interest to WTP to increase efficiency and throughput by decreasing the water content. Therefore, a large degree of dilution with water is not desirable.

The experts were also concerned with in-situ rheology modification due to physical attrition, where large particles break up into smaller particles. Referring to Figure 6, the top 20% of waste particles are sized between 70 and 100 microns. The phenomenon of attrition was not specifically addressed during the workshop and does not seem to be discussed extensively in the open literature. Attrition is an important consideration for slurry pipelines and a number of tests are used to measure its magnitude. The release of fines or their reduction in diameter is therefore likely to modify the coefficient of rigidity and the yield stress, but the extent under the influence of pulse jet needs further investigation.

3.4.2 Challenges and Technical Gaps

The complexity of the nuclear waste leads to wide variability of the rheological behavior especially the non-Newtonian behavior which challenges any design for transportation and mixing. Rheology modifiers [83] are widely used in industrial applications to control the rheological behavior of working fluid for specific purposes. The major challenge encountered in the Hanford nuclear waste is the wide variation in material properties (based on the current knowledge) of the waste, and the lack of comprehensive characterization of the NNMS waste. Furthermore, the range of potential rheological behaviors could be even broader and more complex when different waste streams are combined, and depending on the performance of PJM, there might exist significant spatial gradients within the vessel with significant changes in the rheological properties over these gradients. In addition, the rheology behavior of waste changes with time which introduces further complexities, especially during the off-normal event such as a power outage.

3.4.3 Proposed Solutions

During the discussion in the first day breakout sessions, experts came up with various ideas for changing the rheological behavior of non-Newtonian flow. A first option would be dilution, which is believed to be the most feasible method for the current application as the solids concentration is confirmed to be the leading order parameter affecting the rheology of the non-Newtonian slurry. As the rheology of the slurry is closely related to the particle size distribution, modifying the PSD through addition/removal of fines would be another feasible approach for the purpose of controlling the rheology. Agglomeration or flocculation can be used to remove the fine particles that lead to the non-Newtonian behavior of the slurry. Modifying the electrostatic interaction (cohesion) of the fine particles was also mentioned as a possible way to change the non-Newtonian rheology. Techniques like the addition of a viscosity modifier, fine bubble aeration, liquid phase chemistry, thickening/clarification, and PH control were discussed for modifying the viscosity of the slurry. The challenges and issues in changing the rheological behavior of non-Newtonian slurry in the process were also discussed. Given the complexity of the Hanford nuclear waste and variability among different streams, the consensus was that there is no single approach that would be effective across tank farms, pre-treatment, and vitrfication facilities.

The possible steps would require a comprehensive review of existing literature in the relevant fields including reports within WTP projects (e.g. technical reports by SRNL/PNNL on rheology modifier) and past EM projects. In order to change the rheological behavior of the waste, a better understanding of the waste property and tests on the actual waste through a sub-scale testing facility will be needed. The ideas proposed above including grinding large particles, agglomeration of fine particles, floatation and anti-foam, addition of surfactants and solvents, and pH modification should be extensively tested in sub-scale experimental facility prior to application in large-scale facilities.

Although many ideas were proposed by experts to achieve this objective, one of the major concerns related to changing the rheological behavior of the non-Newtonian slurry is the downstream effects need to be investigated with any adopted approach and to ensure compatibility with the downstream processing requirements. For example, dilution is believed to be an effective method to control the yield stress of the non-Newtonian slurry given the strong correlation between the yield stress and the solid concentration. However, dilution results in substantial increase of the stream volume that needs to be processed by the facilities. This inevitably leads to extended duration of operation. Any additives added into the process for the purpose of rheology control need to be considered for the operation of the whole system under the realistic conditions.

Another outstanding issue is the difficulty to design rheology modifiers without extensive characterization of each tank as the feed stream is highly variable, and the content of each tank is different. Hence, it is critical to have good inline instrumentation as well as in-vessel monitoring systems to improve the understanding of the nature of materials in the plant. Clear knowledge of the physical and rheological properties of each feed stream is needed for successful implementation of the selected approach to control the rheology. This has been partially covered by the other topics, such as topics 1a and 2d.

There also exist numerous issues and challenges related to each possible approach of changing the rheological behavior of the problematic non-Newtonian slurry. For example, introduction of fine bubble aeration requires investigation on where and how to inject fine bubbles and the effect it has, issues related to use of organics and polymers [84], and the degradation under a radioactive environment need to be solved. The performance of modifiers in a high ionic solution also needs investigation.

To conclude, several recommendations were made based on past industrial experience and WTP studies on altering the rheological properties of the slurry. However, the experts agreed that there is no one-size-fits-all solution. Any of the above recommended steps will require careful engineering studies seeking to perform cost-benefit analysis of rheology modification by making note of key parameters of interest such as downstream compatibility, plant delays, incorporation of uncertainties due to lack of waste qualification, scale-up potential, etc. Finally, sight should not be lost of the fact that the feed rheology can also be altered through the controlled use of blending of the various materials that are currently available in the tank farm.

Additional Reading

WTP-RPP, PNNL reports on modifiers used with simulants:

1. *SRNL-STI-2011-00670, 2011 EM/SRNL Rheology Modifiers Summary Report.*
2. *SRNL-STI-2009-00697, Summary of 2009 Rheology Modifier Program.*
3. *WSRC-TR-2004-00082, Rheological Modifier Testing With DWPF Process Slurries.*
4. *WSRC-MS-2003-00136, Rheology Modifiers for Radioactive Waste Slurries.*
5. *SRNL-GPD-2004-00040, Summary of Rheological Modifiers Testing on RPP Simulant.*
6. *WSRC-MS-2005-00111, Rheology Modifiers Applied to Kaolin-Bentonite Slurries for SRNL WTP Pulse Jets Tank Pilot Work in Support of RPP at Hanford.*
7. *DP-1471, Chemical Dissolving of Sludge From a High Level Waste Tank at the Savannah River Plant*
8. *PNNL-5589, Rheological Evaluation of Pretreated Cladding Removal Waste.*

3.5 Topic 1e: Can we use Newtonian fluids to understand and bound non-Newtonian behavior?

3.5.1 Background

Under this topic, the experts brainstormed on whether Newtonian fluids bound the behavior observed in non-Newtonian multiphase slurries. This topic was considered in three different ways: 1) can experiments using Newtonian fluids be used to bound the non-Newtonian multiphase flows of interest; 2) can experiments using single phase Newtonian fluids be used to approximate NNMS in selected cases, and 3) are the current Newtonian multiphase flow computational models readily extendable to non-Newtonian multiphase flows.

The response from experts to the first point of discussion, regarding whether experiments using Newtonian fluids can bound the behavior of multiphase non-Newtonian fluids, was an overwhelming "no." The word "bounded" was interpreted here to mean that the flow behavior(s) of the multiphase non-Newtonian flows can be adequately captured using Newtonian fluids. The resounding answer of no to this very general question was principally related to the fact that Newtonian fluids are unable to simulate the formation of caverns and other stagnant regions associated with the effects of fluid yield stress and shear thinning. This is particularly true for the periodic PJM process where there are significant periods of time during which the jet cylinders are refilling, and there is no significant energy input into the flow field. This type of behavior cannot be captured using any simple Newtonian analogue system, nor can the flow features associated with shear thinning behavior, shear thickening behavior, and time dependent (thixotropic) behaviors be adequately represented by a Newtonian fluid. (Of course, the ability to create an analogue material that captures these behaviors in full scale tests is also not possible).

With regard to the second question, of whether there are examples of cases where Newtonian fluids can be used to simulate some specific non-Newtonian PJM vessels, or regions of the flow field within the vessel, the experts were able to identify a number of examples where this general approach has been successfully applied in other industrial applications. Most often this simplified approach has been used to evaluate critical regions in the flow field, or to compare the relative performance of several alternative designs where the same overall ranking could be anticipated under both Newtonian and non-Newtonian conditions. For example, under highly inertial conditions where solids particles are well mixed and the stresses at most locations exceed the fluid yield stress, single phase Newtonian flow can provide a good approximation to the flow of non-Newtonian slurries. This technique has been used to successfully design slurry feed distributors for large gravity settlers, and in the design of polymerization reactors. The experts did indicate that in many of these past studies, experiments were typically performed using both Newtonian and non-Newtonian fluids, in order to determine the degree to which the systems differed and the manner in which they differed. Armed with this understanding it was possible to determine the degree to which the less complex, and often more informative (due to the ability to use optically transparent fluids) experiments should be relied upon. It was pointed out that for fine particle suspensions which behave like Hershel-Buckley fluids, transparent analogue systems can be used to capture the shear thinning behavior in systems where the fluid yield stress is exceeded throughout the flow field (or flow field region) of interest.

It was agreed by the experts, however, that considerable caution would be required if this approach (of using Newtonian fluids to bound NNMS flows) was to be used in the development program given that the Hanford waste is not anticipated to be well-mixed, and settling and re-suspension of heavy particles is a periodic occurrence. Since the settling of particles and their subsequent re-suspension (like in WTP-PJM vessels) is characteristically different in Newtonian and non-Newtonian flows; from the discussion above, the use of Newtonian systems would not be a logical choice as the primary development platform, except perhaps for specific experiments as identified above. Furthermore, it was noted that there is a general lack of knowledge of non-Newtonian multiphase flows under turbulent flow conditions and such an approach has not been successfully demonstrated for loaded systems operating under conditions similar to WTP PJM vessels or tank farm conditions In summary, even though under special conditions it is possible to bound behavior of non-Newtonian multiphase flows by Newtonian fluids, according to experts, the complexities of turbulent NNMS flows inside Hanford WTP PJM vessels does not permit such a simplification. Experiments with Newtonian fluid could potentially add value but only if executed wisely within a larger program using non-Newtonian fluids.

With regard to the third argument of adapting Newtonian multiphase numerical models for non-Newtonian multiphase slurry, the experts agreed that a simple extension of a solid stress model to Bingham like fluid (Newtonian + Yield stress) along with a density dependent model for yield stress and viscosity could possibly be used as a first step. However, it was noted that such a simple fix is only a first-order approximation and will again require coupling with detailed experiments to validate the model. This simple model will most likely predict very different characteristics for stagnant regions and will not bound re-suspension characteristics that are a periodic occurrence over the drive and suction phases of WTP PJM vessels. Additionally, such a model will not be able to capture the suspension's transition from Bingham rheology to pressure-sensitive yield strength rheology. Nevertheless, such a modeling approach can inform on many hydrodynamic aspects of the WTP-PJM NNMS vessels.

3.5.2 Challenges and Technical Gaps

As part of the design confirmation activities for heavily loaded PJM vessels at Hanford WTP where non-Newtonian rheology was expected, the use of Newtonian vessels was recommended under the assumption that they bound the non-Newtonian mixing conditions. Further testing to prove the underlying assumption did not yield conclusive data and the recommended approach of using Newtonian vessels was abandoned. During the workshop the experts concurred that Newtonian fluids are bounding of the macroscopic behavior of non-Newtonian flows for specific cases (such as, high shear rates) or within specific sub-regions. While some of the experts did not recognize any advantage in using Newtonian fluids to design applications using non-Newtonian fluids, others indicated past success when applied to specific cases with appropriate knowledge and insight. The experts were concerned that the numerous technical gaps in our current understanding of NNMS flows would not be satisfactorily answered using only Newtonian fluids.

3.5.3 Proposed Solutions

Due to the aforementioned reasons, the majority of experts had very strong reservations related to using Newtonian conditions to bound non-Newtonian conditions from an experimental viewpoint, and, therefore, did not recommend that Newtonian fluids be used with this goal in mind. A Newtonian multiphase model extended to a Bingham-like fluid (Newtonian + Yield stress) was proposed as a possible first step. Although such a model will be a first-order approximation at best, it can still be useful to learn about stress distributions. The Bingham fluid model could be used to model regions (responses) that might be beneficial to inform full-scale testing. Series of experiments with a fluid possessing an yield stress coupled with a simple Bingham fluid model could be used to gauge the influence of fluid yield stress on key mixing concerns (such as dead zones).

The major benefit of using a simple extension of current Newtonian multiphase models is the quick turnaround time since many mature, commercial, and open source versions of Newtonian multiphase flow models are already available. Although the CFD simulations with a Bingham-like fluid model will not accurately predict many of the characteristics of non-Newtonian flows, they can still be leveraged to understand auxiliary physical phenomena, such as understanding of stress distribution, or used limitedly to identify regions of interest for detailed instrumentation during full scale testing or any other experimental test campaign. CFD modeling frameworks are readily available and implementation of a Bingham-like fluid model would require only small investment in time and cost. But the results should be regarded as preliminary only and validation of such a model must be systematically conducted. A more detailed discussion on developing predictive theories and models for NNMS was carried out under Topic 1d: *What predictive theories are available for non-Newtonian multiphase flows?*

Additional Reading

1. *Slurry hydrocracking in the oil industry.*
2. *Scale vessel testing using clay suspension and Newtonian fluids with larger un-dissolved solids, this work was performed by WTP.*
3. *External Review Team (ERT) position paper on Large Scale Integrated Testing (LSIT) and contractor's subsequent response.*

3.6 Topic 2a: What's the accepted practice in scaling for non-Newtonian multiphase slurries?

3.6.1 Background

Scaling of physical problems using dimensional analysis allows us to express them in their simplest form by reducing the number of variables used to describe these problems, and providing a framework to ensure maximum similitude at different scales and using different fluids. The resulting set of dimensionless variables should be enough to scale-up or –down a natural or industrial process, assuming that all the relevant parameters were identified at the outset. This, however, is not always feasible in complex multiphase flow systems [85,86] owing to the number of non-dimensional groups involved and the inability to find appropriate material properties to address changes in scale. In many instances it is not necessary to match all the non-dimensional groups to achieve a high level of similitude. For example, in stirred tank studies the normalized mixing time and power number become invariant above a critical Reynolds number, or in fluidization studies the very large difference between particle diameter and vessel diameter means that it is not necessary to reduce the particle diameter in proportion to the reduction in vessel diameter in a reduced scale model. Indeed, in the case of fluidized beds reducing the particle diameter in proportion to the bed diameter is generally problematic because (for practical reasons) it is not always possible to fabricate a different particle size/density that will exactly mimic the behavior of the original one, and even more importantly it is not possible to significantly reduce the size/density of a particle without modifying the physics of the problem since other forces, such as Van der Waals and electrostatics, may become dominant in a small system whereas they could be safely ignored at larger scales. In other instances however, the fluid and particle properties can be adjusted to compensate to some degree for the change in scale, resulting in a much higher degree of similitude compared to using the full scale fluids or full scale simulant. It is therefore important to test any assumption made in the derivation of the dimensionless variables with experiments conducted at different scales and quantify the uncertainty associated with these assumptions. Modeling and simulations can be conducted along with experiments to help understand the experimental data, which in turn can be used to refine the modeling approach and numerical codes.

The experts strongly agreed that conducting sub-scale experiments is important in understanding the flow dynamics and operational performance of PJM vessels. Sub-scale experiments are cheaper to conduct and can usually be equipped with sensors that are able to gather more data. These experiments are faster to conduct and can, thus, span a wider range of operating conditions. In order to design an appropriate sub-scale vessel, the leading-order dimensionless variables need to be determined from the accumulated experience of industrial practitioners. Since some full-scale testing will be conducted, it will be possible to verify the validity of the leading dimensionless parameters in reproducing key observations, such as particles re-suspension. In case key phenomena cannot be reproduced with sufficient accuracy, the assumptions in the dimensional analysis need to be revisited and alternatively lower scaling factors may be used in order to minimize the risk and uncertainty inherent to scaling these complex systems.

3.6.2 Challenges and Technical Gaps

The main issues raised during the workshop were due to the wide range of scales encountered in large multiphase non-Newtonian vessels. As far as WTP is concerned, the vessel diameters range from 10ft to 47ft while the PJM nozzle is only 4in. While the complexity of the geometry of the full-scale vessels with all the internals makes it difficult to scale down the design, fabrication techniques are available to meet these requirements. Due to the PJM working mechanism, the flow is unsteady with transitions from possibly stagnant regions to very slow flowing to highly turbulent multiphase jets. While the wide range of length scales and time scales, and the limitations associated with creating the required simulant properties, makes it very difficult to achieve complete similitude in full scale models and reduced scale models, the benefits (described above) of physical modelling, and in particular reduced scale models, are very significant. The introduction of appropriate scale factors can compensate for the lack of similitude assuming that the appropriate flow regimes and fundamental behaviors are captured in the model, and assuming that appropriate and a sufficient number of experiments are performed, preferably over a range of scales. Caution is required because certain physics may not even be considered in the dimensional analysis due to the inability to define the appropriate parameters, and while limiting the scale reduction to low scaling factors can reduce the mismatch by reducing the effects of scale, problems will still exist of the simulant not capturing the salient behavior of the actual materials. For example, the effect of chemistry due to the radioactivity and certain process needs to be accounted in terms of the slurry behavior. Therefore any non-dimensional analysis must be verified experimentally, which may be difficult and expensive to conduct for different scale factors for a wide range of flow conditions. In order to simulate the non-Newtonian fluids relevant to Hanford it is especially important to adjust the rheology of the simulants as a function of scale using the framework of dimensional analysis.

3.6.3 Proposed Solutions

Considering the time and cost of full-scale testing, it is strongly recommended by the experts that scaling should be considered as a high priority considering its ability to augment full-scale testing with sub-scale experiments. The study of scaling starts with the performance of a dimensional analysis to produce non-dimensional groups. An understanding of the physics involved in the multiphase non-Newtonian flows can help reduce even further the set of dimensionless groups and also identify and prioritize key independent parameters that have the most influence on the process. These critical groups need to match as closely as possible between the small- and full-scale experimental vessels. Due to the fact that some mismatch of the dimensionless groups is usually unavoidable [87-89], it is important to conduct validation studies at different scales in order to estimate the uncertainty and risks associated with the different assumptions and simplifications. Similar work was conducted in the past in analyzing dimensionless groups in fluidized beds and it was suggested to revisit this work as well as some of the assumptions used to create a simplified set of groups deemed necessary for scaling. It was also recommended to conduct modeling and simulation [90] along with experiments in order to develop a robust mathematical description of the physics that can be helpful for further design and troubleshooting of the process. It was noted at the workshop that the combination of both experiments and modeling has worked well for the industry.

The direct benefits of scaling laws are the ability to produce faster and cheaper reliable data at a small- and medium-scale instead of the lengthy and prohibitively expensive full-scale testing. Also smaller vessels are usually better equipped with sensors and can deliver high precision data over a wider range of operating conditions. These experimental data can be used not only to inform and direct testing in the full-scale unit but can also be used to validate computational models and develop better predictive theories.

Considerable effort by both WTP contractor and PNNL has led to a series of scaling documents, but with more emphasis on Newtonian than NNMS. A review of these reports is a necessary first step.

3.7 Topic 2b: How to simulate the Hanford nuclear waste and account for that uncertainty in an experimental test plan (PSDD and chemistry)?

3.7.1 Background

The Hanford nuclear waste, or for that matter, most of the nuclear waste at other sites under the purview of EM, is a complex mixture of heavy metals, radioactive material, and chemicals capable of causing serious contamination to the subsurface, water aquifers, or the nearby flowing rivers. The nuclear waste stored in tank farms is a complex mixture of sludge, saltcake and supernatant liquids. The Hanford waste is made up of streams from different processes during the Plutonium production with very limited data on actual waste qualification. Among other complexities of the Hanford waste, the uncertainty in qualification of suspended waste particles in terms of their size, shape, density, particle-particle interactions causing agglomeration, etc., is in focus here. As shown in Figure 6, the waste exhibits a very wide particle size and density distribution (PSDD) with particle size ranging from submicron particles to 1 mm sized particles. The particles in the waste have different shapes and experience agglomeration and breakup under different processes. Figure 9 shows some Scanning Electron Micrographs (SEM) obtained for the sludge particles [91-93]. In addition to the wide PSDD and shape factors, there exist complex waste chemistry affecting solids agglomeration and dissolvability. Further compounding the analysis is the fact that the waste properties vary widely from tank to tank.

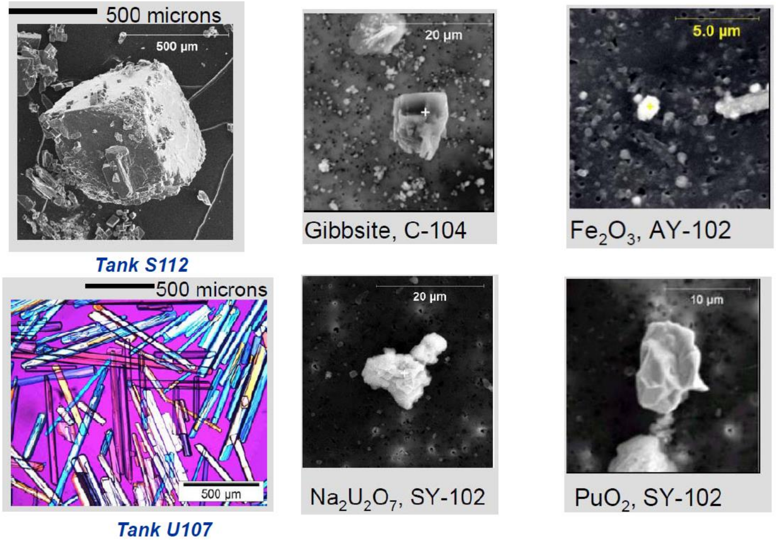


Figure 9 Scanning Electron Micrographs of sludge particles in Hanford nuclear waste.

The confirmation of the design of mixing vessels at Hanford WTP is based on performing experiments with waste simulant that is desired to be representative of the actual waste. The simulant development is one of the most important aspects of the design confirmation study and there are many practical reasons for the development of a simulant with a defined particle-size and density that will mimic the fluid dynamic and rheological properties of Hanford Nuclear waste in an appropriate fashion. While it is necessary to include all the important factors in the development of the simulants, and to account for the relevant uncertainties through carefully planned experiments, it is not necessary to identically match the simulants but rather the behavior. Due to the hazardous environment and the associated cost of sampling and analyzing nuclear waste, the experts reconciled to the reality that the waste might not be fully qualified ever, and therefore, recommended basing design on the most conservative particle properties derived from the combination of available data and any limited future sampling.

Due to the lack of waste qualification and various chemical processes undergone by the waste as it finds its way through the WTP, the design confirmation studies should include off-design waste specification. Given the infinite possibilities of off-design waste specification, such objective evaluation of waste uncertainty on mixing performance becomes intractable, and even more so at full vessel scale levels (as currently planned at Hanford) due to the prohibitive costs. Under this topic, the experts discussed ways to include the actual waste uncertainty into the design confirmation studies.

3.7.2 Challenges and Technical Issues

It is critical to understand the rheology and PSDD of the real nuclear waste material at the Hanford tank farms in order to properly simulate the nuclear waste and account for uncertainty in an experimental test plan. The lack of waste qualification of the real nuclear material at the Hanford tank farms as discussed in Section 2.1.2 was identified as the major challenge for incorporating the uncertainties in PSDD and chemistry into the experimental test plan. Furthermore, without proper quantification of the accuracy of the waste characterization, it is challenging to define the uncertainties associated with PSDD and waste chemistry in the developed stimulants.

So far considerable effort has been invested in the development of representative simulants based on the historical measurements of PSDD from tank waste samples. The uncertainties associated with the waste beyond what has been characterized thus far (such as cohesion and agglomeration issues) were identified to be a gap that needs to be filled.

3.7.3 Proposed Solutions

- **Comprehensive Review:** Large quantity of data has been collected by DOE-ORP through work contracted out to PNNL and BNI. The experts agreed that a comprehensive review of the existing data that has been collected by PNNL and BNI is a necessary first step.
- **Better Waste Qualification:** The lack of actual waste qualification is the biggest source of uncertainty and experts recommended more sampling based on cost-benefit analysis. Robotic sampling and development of remote capabilities for analysis was recommended to streamline waste sampling and analysis. Current activities involving transfer of waste from single shell to double shell tanks presents itself as an opportunity for increased waste sampling and analysis.
- **Sub-Scale Testing Coupled with Scaling/Dimensional Analysis:** Due to the prohibitive cost incurred in objective evaluation of waste uncertainty at full-scale, the experts recommended testing over range of scales smaller than the actual vessels. According to experts, the appropriate sub-scales and simulant make up (PSDD) should selected on the basis of dimensional analysis with the highest priority given to the most critical non-dimensional groups in order to achieve the higher degree of similitude possible. Past empirical experience with comparable systems should be used to (a) guide the specific form of the non-dimensional groups and (b) assist in developing an appropriate experimental strategy. Sub-scale tests are also ideally suited for parametric study of variables affecting key waste properties, such as, density, and porosity, etc, at least in those respects where the flow exhibits adequate similitude with the full scale system. Considering the time and cost of full-scale experimental test, small- and medium-scale testing has been recommended as the key approach to investigate the uncertainties due to wide PSDD, shape, and

complex chemistry. Acknowledging the limits to data collection in FSVT, a series of sub-scale tests to determine the failure point under the worst case scenario was recommended while matching the most critical non-dimensional group as accurately as possible. Sub-scale testing over a wide range of simulants will provide critical failure data points that will point to additional testing at full scale.

- **Modeling:** Recognizing that the CFD of Newtonian multiphase flow is much further along and models exist that have been implemented in numerical tools, the experts recommended Newtonian CFD modeling as a cost-effective tool in understanding the effect of different simulant makeups on mixing and transport of waste streams under lightly loaded conditions. Modeling can be used in conjunction with scaling analysis to identify critical non-dimensional groups for defining sub-scale testing mentioned above.
- **Leveraging Industrial Experience:** Although several issues are unique to Hanford waste, the effect of particle settling and agglomeration due to precipitation of ions from chemical reactions has several parallels in other industries (such as, mining) that produced solids by sulfidation and precipitation. The experts recommended consulting with such industries to study the effect of chemistry that cannot be readily incorporated in waste simulants.

The direct benefits of simulating the Hanford waste are to reduce uncertainty, experimental time, cost, and addresses safety issues. Sub-scale testing over a range of scales may be conducted at offsite facilities using a simulant and available state-of-the-art techniques to safely test at a lower costs and under a wider parametric space to produce reliable data that will complement the data obtained during full-scale testing. These experimental data can be used not only to inform and direct testing in the full-scale unit but will also provide insight into defining critical factors that are important during the Hanford waste treatment process.

Additional Reading

1. *WTP/RPP-MOA-PNNL-00624, Kurath, D. E. to Hazen, H. R., LSIT Analytical Electronic Data Transmittal Supporting Simulant Qualification for Computational Fluid Dynamics Testing, March 2012.*
2. *24590-WTP-GPG-RTD-004, Rev. 3, Guidelines for Simulant Development, Approval, Validation, and Documentation, 2012.*
3. *24590-WTP-GPG-RTD-001, Rev. 0, Guidelines for Performing Chemical, Physical, and Rheological Properties Measurements, May 2012.*
4. *WTP-RPT-201, Simulated waste for Leaching and Filtration Studies – Laboratory Preparation Procedure.*
5. *WTP-RPT-190, PEP Run Report for Simulant Shakedown/Functional Testing.*
6. *WTP-RPT-189, Deposition Velocities of Non-Newtonian Slurries in Pipelines: Complex Simulant Testing.*
7. *WTP-RPT-184, Development and Characterization of Boehmite Component Simulant.*
8. *WTP-RPT-180, Preparation and Characterization of Chemical Plugs Based on Selected Hanford Waste Simulants.*
9. *WTP-RPT-111, Non-Newtonian Slurry Simulant Development and Selection for Pulse Jet Mixer Testing.*
10. *WTP-RPT-088, AP-101 Simulant Validation for Cesium Ion Exchange Processing using SuperLig® 644.*
11. *WTP-RPT-060, Filtration of Envelope C Waste Simulant Treated by the Sr/TRU Precipitation Process.*
12. *WTP-RTP-057, AP-101 Diluted Feed (Envelope A) Simulant Development Report.*
13. *BNFL-RPT-033, Development of Inactive High Level Waste Envelope D Simulant for Scaled Cross-flow Filtration Testing.*
14. *WTP-RPT-076, Characterization of Hanford Tanks 241-AN-102 and AZ-101 Washed Solids with X-Ray Diffraction, Scanning Electron Microscopy, and Light-Scattering Particle Analysis.*

15. *WTP-RPT-153, Estimate of Hanford Waste Insoluble Solid Particle Size and Density Distribution*.
16. *WTP-RPT-154, Estimate of Hanford Waste Rheology and Settling Behavior*.
17. *WTP-RPT-176, Development and Characterization of Gibbsite Component Simulant*.

3.8 Topic 2c: Is there a need to maintain a testing facility during plant operation to test for off-normal conditions or for troubleshooting?

3.8.1 Background

The hazardous environments under which the applications handling nuclear wastes are operating do not typically lend themselves to be readily accessible for future troubleshooting or maintenance. The WTP plant at the Hanford site is designed around black-cells that are enclosed concrete rooms within the WTP Pretreatment facility containing mixing vessels and densely spaced piping. Due to high levels of radioactivity once the plant begins operations, the cells are designed to be sealed with no access by personnel over the anticipated 40-year operating lifespan of the plant. Under this topic, the experts were apprised of the current plans for long-term plant operations with the objective of stimulating a discussion on the necessity or usefulness of maintaining a parallel testing facility during the plant operations.

3.8.2 Challenges and Technical Gaps

Confirmation of the design of PJM mixing vessels has proven to be very challenging with efforts on-going in this regard. Even with the design confirmed, the operating conditions tested are based on well-defined operating envelopes based on best estimates for material rheological and physical properties that include some foreseeable off-normal conditions. However, such testing is still very limited as it cannot incorporate the large sources of uncertainty arising out of the lack of actual waste qualification. Additionally, during the normal plant operations, there is always the possibility that some PJMs may go offline in a given vessel, and the infinite number of such possible failure scenarios cannot all be foreseen and included in testing campaigns, however efforts can and will be made to identify the worst case scenarios and to confirm the ability of the proposed design to address these most difficult scenarios.

The current plan at Hanford WTP calls for confirming the design of PJM vessels through full-scale vessel testing as mandated by the former Energy Secretary Dr. Steven Chu. The testing will be performed on actual black-cell vessels that will be installed in their respective black-cell subsequent to full-scale testing. Currently there are no plans to identify critical vessels or other equipment exposed to the risk of off-normal conditions caused by very different waste rheology, PJM failure, or other catastrophic failures during the full scale test campaign.

3.8.3 Proposed Solutions

An overwhelming majority of the experts recommended a testing facility during the plant's life cycle for various reasons that are described below, but the experts differed on the scale and scope of the testing facility with recommendations including sub-scale models of all vessels, full-scale models of critical vessels, a pilot-scale model (along with process simulator) of the entire WTP, or a combination of the aforementioned. The issue of identifying appropriate sub-scale models for the testing facility could be resolved by embarking on a scaling/dimensional analysis that was discussed in detail under Topic 2a. According to experts, some of the advantages of above recommendations are:

- **Smooth Plant Operations:** Due to the limited nature of the testing to confirm design of the mixing vessels and large sources of physical uncertainty arising from waste properties and chemical processes, a parallel facility will provide a cost-effective platform to test the effect of off-design specification waste on PJM vessel performance. Other off-normal conditions (such as, failure of some PJM's, restart from power outage, etc.) that cannot all be currently anticipated can also be effectively studied in this facility in a cost-effective and timely manner.

Advantages of a testing facility

- ✓ *Trouble shooting and testing off-normal conditions*
- ✓ *Failure anticipation and preventive maintenance*
- ✓ *Model development*
- ✓ *Build confidence in process safety*
- ✓ *Development of new sensors*
- ✓ *Everything at significantly reduced cost than building a new facility each time a need arises*

- **Anticipation of Failure and Preventive Maintenance:** Even a comprehensive testing campaign aimed at confirming design of these vessels cannot objectively include all the possible scenarios that might cause the vessel failure. A parallel testing facility running in conjunction with the plant can provide a very useful window into the long term working and reliability of the black-cell vessels. The data obtained from this parallel facility can be leveraged to anticipate failures and perform pre-emptive maintenance to avoid costly plant shutdowns causing project delays.
- **Development and Testing of New Instrumentation:** The parallel testing facility will also provide a great prototypic platform to develop or test new instrumentation (probes, sensors, etc.). Availability of this testing facility can be used to develop and test instrumentation needs for other DOE projects as well.
- **Development of Models:** The data obtained from this parallel facility will be beneficial in further enhancing our fundamental understanding of NNMS. The data will not only be invaluable in improving the current theory of NNMS flows and fill critical gaps, it will provide fundamental data required to develop, validate, and quantify the uncertainty of the hierarchy of numerical models ranging from simple reduced order models (ROM) to sophisticated CFD like models having state-of-the-art treatment for stresses in the solid phases and closures for inter-phase interactions derived from first-principles. This suite of verified and validated models provides an excellent tool to perform parametric studies with respect to critical variables at details not possible from any experiments. In addition, the models developed here are not solely limited in their use to PJM vessels and will prove to be great tool in other similar endeavors involving NNMS flows. Verification and validation of numerical models is a time-intensive and costly exercise and the leveraging of data from this parallel facility is a tremendous opportunity.

The experts also noted that, over the long term, the cost of this parallel facility will be justifiable based on the above benefits. It will also provide a training facility for safety and emergency operations. The experts cited various industries that maintain a parallel testing facility but the exact size and scope of the parallel facility could not be agreed upon by the experts as there is no one-size fits all solution. Nevertheless, the experts strongly supported the idea of parallel facility and several experts cited examples of their clients who have intentionally kept all of the testing vessels and capability intact, at least until the plant gets through the commissioning stages. The experts cited a number of incidents over the years where they restored a testing facility back in service to answer critical questions that arose post-commissioning of the plant.

3.9 Topic 2d: What kind of monitoring is needed at WTP and how will the data be used for control and troubleshooting during plant operation?

3.9.1 Background Information

During the design phase of the Hanford WTP it was decided to place WTP-PJM vessels in a sealed environment with no human access in order to minimize health hazards to the personnel maintaining the facility. These cells, referred to as "Black Cells," (shown as yellow regions in the Figure 10) provide a unique engineering challenge as they are expected to run without direct human intervention for more than 40 years. The amount of radioactivity in these cells has greatly reduced the number of sensors which could be used to monitor them, and as a result the current plan specifies a very limited sensing of level measurements for PJM operations.

This limited monitoring is currently raising concerns and this topic was placed before the group of experts for their opinion. The main benefit of proper monitoring of the "black cells," using various sensors and instrumentation, at the WTP plant is the ability to anticipate potential failures beforehand, raise the level of safety, and improve the efficiency of plant operations. In addition these instruments and sensors will act as virtual continuous experiments that will provide data for years to come regarding non-Newtonian multiphase flows. This data not only can help to increase the understanding of NNMS it will also help in reducing costs and increasing efficiency of other non-Newtonian processes and applications of interest to EM.

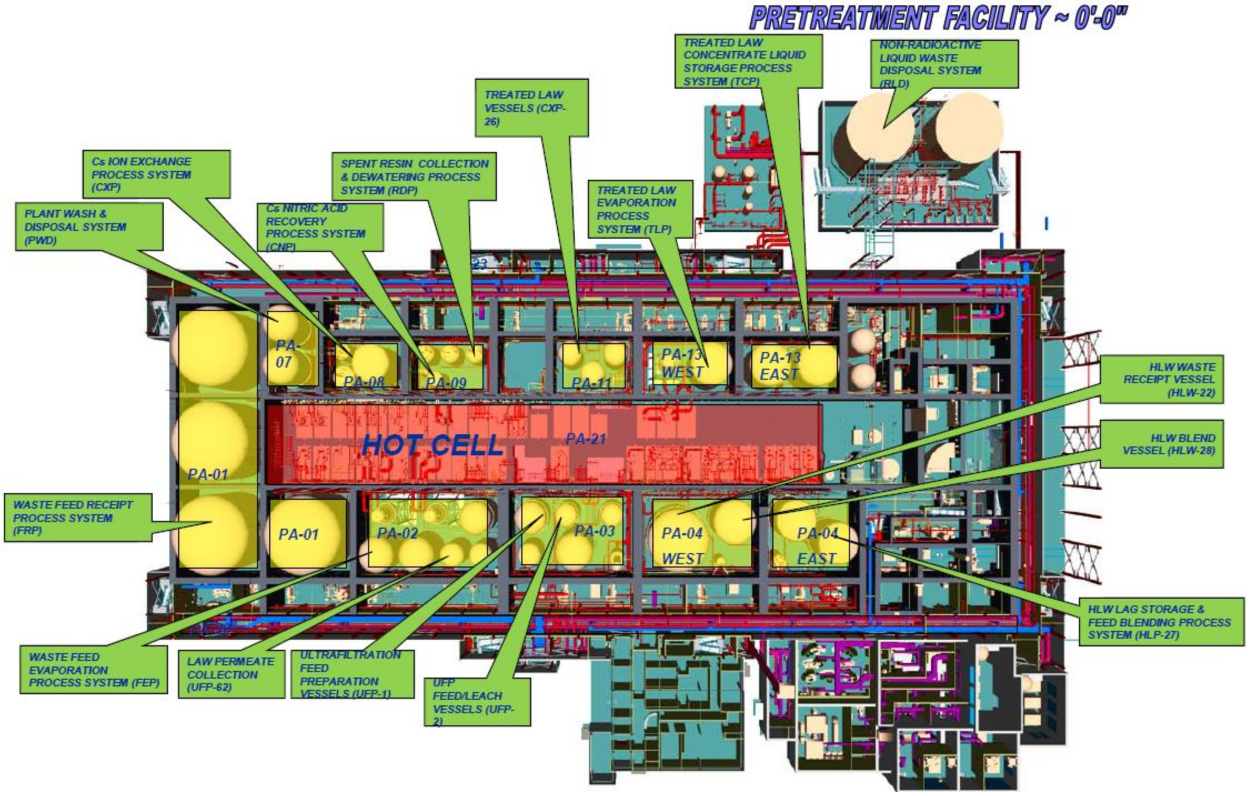


Figure 10: Isometric view of the Pre-treatment section of Hanford's WTP

3.9.2 Challenges and Technical Gaps

- **Lack of Monitoring of Criticality in Black Cell Tanks:** The current lack of instrumentation in the "black cells" raised major concern among the workshop attendees. In particular the lack of continuous radiation monitoring to detect any potential buildup was deemed as a critical flaw in the current design. It will also be necessary from a safety and operational point of view to monitor several other process variables related to the transport of slurry between different vessels to ensure its properties are within specified limits. The most important of these are erosion and corrosion in the pipes, hydrogen release in the vessels, and plugging of the slurry transfer lines.
- **Concern Over Long Term PJM Reliability Without Monitoring:** Since the PJM's are the primary flow controllers in the tanks, monitoring of the state of individual PJM's in a continuous manner has been deemed as a critical need identified by the experts at the workshop. An uncontrolled array of PJM's will likely become unstable, as decreased performance of one PJM in an array may lead to local solids buildup, which will further decrease performance of that PJM and jeopardize the ability of that vessel to meet safety and mixing requirements. If detailed in-situ monitoring of individual PJMs in a sealed tank can't be done, at a minimum the air flow into each PJM should be monitored with appropriate orifice metering (or some other appropriate means). The experts agreed that individual control on each PJM of a given array should be considered and used at WTP to manage possible failures and improve performance. The experts recommended sub-scale testing to understand how non-synchronized firing of the PJM's could be used at full-scale and confirm any conclusions during planned full-scale testing.

- **Cost/Benefit Analysis of Monitoring:** Given the hazardous radioactive environment, it is recognized that some of these technologies might not be deployable as is and will require careful assessment. Use of any monitoring technique should include a cost/benefit analysis.
- **Need for Efficient Process for Nuclear Certification of Sensors:** During the workshop discussions, the requirement of an efficient certification process for the fabricators of the monitoring systems for nuclear applications was discussed in detail. The current WTP operations present a significant opportunity to develop the standards for this industry.

3.9.3 Proposed Solutions

- **Monitoring Radioactivity and Flow Features in the Tanks:** At a minimum, access tubes in array form to the exterior of each tank need to be provided through the concrete wall surrounding each of the black cells. An array of radiation detectors at the exterior of the tank will permit determination of distribution of radioactive material (in particular, to provide early warning of the buildup of highly radioactive and/or fissile materials). An array of acoustic sensors may provide a map of the distribution of suspension/fluids via sonar techniques. External acoustic sensors also may (through appropriate modeling) be able to determine attenuation of PJM jets (e.g., flow sound die-off away from the jet apex). Since such sensors would necessarily degrade in a highly radioactive environment, access tubes would permit replacement and upgrading during the expected 40 year operating lifetime.
- **Instrumenting the Pipes Entering the Black cells:** Piping leading to each tank should be monitored to determine as best as possible the material flowing into and out of each tank; e.g. monitoring of radioactivity in the slurry before and after the mixing vessels, using radiation detectors and, if possible, X-ray tomography to determine slurry concentration distribution in the inlet pipe, as well as velocity distribution.
- **Advanced Testing of Sensors:** Due to the harsh working environment of these sensors a thorough testing of all instruments is essential before installing them into the vessels. These tests should be performed in an appropriate test and calibration system to confirm their ability to work under these harsh conditions, and that an appropriate level of measurement accuracy can be achieved. Untested instruments could be responsible for a number of false alarms disrupting plant operations, and therefore robust and accurate performance is essential. Where possible these sensors should be evaluated as part of any scale model testing program, with appropriate adjustments in measurement ranges etc. to properly address the differences between the sub-scale model and the full scale configuration. Testing these sensors in the sub-scale models may also provide insight into potential failure mechanisms.
- **Periodic Upgrading of the Sensors:** Since the WTP is planned to be in operation for over 40 years, any way to periodically replace or upgrade sensors as failure occurs and technology improves will greatly increase the reliability of operations. Additionally, this will improve the quality of the data being collected, which will aid in improving the understanding of NNMS.

The experts from mining industry also drew various parallels with slurry flows at Hanford WTP and connected it with the empirical data often used in their applications for predicting the performance or failure. The experts identified various parameters from mining industry that could be further refined to suit Hanford WTP needs. Most non-Newtonian mixing processes examine four parameters

- Torque per volume

- Power per volume
- Power per area
- Retention time

The torque per volume correlation accounts for the importance of the overall yield stress but the data pertains to rotating agitators. The information is therefore difficult to translate to agitation by oscillating columns in pulse jet mixing vessels at Hanford. The experts would have to develop a new practical parameter that the engineers can use in their design.

The power per volume correlation pertains mostly to Newtonian mixing. Data on power number are available for different impellers but equivalent numbers are absent for pulsejet. A power correlation if developed would be able to encompass some of the difficulties of various ranges of rheology without excessive impact on operation.

The powers per area and retention time are often used in mineral processing plants as a measure of attrition. A similar correlation would have to be developed to give the engineers meaningful tools for the operation of the plant.

3.10 Topic 2e: What is the existing industrial experience useful for long-term black-cell operations?

3.10.1 Background

The Hanford WTP waste treatment plant is essentially a chemical mixing process that will go into continuous operation for over 40 years whose various vessels will operate in both steady- and non-steady-state chemical modes. Long term operations is a vital concern, and developing partnerships with industry will help in reducing long term costs and in increasing reliability by having access to proven technology, technical innovation, and experience.

3.10.2 Challenges and Technical Gaps

In this topic area, the general discussion was focused on the issues that are inherent to black-cell long-term operations. Firstly, the highly radioactive mixing tanks will be inaccessible to humans for the treatment plant's lifetime. Second, fresh leaks of the 56 million gallons of nuclear waste stored in 177 underground tanks will have a significant long term effect on the environment, therefore processing of the Hanford waste has a high priority. Third, the Hanford clean-up process, which separates the waste into high-level and low-activity wastes, sends the waste to WTP for processing, and this operation must function for at least 40 years. In addition to this, the pulse jet mixing scheme may present additional problems, (i) the accumulation of clustered radioactive material (e.g., improper mixing or solids accumulation) could result in criticality and (ii) forced stirring of the solids-heavy wastes could result in erosion and corrosion of the waste treatment vessels. A primary issue of concern was how to assess the erosion/corrosion in these mixing vessels and in the transfer lines. Although PNNL and BNFL have conducted some work on corrosion and erosion [94-96], additional work is needed.

3.10.3 Proposed Solutions

Possible steps to address the challenges discussed above include conducting a lessons-learned exercise from the nuclear industry. For example, in 2005, a pipe feeding a black cell tank at Sellafield cracked open and leaked uranium and plutonium into 22,000 gallons of nitric acid. The cell contained the leak;

however, operators did not discover the leak until three months later. The plant was subsequently shut down for two years. In addition to existing experience in the nuclear industry, lessons learned from the mining industry about handling hazardous tailings would also be valuable. The processing of chemical and biological weapons, deep space exploration systems and instrumentations are other areas of expertise that could be used. The design and analysis of the WTP facility using commercial simulators (e.g., Honeywell, IDEAS, Aspen Plus, etc.) was also proposed.

Mineral processing industry regularly deals with harsh environments, and the methods they use to comply with environmental regulations could be adopted at Hanford site as well. Some of these methods are:

- Double contained pipes for tailings in pristine areas
- When double contained is not used, lined trenches with leak detection
- Leaks monitored through probes
- Installation of vaults to contain leaks
- Rubber-lined pipes, chromium carbide overlaid pipes for wear resistance
- Bends at five times the pipe diameter for long radius elbows
- Erosion monitors at certain strategic elbows
- Monitoring loops at start of long distance pipelines with pressure measurements to evaluate changes of rheology
- Chemical destruction of cyanide or cyanide recovery
- In-line flocculation in pipelines to control yield stress at the point of disposal
- Special test rigs such as stand wheels and toroidal wheels to measure attrition of friable solids
- Multi-layer models for engineering pipelines of mixtures of coarse and fine particles
- Seepage monitoring under dykes

Additional Reading

1. *Presentations from the 2008 DOE Slurry Retrieval, Pipeline Transport & Plugging and Mixing Workshop could provide additional input in the risks associated with solids handling and unique process designs.*

4 SUMMARY

The previous section summarized the technical issues and proposed solutions to increase the understanding of NNMS flows in applications across various offices managed by DOE, particularly Office of Environmental Management. During the workshop several fundamental R&D needs were identified by the experts. Fulfilling these R&D needs may require a time-frame longer than the time available for addressing the issues faced at Hanford WTP; nonetheless, they are important for advancing the engineering science of NNMS flows. The impact of these fundamental R&D efforts would not be limited to WTP applications solely, but a host of applications found in many other industrial processes will also stand to benefit from a better understanding of NNMS flows.

Addressing the fundamental R&D needs will require a holistic design approach identified as one of the key recommendations from this workshop. This holistic design approach calls for simultaneous research efforts in the development of predictive theories, numerical modeling, dimensional analysis, sub-scale testing, and advanced instrumentation techniques that will all together provide better insight into the dynamics of NNMS flows. Technical gaps were identified under each of these design elements that in many instances require fundamental R&D due to a complete lack of necessary information. Embarking on such an endeavor will require not only monetary and time investments, but will also require bringing together a diverse group of researchers working from a common understanding of the current state-of-the-art in NNMS flows and a common goal to assign future R&D efforts. This workshop report strived to provide information that can be used to begin to formulate research efforts around a common starting point by identifying experts, challenges, gaps, resources and recommendations for possible future research paths. This information and the possible solution strategies defined in this report provide a technical basis to conduct future workshops aimed at developing detailed R&D plans necessary for addressing technical issues identified in this workshop.

To increase the understanding of NNMS and accelerate development and deployment of NNMS computational tools, experimental R&D efforts are needed. New non-intrusive measurement techniques that can be used for opaque NNMS systems for measuring NNMS characteristics such as density, yield stress, viscosity, particle concentration, etc. are needed. Techniques are also needed for measuring velocity and stress distributions in slurry flows. Future work should also include modifications to existing sensors for NNMS measurements such as acoustics, ultrasound, MRI, x-ray and γ-ray tomography, positron emission particle tracking, etc. Many experimental and instrumentation techniques were discussed during the workshop and it was generally agreed that some of the widely used instrumentation techniques will require significant development in order to be used for opaque slurry flows. Representative materials that can be made optically transparent should also be investigated to further our understanding of NNMS flows.

New predictive theories and numerical models are needed for designing NNMS applications in the future. Many modeling approaches were discussed during the workshop but a common understanding of the need to model a non-Newtonian colloidal suspension coupled to a (settling) solid phase of large particles was established and recommended as a natural starting point to any future NNMS modeling R&D efforts.

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APPENDIX A WORKSHOP AGENDA

NETL's non-Newtonian multiphase slurry workshop

Understanding rheological changes in non-Newtonian slurries

August 19-20, 2013

NETL Morgantown Campus

Morgantown, West Virginia

Meeting Objective

Develop a roadmap to address technical issues associated with storage/handling/treatment of non-Newtonian multiphase slurry waste

- Develop fundamental understanding of the mechanisms responsible for rheological changes in non-Newtonian multiphase slurries
- Assessing the state-of-the-art in knowledge of non-Newtonian multiphase slurries
- Define steps to be taken to scale-up with confidence

<table>
<tr><th colspan="6">Monday, August 19
B26-G51C</th></tr>
<tr><th>Start</th><th>End</th><th colspan="3">Topic</th><th>Facilitator</th></tr>
<tr><td>8:00</td><td></td><td colspan="3">Arrival/Orientation/Coffee</td><td></td></tr>
<tr><td>8:25</td><td>8:30</td><td colspan="3"><i>Safety and Security Briefing</i></td><td></td></tr>
<tr><td>8:30</td><td>8:45</td><td colspan="3">Welcome and Introduction</td><td>M. Syamlal</td></tr>
<tr><td>8:45</td><td>9:00</td><td colspan="3">Welcome and DOE-EM perspectives</td><td>R. Rimando</td></tr>
<tr><td>9:00</td><td>9:20</td><td colspan="3">Slurry Handling: Flow and Mixing, what we can and cannot do</td><td>A. Etchells</td></tr>
<tr><td>9:20</td><td>9:40</td><td colspan="3">Constitutive Modeling of Dense Granular Flow</td><td>K. Kamrin</td></tr>
<tr><td>9:40</td><td>10:00</td><td colspan="3">Migration & Rheology in Concentrated Suspensions</td><td>D. Leighton</td></tr>
<tr><td>10:00</td><td>10:30</td><td colspan="3">Breakout Session Organization and Topic Area One Introduction</td><td>C. Guenther</td></tr>
<tr><th colspan="6">Parallel Discussions on Topic Area One: State-of-the-art in non-Newtonian Multiphase Slurry Flows</th></tr>
<tr><td>10:30</td><td>12:30</td><td>Group 1
C. Guenther
B26-G22</td><td>Group 2
S. Benyahia
B2-SBEUC Viz Room</td><td colspan="2">Group 3
R. Garg
B2-AVESTAR Conf. Room</td></tr>
<tr><td>12:30</td><td>1:30</td><td colspan="4">Lunch (on your own)</td></tr>
<tr><td>1:30</td><td>2:00</td><td colspan="3">Topic Area Two Introduction</td><td>C. Guenther</td></tr>
<tr><th colspan="6">Parallel Discussions on Topic Area Two:
Scaling up with confidence and Ensuring Safe and Reliable Long-term Operation</th></tr>
<tr><td>2:00</td><td>4:30</td><td>Group 1
C. Guenther
B26-G22</td><td>Group 2
S. Benyahia
B2-SBEUC Viz Room</td><td colspan="2">Group 3
R. Garg
B2-AVESTAR Conf. Room</td></tr>
<tr><td>4:30</td><td>5:00</td><td colspan="3">Day One Closing Remarks</td><td>C. Guenther</td></tr>
</table>

Tuesday, August 20 **B26-G51C**			
Start	**End**	**Topic**	**Facilitator**
8:00		Arrival/Orientation/Coffee	
8:30	10:15	Topic Area One: State-of-the-art in non-Newtonian Multiphase Slurry Flows	**C. Guenther** **S. Benyahia** **R. Garg**
10:15	10:45	Break	
10:45	12:30	Topic Area Two: Scaling up with confidence and Ensuring Safe and Reliable Long-term Operation	**C. Guenther** **S. Benyahia** **R. Garg**
12:30	1:30	Lunch (on your own)	
1:30	2:30	**Development of Draft Roadmap**	**C. Guenther**
2:30	3:00	**Closing Remarks, Next Steps and Adjourn**	
3:00	4:00	Optional NETL lab tour. Please sign up on Day 1.	

APPENDIX B WORKSHOP PARTICIPANT LIST

Name	Affiliation
Alberto Aliseda	University of Washington
Altan Turgut	Naval Research Laboratory
Andrea Prosperetti	Johns Hopkins University
Arthur Etchells	AWEIII Enterprises
Baha Abulnaga	Fluor Corporation
Balaji Gopalan	NETL/WVURC
Beric Wells	Pacific Northwest National Laboratory
Bill Rogers	NETL/U.S. DOE
Chris Guenther	NETL/U.S. DOE
Darwin Kiel	Coanda Research & Dev. Corp.
David Leighton	University of Notre Dame
David Rector	Pacific Northwest National Laboratory
Duan Zhang	Los Alamos National Laboratory
Duane Miller	NETL/URS Corporation
Erich Hansen	Savannah River Nuclear Solutions
George Bergantz	University of Washington
Gretar Tryggvason	University of Notre Dame
James Fort	Pacific Northwest National Laboratory
Jeffrey Morris	City College of New York
Jennifer Sinclair Curtis	University of Florida
Joel Peltier	Bechtel
John Schultz	U.S. Department of Energy
Ken Kamrin	Massachusetts Institute of Technology
Lian-Ping Wang	University of Delaware
Madhava Syamlal	NETL/U.S. DOE
Melany L. Hunt	California Institute of Technology
Michael Thien	Washington River Protection Solutions
Perry Meyer (Observer)	Defense Nuclear Facilities Safety Board
Rahul Garg	NETL/URS Corporation
Rekha Rao	Sandia National Laboratory
Richard Calabrese	University of Maryland
Ricky Bang	U.S. Department of Energy
Rodrigo Rimando	U.S. Department of Energy
S. "Bala" Balachandar	University of Florida
Sankaran Sundaresan	Princeton University
Sofiane Benyahia	NETL/U.S. DOE
Thomas Michener	Pacific Northwest National Laboratory
Tingwen Li	NETL/URS Corporation
William Hartt	P&G

Below is a short description of the research activities and academic background of the workshop attendees who responded to this request.

Altan Turgut
Altan.Turgut@nrl.navy.mil
Background:
Altan received the PhD degree in Marine Physics from the University of Miami in 1990. His research interests include the development of acoustical methods for remote sensing of sediment properties.

Andrea Prosperetti
prosperetti@jhu.edu
C.A. Miller Professor
Johns Hopkins University
Background:
Professor Prosperetti's interests are in the general field of the analysis and computation of multiphase flows with special emphasis on particles, drops and bubbles. His most recent work deals with the formulation of averaged equations for disperse particle flows and in the formulation of physics-based closures by means of computational ensemble averaging. To this end he has developed a novel computational method for the full-Navier-Stokes simulation of finite-size particles at finite Reynolds numbers which has recently been implemented in a GPU environment. Professor Prosperetti is the Editor in Chief of the International Journal of Multiphase Flow

Baha Abulnaga
Baha.Abulnaga@fluor.com
Technical Director for Fluor
Subject Matter Expert on Slurry Systems and Pipelines
Fluor Corporation
Background:
He is the author of "Slurry Systems Handbook" – McGraw-Hill 2002. He has developed a mathematical model for open channel flows of non-Newtonian slurries based on the use of the Reynolds Number and the Hedstrom Number, known as the "Abulnaga approach". He has published papers on a two-layer approach, Densimetric Froude Number, Hydraulic jumps for open channel slurry flow as well as transient analysis of pipe flow. He co-invented a process for recovery of ultra-fine catalysts from Slurry Hydrocracking processes owned by Chevron. He is also listed as an inventor for a liquid piston engine with an oscillating column, an impeller for a slurry centrifugal concentrator and has developed special impellers with split vanes for slurry pumps. He holds degrees in Aeronautical Engineering, Materials Engineering and Economic Development.

Balaji Gopalan
gopalanb@netl.doe.gov
Research Engineer
West Virginia University Research Corporation
Background:
Dr. Gopalan's research focuses on study of turbulent multiphase flow with dilute to dense concentration in a Lagrangian framework. His primary interest is exploring these phenomena using experimental measurements including pattern recognition and automated particle tracking, holography, particle image velocimetry and laser Doppler velocimetry.

Beric E. Wells

Beric.Wells@pnnl.gov
Senior Research Engineer
Pacific Northwest National Laboratory
Background:
Mr. Wells has developed his knowledge of the Hanford tank wastes during evaluations of gas release phenomena, liquid and solid pipeline transport and tank leak detection, and waste dilution and jet mixing of Newtonian and non-Newtonian fluids with analytical and numerical simulations of physical and chemical processes. He developed a unique approach for approximating Hanford waste solid particle size and density distributions, and is the lead author of the summary of Hanford waste physical and rheological data and gaps. Recently, Mr. Wells has supported the Hanford Tank Farm contractor for DNFSB 2010-2 deliverables developing waste simulants for the waste feed delivery systems and evaluating the capabilities of those systems to deliver waste feed to the WTP.

Chris Guenther

chris.guenther@netl.doe.gov
Director, Computational Science Division,
Office of Research and Development,
National Energy Technology Laboratory
Background:
Chris Guenther's research experience has focused on model development and validation of reacting, densely loaded gas-solid systems. The primary focus of this research was centered on developing full-scale Eulerian-Eulerian models for advanced fossil energy coal gasification devices. His current work has been leading a team of NETL, contractor and university researchers in providing comments and recommendations into the use of Pulse Jet Mixers (PJM) at the Waste Treatment & Immobilization Plant (WTP) to process nuclear waste at the Hanford site located in the state of Washington. His team has provided surveillance of DOE's Office of River Protection (ORP) contractor's verification and validation of computational fluid dynamics software, as it was being applied for design confirmation of the Pulse Jet Mixing vessels. Recently, his efforts have shifted to reviewing and providing recommendations to ORP into the full-scale vessel test plans for design verification of WTP PJM vessels.

Darwin Kiel, Ph.D.

darwin.kiel@coanda.ca
Mechanical Engineering
University of Alberta
Ph.D. Engineering (fluid dynamics)
University of Cambridge
Background:
Darwin obtained his B.SC.as well as his M.Sc. in mechanical engineering from the University of Alberta, and his Ph.D. in Engineering (fluid dynamics) from the University of Cambridge. Darwin worked for Nova Corporation in Calgary (AB) as a senior research scientist for three years prior to founding Coanda Research and Development Corporation (Coanda). Coanda is an industrial fluid dynamics research and development company devoted to supporting industry and government in the field of fluid dynamics and process engineering. With over fifty employees located in its offices and laboratories in Burnaby (BC), Edmonton (AB) and Calgary (AB), Coanda is able to offer extensive capabilities in physical modelling, computational fluid dynamics, analytical modelling and instrumentation development. Over the last 18

years Coanda has worked on diverse problems for many industries, including extensive work in the area of multi-phase non-Newtonian flows.

David Leighton
dtl@nd.edu
Professor
University of Notre Dame
Background:
Principally known for his seminal work on particle migration in concentrated suspensions, Professor Leighton's research interests are in the areas of fluid mechanics and separation processes. Of particular interest is the way in which mathematics may be applied to improve our understanding of physical processes that occur in these areas. Current research projects include the study of flow-induced microstructure in concentrated suspensions, shear-induced migration and segregation in bidisperse suspensions, and dispersion in chip-based micro-laboratories. Most recently, his research group has been studying the balance between inertial migration and shear-induced dispersion in dilute rotating flows.

Duan Z. Zhang
dzhang@lanl.gov
Scientist, Team Leader, Theoretical Division
Los Alamos National Laboratory
Background:
Dr. Zhang's research includes theories and computational methods for multiphase flows, dense granular flows, and fluid-structure interactions. He has developed double averaged equations to consider effects of meso-scale structures in multiphase flows, uncovered time correlations in dense granular systems. Recently he has developed the dual domain material point method to study extreme deformation of materials, such as solid pulverization and transitions from fluid-structure interactions into multiphase flows. His theories and numerical methods have been implemented into CartaBlanca code, which has many users in defense, petroleum, chemical and mining industries.

Erich Hansen
erich.hansen@srnl.doe.gov
Fellow Engineer
Savannah River National Laboratory
Background:
Mr. Hansen's has worked over the past 18 years supporting the various waste processing facilities at the Savannah River Site ,with respect to physical characterization of simulants and actual wastes and addressing mixing, pumping and transfer problems. He is also the lead at SRNL for rheology. Presently he is a member of an expert review team that has been involved in the review of both Hanford tank farm and WTP scaled testing programs to address technical issues raised by stake holders. He is also presently involved with the Full Scale Vessel Testing program, leading the sampling efforts, but is also involved with many other aspects of the program for test document, execution and reporting of results.

George Bergantz
bergantz@u.washington.edu
University of Washington
Professor
Background:

Professor Bergantz's interests are in the quantitative treatment of geologic transport processes at a variety of scales and in a variety of settings. His research group has as its main emphasis the physics of magmas, hydrothermal systems, metamorphism and eruption processes. The group's studies provide complementary elements for the view that the generation of petrologic diversity and magmatism is a crustal-scale process. To this end, the group is working on tying together the process of melt generation and transport in the deep crust and mantle, the ascent and hybridization of magmas in the mid-crust and the assembly and life-cycles of volcanic systems.

Gretar Tryggvason
gtryggva@nd.edu
Professor
University of Notre Dame
Background:
Professor Tryggvason's research focuses on computations of multiphase flow, with a particular emphasis on direct numerical simulations (DNS) of gas-liquid and liquid-liquid flows. He has developed numerical methods for simulations of flows with sharp interfaces, including flows with phase change, such as boiling and solidification, electrohydrodynamics, and mass transfer and reactions. He and his collaborators have used these methods to study a broad range of problems, including turbulent bubbly flows and droplet breakup and collisions. Recent work has focused on various multiscale aspects of multiphase flows, including the use of analytical descriptions of small-scale processes and the use of DNS to develop models for the average behavior of the large- flows.

Jeff Morris
morris@ccny.cuny.edu
Professor and Chair of Chemical Engineering
City College of New York
Background:
Professor Morris and his research group is interested in developing a fluid mechanical description appropriate for complex fluids, particularly slurries, suspensions, and colloids. Applying simulation and experiment, combined with ideas of statistical and continuum mechanics, the research seeks to develop understanding of flow-induced microstructure and the resulting mixture rheology. Of particular interest are rheologically-induced phenomena unique to mixtures, including bulk particle migration, and the large-scale fluid mechanics of rheologically complex materials. He is author of the text "A Physical Introduction to Suspension Dynamics" with E. Guazzelli.

Jennifer Sinclair Curtis
jcurtis@che.ufl.edu
University of Florida Distinguished
Professor
Background:
Professor Curtis focuses on fundamental predictive models for fluid-particle flows (gas-solid and liquid-solid systems). Her current research is on the development of fundamental models in the 'transitional' regime - between the inertia-dominated and the macroviscous regimes of fluid-particle flow – for which there is a lack of detailed, non-intrusive flow measurements. Her research involves laser Doppler velocimetry experimentation in a unique, pilot-scale, slurry flow loop. By varying the flow velocity, particle concentration, and particle size, her group spans the range of particulate flow regimes.

Ken Kamrin
kkamrin@mit.edu
Professor, MIT
Background:

Prof. Kamrin's research focuses on theoretical and computational continuum mechanics with an emphasis is on highly-deforming bulk materials such as granular materials, complex fluids, and plastically compliant solids. A significant overarching goal is to improve the modeling of problems that combine fluid- and solid-like behaviors together, either geometrically (as in fluid-structure interaction), or constitutively (as in viscoplastic material flow). Recently, Kamrin has developed a nonlocal continuum approach that greatly improves flow predictions of granular materials in general geometries. Kamrin also developed a rapid, fully-Eulerian simulation method for general problems where fluids interact with soft solids, as a well as a toolbox of new techniques to aid in homogenizing surface interactions when fluids flow against textured surfaces.

Lian-Ping Wang
lwang@udel.edu
Professor of Mechanical Engineering and Physical Ocean Science and Engineering
University of Delaware
Background:

Professor Wang uses advanced simulation tools and theoretical methods to study multiphase flows and transport. He is interested in studying fundamental physics in turbulent multiphase flows, as well as computational fluid dynamics modeling of complex flows in industrial, natural, and biological systems. He is currently developing computational tools to study collision rates and growth of cloud droplets in atmospheric clouds and its impact on warm rain development. He also develops numerical methods to study complex fluid flow and particle transport in fuel cells and soil porous media. Recently, he has developed a particle-resolving simulation tool to study turbulence modulation by finite-size particles.

Madhava Syamlal
Madhava.syamlal@netl.doe.gov
Focus Area Leader
National Energy Technology Laboratory
Background:

Dr. Syamlal leads the Computational Science and Engineering Focus Area at NETL, responsible for the development of science-based simulations that span a broad range of scales for accelerating energy technology development. He also serves as Director of the Carbon Capture Simulation Initiative, a multi-lab, multi-university, industry team that is developing the simulation tools needed for accelerating carbon capture technology development. His expertise is in developing the theory and numerical techniques for multiphase computational fluid dynamics. He has been the founding architect of the widely used open-source code MFIX and made major contributions toward developing software for coupling device- and plant-scale simulations and the C3M chemical kinetics software. He participated in the NETL team that reviewed the modeling of WTP mixing vessels.

Melany L. Hunt
hunt@caltech.edu
Professor and Vice Provost
CalTech
Background:

Professor Hunt's research interest includes liquid-saturated flows of particulate materials. Her group has designed a new particle-liquid rheometer to measure the shear and normal forces for a liquid-solid mixture. These experiments provide a unique opportunity to explore the transition from transport in a pure Newtonian fluid to transport occurring during a dense flow of particles.

Rahul Garg
rahul.garg@*netl.doe.gov*
Research Engineer
URS Corp.
Background:
Dr. Garg focuses on modeling and simulations of reactive multiphase flows. His research has revealed several aspects of the physics of gas-solid flows through the use of particle-resolved direct numerical simulations. He is a core member of the development team for MFIX, which is NETL's in house code for reactive multiphase flows and has been active in developing DEM and MPPIC models in MFIX. Dr. Garg has been providing oversight to the Office of River Protection for the Hanford project over the last two years, initially on contractor's CFD V&V plan to design mixing vessels at WTP and currently reviewing and providing recommendations on the full scale vessel testing plan.

Rekha Rao
rrrao@sandia.gov
Principal Member of Technical Staff
Sandia National Laboratories
Background:
Dr. Rao is a developer and user of finite element software and mathematical models for computational fluid dynamics and multiphysics applications, including free and moving boundary problems and non-Newtonian fluid mechanics. She has worked on a variety of projects during her 22+ years at Sandia, including low-level radioactive waste disposal, flow-through porous media, viscoelastic flows, coating flows, polymerizing suspensions for encapsulation, fluid-solid interactions, injection loading of green ceramics, foam process models for encapsulation, mold filling for manufacturing, thermal batteries, and nuclear waste reprocessing. She is interested in developing the simplest possible engineering models for complex phenomena, while including as much physics as necessary to validate the models experimentally.

S. "Bala" Balachandar
bala1s@ufl.edu
University of Florida
Department of Mechanical and Aerospace Engineering
William F. Powers Professor
Background:
Professor Balachandar has expertise in modeling and large scale simulations of transitional and turbulent multiphase flows. He has been investigating the complex interaction between carrier phase turbulence and suspended particles in the context of a variety of environmental and geophysical flows. His research group has also been making fundamental progress in the field of compressible multiphase flow, advancing modeling and simulation capabilities appropriate for shock-particle interactions and explosive dispersal of particles. Of particular interest are multiscale strategies that couple from the microscale physics around clusters of particles to meso and macro-scale predictive simulations.

Sankaran Sundaresan
sundar@princeton.edu
Professor
Princeton University

Background:
Professor Sundaresan's research has uncovered the origin and hierarchy of instabilities leading to formation of various meso-scale structures in gas-liquid flows in trickle beds, fluid-solid flows in gas- and liquid-fluidized beds, granular flows, and dilute gas-solid flows in vertical pipes. He has developed coarsened equations of motion for two-phase flows, to enable the simulation of flows in large process vessels, which is otherwise not feasible with existing simulation methods. Another area of his research is in the flow of dense assemblies of granular materials, encountered in many devices used to handle and mix particles. He is developing models for the frictional stresses transmitted through sustained contact of particles with multiple neighbors, which play an important role in the flow behavior obtained in such devices.

Sofiane Benyahia
sofiane.benyahia@netl.doe.gov
Research Engineer
NETL/DOE

Background:
Dr. Benyahia's research focuses on modeling and simulations of fluidization and fluid-particle systems. His current research is on the effects of cohesive forces on the fluidization of small particles. He has applied both continuum kinetic theories as well as discrete particle methods to better understand the flow behavior of fluid-particle systems. He has collaborated with leading researchers to validate turbulence theories, granular frictional models, and sub-grid multiphase models.

Tingwen Li
tingwen.li@contr.netl.doe.gov
Research Engineer
URS Corp.

Background:
Dr. Li is an onsite contractor of NETL and has been the member of NETL's expert team for review of Bechtel's CFD plan for modeling of pulse jet mixing (PJM) vessels at the Hanford Tank Waste Treatment and Immobilization Plant (WTP) since 2011. His research interests are in area of multiphase flow and CFD. Specifically, he has extensive experience in modeling various gas-solids fluidization systems and several relevant industrial processes.